origin and evolution of ATMOSPHERES and OCEANS

Approximately fifty physicists, earth scientists, and astronomers met April 8 and 9, 1963, at the Goddard Institute for Space Studies in New York City to discuss the origin and evolution of atmospheres and oceans. The conference, organized by H. H. Hess of Princeton University and A. G. W. Cameron of the Goddard Institute, was the fourth held at the Institute on topics which have a special bearing on the main lines of inquiry in the space program. Previous meetings have dealt with the origin of the solar system, the planet Jupiter, and radio sources. The authors are all associated with the Goddard Institute.

By *A. G. W. Cameron, P. J. Brancazio,* and *N. W. Panagakos*

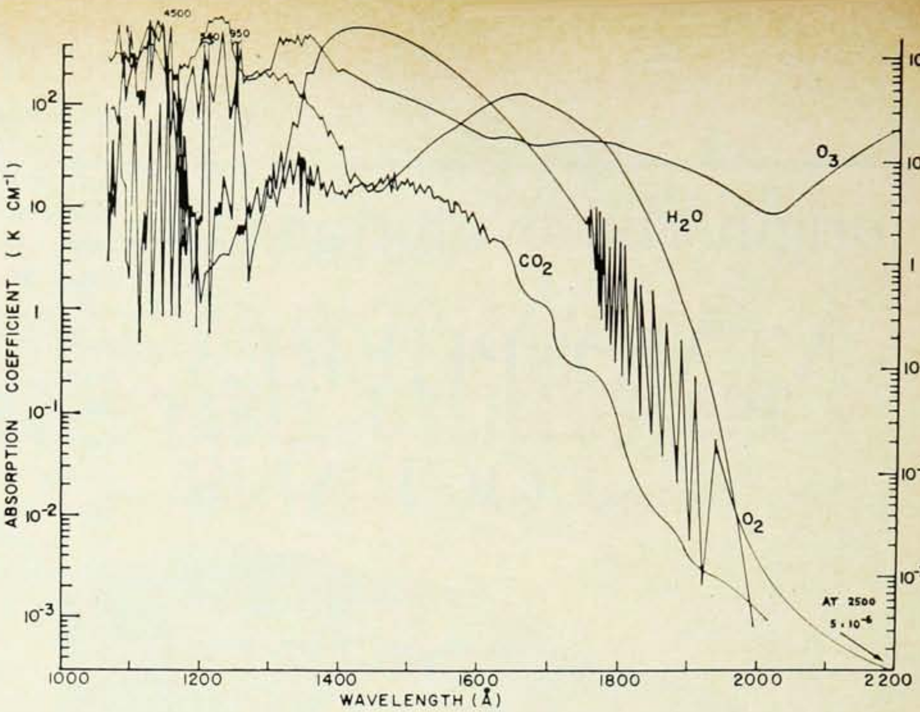
In recent years it has become evident that the atmosphere and oceans have been produced by the outgassing of volatile materials from the earth's interior, principally from volcanoes. In 1950 W. W. Rubey presented geological evidence indicating that sea water has progressively accumulated in this way. At about the same time, Harrison Brown pointed out that the very low abundances of the noble gases in the earth's atmosphere constituted compelling evidence that at least the atmospheric oxygen and nitrogen were almost entirely of secondary origin, having been outgassed, possibly in different chemical form.

The main purpose of the 1963 conference was to consider new evidence for mechanisms which might add to or subtract from the contents of the atmosphere and oceans, and to consider mechanisms which could contribute to the origin of atmospheres of other planets. H. H. Hess opened the discussion with a consideration of the problems of convection currents in planetary mantles. The important factor is the time between nucleosynthesis and the formation of the solid planet. The protoplanet will contain radioactive materials which generate heat, and the rate at which it is generated will decrease as the activity of the radioisotopes decreases. A planet may or may not have convection, depending on whether enough radioactive materials remain in the mantle to cause vigorous heating at the base.

K. K. Turekian of Yale University discussed some models for the degassing of argon from the earth. He showed that at least eighty percent of the argon now in the atmosphere must have come from the mantle. He proposed that the most useful degassing model appeared to be one with continuous degassing of the earth as a whole. Turekian pointed out, however, that one should be careful in applying the results thus obtained to the escape of the other rare gases from the earth.

L. V. Berkner of the Southwest Center for Advanced Studies, Dallas, Texas, discussed the origin of oxygen in the earth's atmosphere. According to Berkner, the existence of an appreciable atmosphere of oxygen implies the presence of life. He pointed out that the production of oxygen in the primitive atmosphere from the photochemical dissociation of water would in turn lead to a layer of ozone in the atmosphere. The ozone layer is a buffer against the destruction of terrestrial life as we know it by the ultraviolet rays of the sun. If the amount of oxygen in the atmosphere were very small, the ozone layer would occur at ground level, and the sun's ultraviolet radiation would

H. H. Hess, left, of Princeton University's Geology Department, talks to G. J. F. MacDonald, center, of the University of California at Los Angeles, and Thomas Gold of Cornell.



Ultraviolet absorption by various atmospheric constituents, as presented by L. V. Berkner of the Southwest Center for Advanced Studies. The absorption beyond 2000 angstroms is almost entirely due to ozone.

penetrate to the surface. In such a harmful environment, life would be unable to emerge from the seas onto land.

Tracing the history of the earth's atmosphere, Berkner pointed out that a sufficiently long period of time had to elapse for marine life to produce sufficient oxygen to change the composition of the atmosphere and produce high-lying ozone layers. When this took place, life was able to emerge—first in plant form, then in animal form in perhaps a few million years.

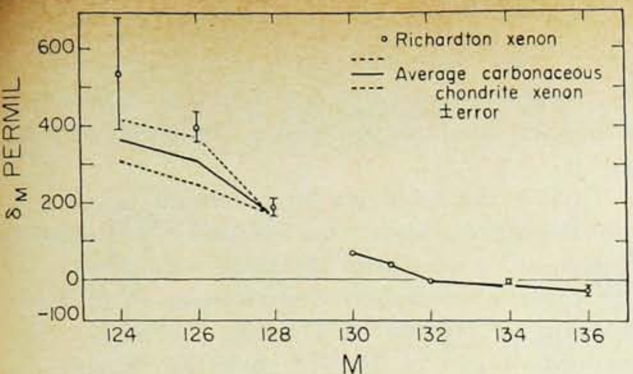
The helium problem was examined by G.J.F. MacDonald of the University of California at Los Angeles. He pointed out that if it is assumed that the escape of gases from the earth's atmosphere is due only to temperature effects, then the rate of influx of helium by outgassing is larger than the rate of escape. The helium in the earth's atmosphere should be building up at a rapid rate, but this is not the case. MacDonald noted that analyses of satellite drag data by I. Harris and W. Priester showed that an additional heat source derived from the solar wind is necessary to account for the time variations in the temperature of the upper atmosphere. He also noted that if the earth's magnetic field was at one time significantly stronger, as indicated by measurements of ancient baked clay, the interaction between the field and solar plasma could increase the heating of the upper atmosphere. This could account for a greater rate of escape of helium, averaged over a long time scale.

R. O. Pepin discussed some of the recent work done by J. R. Reynolds and his group at the University of California, Berkeley, in the field of "xenology"—the study of the isotopic abundances of the xenon isotopes. These studies are providing considerable information about the early history of the solar system; for example, the anomalously high abundance of ^{129}Xe resulting from the decay of primordial ^{129}I allows us to obtain the formation ages of meteorites. He pointed out that the relative abundances of the xenon isotopes differ for different types of meteorites and, in particular, the isotopic abundances of the xenon isotopes in the earth's atmosphere differ from the abundances found in meteorites. The problem is to account for all these anomalies.

In this respect, Pepin cited the work of W. B. Clarke, who conducted heating experiments on irradiated uranium oxide samples. Clarke found that the xenon evolved at low temperatures was isotopically different from that evolved at high temperatures. The inference is that the isotopic anomalies may be due to temperature fractionation effects on a fissionogenic component of the xenon gas.

Among the studies done by the Berkeley group was an analysis of some deep-seated terrestrial rocks. They found that the xenon evolved from these rocks contained a fission component resulting from uranium spontaneous fission. This suggests the feasibility of a U-Xe dating method, to be used in conjunction with other established dating techniques.

Peter Signer of the University of Minnesota showed that the abundances of primordial gases in meteorites are generally similar to those in the atmosphere or in the sun only when there is a great amount of this gas in the meteorites. If the



Comparison between the general anomalies in xenon from the Richardton stone meteorite (an ordinary chrondrite) and in xenon from carbonaceous chondrites.

Seated in the cabin of his balloon observatory, Audouin Dollfus of the Observatoire de Paris prepares for a flight in which he attempted to detect extraterrestrial water.

amount of gas is small, then a very large degree of fractionation can occur among the elements.

In order to understand the composition of the earth's atmosphere, one must be able to explain the differences between the isotopic abundances of xenon isotopes in meteorites and in the earth. A.G.W. Cameron of the Goddard Institute for Space Studies interpreted the differences in abundances of the light "shielded" xenon isotopes as resulting from neutron capture in the sun during the deuterium-burning stage of early solar history. However, this interpretation requires that the bulk of the xenon in the earth's atmosphere should have once been in the sun, and that it has since been captured by the earth from the solar wind.

The composition of Mercury's atmosphere raised considerable discussion among participants at the conference. Mercury is the smallest planet, and, because of its small size, has been generally believed to have no atmosphere, or a very tenuous one at best. George Field of Princeton University discussed measurements of the differential polarization of scattered light from Mercury made by Audouin Dollfus of the Observatoire de Paris, Meudon, France, who had interpreted them as showing the presence of a small atmosphere.

Field suggested that the atmosphere of Mercury may be composed of a considerable amount of radiogenic argon which escaped from the interior of the planet. The observed atmosphere would require that Mercury had outgassed to about the same extent as the earth. However, if the atmospheric constitution is to be nearly pure argon, the temperature of the upper atmosphere should not exceed 1400 degrees. Above this temperature, evaporative escape would take place. A problem arises in that theoretical estimates place the temperature of an upper atmosphere of pure argon at well above 1400 degrees, since argon is a very inefficient radiator of electromagnetic energy. It was agreed that much more study is needed for an understanding of the manner in which an argon atmosphere—if it exists—could be maintained on Mercury.

Important new data concerning the presence of water vapor on Mars and Venus was presented by Audouin Dollfus. Reporting on observations made with a specially designed telescope which he carried aloft in a balloon, and on observations made from an elevated mountain observatory, Dollfus said he measured 0.01 gm/cm^2 of water vapor for Venus above the cloud-top level.

For Mars, Dollfus found 0.02 gm/cm^2 of water vapor, enough to cover that planet to a depth of a fifth of a millimeter. This is five times as much as had been generally estimated. The disagreement between Dollfus' observations and those of several other scientists who give lower values for the water-vapor content of the Martian atmosphere raised sharp debate at the conference. Participants concluded that various experiments may have been subject to unforeseen sources of error, and that it is extremely important to make new measurements.

H. D. Holland of Princeton University suggested that pools of molten sulphur, rather than oceans of water, will be found on the surface of Venus. When that planet was formed, much less water was accreted than when the earth was formed, he suggested. The main substance ejected from Venusian volcanoes probably is sulphur dioxide, which would react with carbon monoxide to form liquid sulphur on the surface.

Thomas Gold of Cornell University suggested that some of the depressions on the moon's surface may be regions of collapse caused by underground rivers which result from an "outgassing" process taking place in the moon.

He reasoned that if there is water in the interior of the moon, radioactivity should produce enough heat to vaporize it. The water vapor would then seek to rise from the interior to the surface, but it would be trapped by a permafrost or ice layer which must exist below the surface at a depth of 150 feet. However, large meteorites striking the lunar surface could form craters extending below the ice layer; the water in the area of the explosion would then flow underground towards the crater. The extensive area that is drained might then collapse, forming the rills that are a common feature in moon photographs. Gold pointed out that these rills or depressions, converging on craters in flat ground from many angles, could hardly be caused by stresses from the craters themselves. Unlike the stress pattern, the rills do not converge in a straight line, but zigzag—sometimes for hundreds of miles.

Gold also suggested that Venus may possibly be covered by water which has escaped from the interior of the planet. The consensus among scientists has been that if there is water on Venus, it is in the planet's atmosphere and does not exist in appreciable amounts. However, Gold cautioned against ruling out the possibility of water on the surface. His contention was that it is too difficult to explain what happened to the water that must have been present on Venus at some time in its past if this were not the case.

Venus resembles the earth closely in many of its properties. Hence, Gold reasoned that water should have been outgassed from Venusian volcanoes to the same extent that this outgassing had occurred on earth. If Venus' surface temperature is somewhat less than that measured by instruments on Mariner II (perhaps a little less than 600° K), then water would be in equilibrium with steam. Hence, Venus should possess a very massive lower atmosphere composed primarily of steam.

Discussing the atmosphere of Venus, Carl Sagan of Harvard University reviewed many of the great uncertainties in the measured parameters of the planet. He also discussed some of the chemical equilibria that could influence the composition of gas in the Venusian atmosphere.

Sagan noted that the planet must be extremely hot at the surface, a temperature of perhaps 650° K on the dark side and about 750° K on the bright side. The pressure at the base of the Venusian atmosphere appears to be at least 30 atmospheres, which would indicate that there may be an appreciable amount of water vapor. Nevertheless, because of the high temperatures, the amount of water in the Venusian atmosphere would be enormously less than that in the earth's oceans. Hence, Sagan disagreed with Gold's suggestion that an approximation of the Venusian atmosphere could be obtained by heating the surface of the earth.

Despite the relatively large amount of observational data on Mars, there is still a considerable degree of uncertainty about the abundances of the planet's atmospheric constituents, according to Richard M. Goody of Harvard University. The amount of carbon dioxide could be reliably determined if the atmospheric pressure at ground level were known, but this is uncertain by at least a factor of two. The amount of oxygen is probably very small. One clue to the abundance of oxygen in the Martian atmosphere might be obtained by detecting that element's allotrope, ozone. This raises a problem, however. If there is oxygen on Mars, ozone should be present even at the ground level. Berkner pointed out that ozone formed near the ground may react with anything that can be oxidized, unless the entire surface of Mars is sufficiently covered by an oxide layer that further oxidation is impossible. It is possible that the continual weathering by wind on Mars would expose fresh rock surfaces and that the subsequent loss of ozone would eventually result in a very small amount of oxygen in the atmosphere.

P.J.E. Peebles of Princeton University presented new calculations showing that Jupiter and Saturn have approximately the same composition, predominantly hydrogen and helium, and that the ratio of hydrogen to helium is similar to that of the sun. Using a variety of reasonable values for different mixtures of hydrogen and helium—and with a core of heavier elements near the center of the planet—Peebles found that a helium-hydrogen ratio by number of 0.075 to 0.08 for Jupiter, and perhaps twice this amount for Saturn, was required in order to reproduce the mechanical properties of these planets. The amount of heavier elements has not been well determined, but it is only a few percent by mass.

Rupert Wildt of Yale University Observatory summarized the results obtained by H. Spinrad of the Jet Propulsion Laboratory, who showed that at times there are clouds of ammonia in the upper atmosphere of Jupiter which have velocities as high as four kilometers per second relative to the underlying atmosphere. This has become known as the "Spinrad effect". Spinrad has also determined some preliminary values for the composition of the Jovian atmosphere. His work indicates that the ratio of carbon to hydrogen on Jupiter is greater than that in the sun, and that it is higher still in the atmosphere of Saturn.