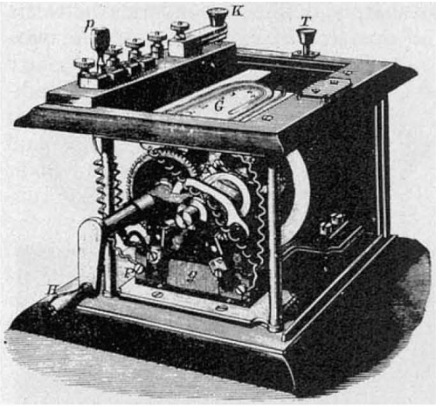
Among the most stringent constraints are the abundances of rare-gas isotopes, reviewed by M. Ozima (Univ. Tokyo). For instance, it is well established from the relative abundance of radiogenic ^{40}Ar that a period of intense outgassing from the Earth's mantle occurred within the first billion (10^9) years of the planet's history. But it emerged at the meeting that the significance of two other possibly crucial processes relevant to primordial atmospheres — one catastrophic but speculative, the other slow but sure — has become quantifiable only during the past year or so.

The first of these processes relates to impacting planetesimals. There is every reason to suppose that such bodies, particularly during the late stages of accretion, contained volatiles such as water. Laboratory experiments in which serpentine (a hydrated magnesium silicate) is shocked by projectiles from a gun to pressures as extreme as 60 GPa suggest that, by the time the Earth had grown to 50 per cent of its present radius, impact pressures would be sufficient to remove water and other volatiles completely from incoming planetesimals (T.J. Ahrens, Caltech). The Earth's primordial atmosphere could have been generated by these means as much as by volcanic outgassing.

But, as M.A. Lange (Alfred-Wegener-Institut, Bremerhaven) and Ahrens described, a primordial atmosphere should also have been eroded by impacts. As much as 45 per cent of the kinetic energy of incoming kilometre-sized planetesimals could have been transferred to crustal ejecta and thence to the atmosphere via blast waves, one such impact possibly removing over a millionth of the atmospheric mass. But after including such calculations in accretion models and considering all the uncertainties, it is still impossible to judge whether planetesimal impacts were net deliverers or removers of the primordial terrestrial atmosphere.

100 years ago



By the use of the secohmmeter it is now possible not merely to measure the coefficients of self and mutual induction absolutely, but also to secure the same high degree of sensibility with comparison tests completed during the growth or dying away of a current.

From *Nature* **36**, 129; 9 June 1887.

Another process crucial to atmospheric evolution is hydrodynamic escape, whereby trace gases are dragged out of an atmosphere by a light, dominant species, such as hydrogen on the early Earth. It remains an open question as to how much hydrogen enveloped the Earth at the time of its formation although, as H. Wanke (Max Planck Institut für Chemie, Mainz) emphasized, reactions between iron and water (both abundant then) should have generated large quantities. But it is only in the past year, as reviewed by D. M. Hunten (Univ. Arizona), that the process of hydrodynamic escape has been placed on a sufficient theoretical footing for it to be readily incorporated into planetary models.

A crucial aspect of this escape process is that it is very sensitive to atomic mass, providing a means of fractionating rare-gas isotopes — an attribute exploited in a new model of terrestrial planetary evolution by R.O. Pepin (Univ. Minnesota). Incorporating as sources of primordial noble gases the solar nebula and the more 'exotic' products of a pre-solar supernova, and invoking adsorption on nebular grains and hydrodynamic escape as means of fractionating both elements (by the former) and isotopes (by both), Pepin could produce an excellent fit to the terrestrial and martian abundances of primordial isotopes of xenon and krypton. (The abundances on Venus are poorly determined.) In such a model all the uncertainties associated with planetesimal accretion apply, while some special pleading seems necessary to account for abundances of a few of the other rare-gas isotopes. Behind this and other models there is also a debate about the extreme-ultraviolet flux from the early Sun. A strong flux of more than 20 times the present value would have been needed for more than 100 million years to drive off the hydrogen and provide the required fractionation, and significant questions remain as to how the emission of such radiation, not to mention the opacity of the nebular gas and dust, did in fact evolve.

Several speakers at the meeting stressed the need, first highlighted by T. Matsui and Y. Abe last year (*Nature* **319**, 303; and **322**, 526; 1986) to consider, when modelling the late stages of planetary accretion, the thermal blanketing that would have arisen from steam in the primordial atmosphere. Detailed calculations of water and energy budgets (K. Zahnle *et al.*, NASA Ames) support the idea that a magma ocean should have formed under a runaway-greenhouse atmosphere generated by the time the Earth had grown to one half its final radius. Zahnle emphasized the role of the melt, not only as a reservoir of water during accretion but also as a source of sudden degassing when, during the subsequent cooling, the magma ocean reached the solidus temperature and the solubility of water decreased.

Several times the mass of the present-day oceans could have been lost by hydrodynamic escape while the Earth accreted. The analysis of the final condensation of water is complicated by non-ideal behaviour of gases in an atmospheric regime close to the critical point of water, as highlighted by Matsui and Abe (Univ. Tokyo), but their one-dimensional radiative–convective model suggests that a hot proto-ocean would have rained out rapidly during the final stages of accretion.

Greenhouses and bolides must also have played a role on Mars and Venus. The presence of gullies and valley networks on Mars implies that conditions once permitted liquid water to flow on its surface. Paradoxically, the early Sun (during its first billion years or so) was about 25–30 per cent fainter than at present. But J. F. Kasting and O. B. Toon (NASA Ames) calculate that 5 bar of atmospheric CO_2 would have warmed the surface above the freezing point of water. Such an abundance would have required a continuous source, as chemical weathering would have removed atmospheric CO_2 to the crust. Large-scale volcanism seems to be one of the few possibilities, such recycling ceasing once the planet had cooled sufficiently.

The present-day role of the greenhouse effect on Venus is well established, but the history of water on that planet remains a tantalizing issue. The present-day abundance is 100,000 times smaller than that on Earth, whereas the deuterium–hydrogen (D/H) ratio in the atmosphere of Venus, interpreted in the light of known escape mechanisms, implies that at least 100 times more water was initially present. Kasting and Toon showed that liquid water might once have existed there if the net radiative effect of clouds (whose behaviour is currently unquantifiable) was to cool the planet.

But D. H. Grinspoon and J. S. Lewis (Univ. Arizona) offered a provocative new interpretation of the venusian D/H ratio. Dynamical calculations now suggest that active cometary nuclei or their fragments (as well as other bolides) should encounter planets at irregular intervals throughout the history of the Solar System. Given the water content of such bodies, the atmospheric water abundance on Venus should have oscillated between 100 and 400 parts per million — within the uncertainties of current estimates. According to this hypothesis, 99 per cent of the water now on Venus is of cometary origin. If this is indeed the case, then the enhanced D/H ratio in the present atmosphere may reveal little about the history of water on that planet. ☐

Philip Campbell is Physical Sciences Editor of Nature.