Early Stellar Activity, Initial Redox Potential and the Habitability of Planets

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The enhanced UV emission and stronger wind of the young Sun had the potential to remove significant amounts of hydrogen from early terrestrial planet atmospheres [Zahnle \& Walker 1982 Rev Geophys Space Phys 20,280]. Water loss and the onset of a catastrophic runaway CO$_2$ greenhouse have implications for planetary habitability [Kasting et al 1993 Icarus 101,108]. Another effect is the formation of a redox gradient between the surface and interior of a planet. Such a gradient was desirable, even necessary, for the origin and early evolution of life on Earth before the invention of photosynthesis. Chemotrophic organisms require disequilibrium concentration of reductants and oxidants created by mixing within a redox gradient. Submarine hydrothermal systems are spectacular examples where reducing solutions are returned to an oxidizing ocean and bacteria harvest energy from thermodynamically-favored reactions [McCollom \& Shock 1997 Geochim Cosmochim Acta 61,4375]. Photosynthetically-derived oxidants power these modern ecologies: Life on the pre-photosynthesis Earth would have required abiotic maintainance of redox gradients. Removal of atmospheric hydrogen lowers the hydrogen fugacity of the surface with respect to the mantle, creating a gradient. But such a gradient would have been sustainable only when a stable crust formed (perhaps as early as 4.2 Ga on the Earth) and continued equilibrium with the mantle was terminated. Non-mass fractionating mechanisms of volatile removal (e.g., impact erosion [Melosh \& Vickery 1989 Nature 338,487]) would be ineffective in this regard. After elimination of primordial hydrogen, water would be the primary source for hydrogen: UV photolysis and oxidation by crustal Fe would produce hydrogen whose escape to space would leave behind oxidizing equivalents at the surface or in the crust. Planets around non-solar type stars will experience divergent histories of hydrogen loss due to differences in the activity of these stars. They may have lost little hydrogen, lack stong redox gradient, and are relatively infertile sites for early life; or they have lost all hydrogen and water and suffered a runaway greenhouse fate.