Comment on “A Hydrogen-Rich Early Earth Atmosphere”

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Tian et al. (Reports, 13 May 2005, p. 1014) proposed a hydrogen-rich early atmosphere with slow hydrogen escape from a cold thermosphere. However, their model neglects the ultraviolet absorption of all gases other than \(H_2\). The model also neglects Earth’s magnetic field, which affects the temperature and density of ions and promotes nonthermal escape of neutral hydrogen.

Tian et al. assumed pure \(H_2\), they applied an EUV heating efficiency of 15%, which is appropriate for atomic hydrogen but too low for \(H_2\) by a factor of \(\sim 4\). Regardless, one still needs to calculate the exobase temperature for a multigas atmosphere. In the absence of a multigas calculation, Tian et al. assert that the early exobase would be cold, quoting a primitive (anoxic) atmosphere model (4) that used the EUV flux from the present-day Sun. With an enhanced EUV flux (3) appropriate for \(\sim 4\) billion years ago (Ga), the multigas model of (4) actually produces a mean exobase temperature \(>1400\) K, greater than today’s mean value (5).

At this temperature, hydrogen escapes efficiently and cannot build up as a major constituent of the atmosphere. It is unconvincing to then appeal to an early atmosphere highly enriched in \(CO_2\) to engineer a cold Venus- or Mars-like exobase by \(CO_2\) radiative cooling. \(CO_2\) was limited on early Earth by a large loss flux due to seafloor weathering (6). Data from the ancient seafloor (7) indicate that the atmosphere’s \(CO_2\) mixing ratio was less than \(\sim 1\%\) (compared with \(\sim 95\%\) on Venus and Mars), which could not have greatly affected early Earth’s exobase temperature (8).

The exobase temperature is also not the sole arbiter of Earth’s hydrogen escape rate. Satellite measurements prove that today’s hydrogen escape is predominantly nonthermal and that the proportion of nonthermal escape increases with a cooler exobase, maintaining the same diffusion-limited escape rate (9–11). Nonthermal escape is linked to Earth’s magnetic field: H ions accelerated by Earth’s magnetic field collide with neutral H atoms, exchange their charge, and become fast-moving neutral atoms with escape velocity; hydrogen also escapes along open polar field lines. Tian et al. dismiss the importance of nonthermal hydrogen escape from early Earth by comparison with the low nonthermal escape rates on Venus. However, Venus has no magnetic field and has different escape physics (10). Terrestrial helium fluxes further demonstrate the importance of nonthermal escape. Helium continuously fluxes to Earth’s atmosphere from radioactive decay in Earth’s interior. Today’s exobase is sufficiently cold that thermal escape of helium accounts for less than one-millionth of the total helium escape flux (11). Thus, if we only considered thermal escape, we would incorrectly conclude that Earth’s present atmosphere should be relatively rich in helium. In reality, he escapes efficiently by processes that do not depend on the exobase temperature (12, 13).

Finally, data suggest that hydrogen actually did escape from early Earth at rates close to its upper limit. The isotopic mass fractionation of atmospheric xenon is consistent with the idea that hydrogen escaped so strongly that it dragged even xenon, the heaviest gas in the atmosphere, to space (13, 14).

References and Notes
5. The time history of the globally averaged solar EUV flux normalized to present, \(SI_{0.5}\), has been estimated by using recent astronomical observations of representative young Sun-like stars at \(SI_{0.5} = 6.13 \times (r/f)_{-0.13+0.19}\), where \(r\) is time after zero-age main sequence (25). Thus at \(\sim 4\) Ga (\(r = 0.5\)), the EUV flux was \(\sim 14\) times as high as at present. Using figure 3 in (4) and applying a mean EUV flux 14 times the present, which is greater than today’s solar maximum output, one obtains an exobase temperature >1400 K.
8. Using a global carbon flux of 3.8 \times 10^{13} mol/yr inferred from data (4) and the model of (7) gives a \(CO_2\) level at 3.5 Ga only \(\sim 10\) times that of the present. The mesopause (the cold base of the thermosphere where \(CO_2\) cools radiatively) occurs at a pressure level inversely proportional to \(f^{0.65}_{CO_2}\), where \(f_{CO_2}\) is the mixing ratio of \(CO_2\). With \(f_{CO_2}\), some 10 times as high as today, the mesopause would be higher by only \(\sim 2\) mesospheric scale heights (\(\sim 10\) km) compared with today. This altitude is still in the mixed region below the homopause, so diffusive separation in the overlying thermosphere would limit \(CO_2\) abundances and prevent radiative thermospheric cooling.

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Editor's Summary

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