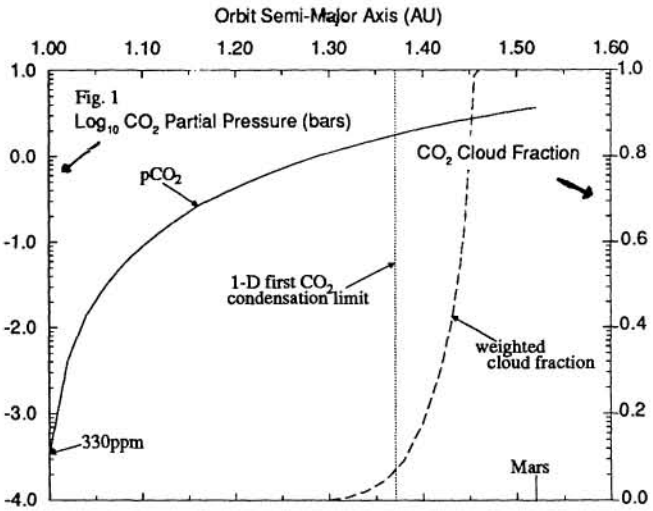
HABITABLE PLANETS WITH HIGH OBLIQUITIES: D.M. Williams[1], and J.F. Kasting[2], [1] Dept. of Astronomy & Astrophysics, [2] Dept. of Geosciences — Penn State University

The obliquities of the terrestrial planets have been shown to vary chaotically and by large amounts in times less than 10 Myr [1-3], thus inviting the possibility for Earth to occasionally reach high obliquity where it might experience climatic conditions unfavorable for life. Although Earth escapes this fate by having its rotation axis stabilized by the Moon [4], many extrasolar Earth-like planets without large satellites should be subjected to periods of high obliquity. The number of worlds supporting life outside the Solar System, then, may be far fewer than has been suggested [5] if high obliquities render moon-less Earths uninhabitable. Climates at high obliquity are particularly harsh on middle and high latitude continents that warm and cool rapidly in response to large insolation swings. These areas exhibit a wide range of temperatures over a seasonal cycle, with extremes reaching well above or below 273 Kelvin, making them seasonally unsuitable for water-dependent life. We demonstrate here that Earth-like planets will have their temperature extremes mitigated at high obliquity if they possess dense CO_2 atmospheres, as is likely for many planets situated in the outer habitable zone (HZ) of a Sun-like star [5]. The climate stabilizing mechanism governing atmospheric CO_2 on Earth-like planets is carbonate-silicate weathering. Planets with atmospheres rich in CO_2 demonstrate small latitudinal temperature gradients and seasonal temperature cycles, and thus remain habitable at high obliquities.

Less than 10^{-3}% of Earth's 60-bar CO_2 inventory resides within its atmosphere; the rest is stored as carbonate minerals within the crust. The present level of CO_2 in the atmosphere represents a balanced exchange between these two reservoirs through carbonate-silicate weathering and volcanic outgassing. In the process of weathering, CO_2 dissolved in rainwater reacts with dissolved silicate minerals to form calcium carbonate, which precipitates onto the sea-floor and is buried as carbonate sediment. CO_2 levels are held in steady-state by the decomposition of crustal carbonate at high temperatures and pressures near subducted plate boundaries, and its subsequent return to the atmosphere through volcanos. The rate at which CO_2 is posited on the ocean floor is sensitively dependent on surface temperature [6]; dissolution concentrations and reaction rates diminish with decreasing temperatures. Weathering is thereby slowed in cold climates, and ceases entirely once surface runoff freezes. Planets farther from the Sun than 1.0 AU would experience cold temperatures, a reduced rate of weathering, and a subsequent rise in atmospheric CO_2. The ensuing greenhouse would deepen, increasing the atmospheric opacity in the infrared, until the surface was warmed enough to bring the rates of weathering and outgassing into equilibrium.

We developed a latitudinally-resolved energy-balance climate model, similar to [7] but with the weathering feedback included, to calculate atmospheric CO2 levels and surface temperatures for planets at many positions within the outer HZ and with a variety of obliquities. Planets under consideration are assumed to be tectonically active with volcanic CO_2 output comparable to present Earth's, and to possess atmospheres with CO_2 in steady-state, so that weathering balances outgassing. These assumptions guarantee that all Earth-like planets have average surface temperatures not far removed from



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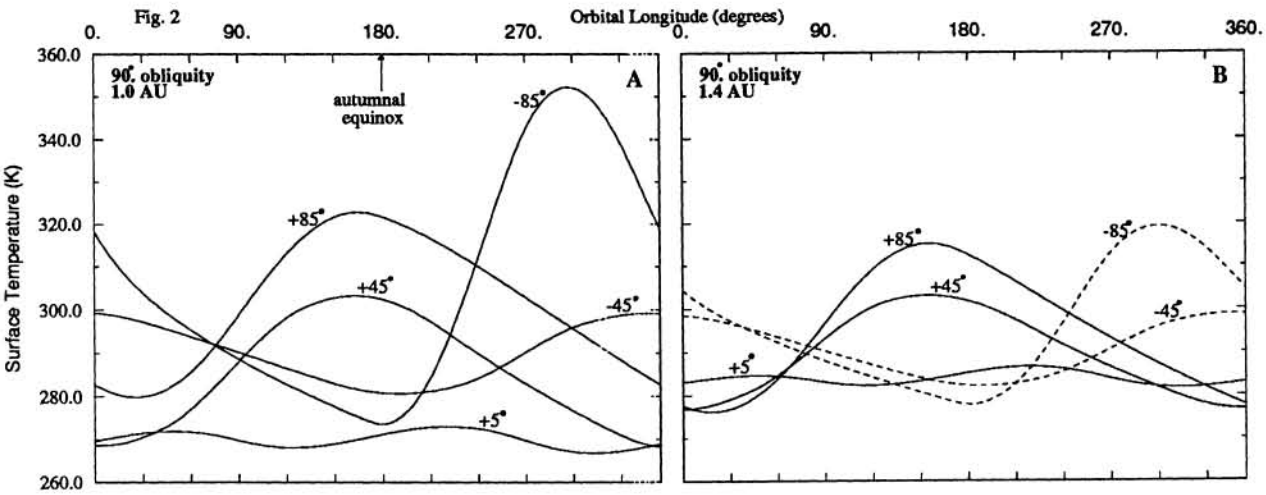

present Earth's, regardless of obliquity or position within the HZ. Fig. 1 shows the CO_2 levels required by our model to maintain Earth's temperatures on planets between 1.0 and 1.52 AU. Also shown in Fig. 1 is a possible outer limit to the HZ where the climate buffer breaks down because CO_2 begins to condense to form surface cooling clouds. A first condensation limit of 1.37 AU found with a globally averaged radiative-convective model [5] is given as a vertical dotted line. We extended these calculations to all latitudes, and found that CO2 begins to seasonally condense at that poles beyond 1.30 AU. While the exact position of the HZ outer edge, where the surface cannot be warmed further by a dense CO_2 atmosphere, is still largely uncertain, we feel justified in concluding that it lies no farther than 1.46 AU where a planet is completely cloudy.

Fig. 1 more importantly illustrates that planets found anywhere between 1.1 and 1.4 AU have atmospheres rich in CO_2, which should serve to buffer their climates against large seasonal cycles and accompanying extremes at high obliquities (Fig. 2a). The reason is that CO_2 is strongly absorbing in the infrared which slows radiative cooling by the atmosphere and ocean, and thus reduces the amplitudes of seasonal temperature cycles. Fig. 2 shows the effect to be more pronounced for predominantly continental latitudes (e.g., +45°) than for oceanic latitudes (e.g., -45°). Oceans cool slowly even without a dense CO_2 atmosphere because of the large heat capacity of water.

Fig. 2 also demonstrates that planets within the outer HZ will have reduced latitudinal temperature gradients; +5° is warmed by 10 Kelvin. The reason is two-fold. First, latitudes receiving little or no insolation (e.g., the poles at low obliquity or the equator at high obliquity) will warm relative the planet average temperature since they are not able to cool as efficiently in darkness. Second, the latitudinal temperature gradient is reduced by enhanced heat transport by winds. While our treatment of atmospheric advection is grossly oversimplified here, we argue as others [8] that the poleward dynamical flux of heat is proportional to the heat content of the atmosphere, which in turn is proportional to the total atmospheric pressure. Thus, dynamical heat transport should be at least four times (3 bar CO_2 + 1 bar N_2) as efficient at reducing latitudinal temperature gradients than it is on Earth at 1.0 AU. Planets within the outer HZ are then, for the reasons described above, likely to be habitable at high obliquities, which serves to show that obliquity variations are not an insurmountable obstacle to finding life around other stars.

REFERENCES

[1] Laskar J. et al. (1993) Nature,361,608.
[2] Touma J. and Wisdom J. (1993) Science, 259,1294.
[3] Ward W.R. (1991) Icarus, 94,160.
[4] Laskar J. and Robutel P. (1993) Nature, 361,615.
[5] Kasting J.F. et al. (1993) Icarus 101,108. [7] Caldeira K. and Kasting J.F. (1992) Nature,359,226.
[6] Walker J.G. et al. (1981) JGR,86,9776 [8] Gierasch P.J. and Toon O.B. (1973) J.Atm.Sci,30,1502.