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How to identify exoplanet surfaces using atmospheric trace species in hydrogen-dominated atmospheres

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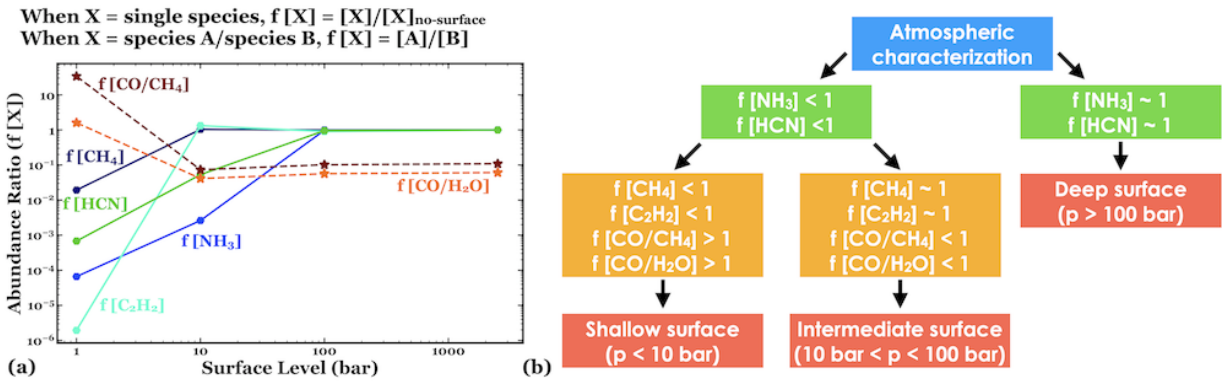
Sub-Neptunes (Rp~1.25-4 REarth) remain the most commonly detected exoplanets to date. However, it remains difficult for observations to tell whether these intermediate-sized exoplanets have surfaces and where their surfaces are located. Here we propose that the abundances of trace species in the visible atmospheres of these sub-Neptunes can be used as proxies for determining the existence of surfaces and approximate surface conditions. As an example, we used a state-of-the-art photochemical model to simulate the atmospheric evolution of K2-18b and investigate its final steady-state composition with surfaces located at different pressures levels (Psurf). We find the surface location has a significant impact on the atmospheric abundances of trace species, making them deviate significantly from their thermochemical equilibrium and "no-surface" conditions. This result arises primarily because the pressure-temperature conditions at the surface determine whether photochemically-produced species can be recycled back to their favored thermochemical-equilibrium forms and transported back to the upper atmosphere. For an assumed H2-rich atmosphere for K2-18b, we identify seven chemical species that are most sensitive to the existence of surfaces: ammonia (NH3), methane (CH4), hydrogen cyanide (HCN), acetylene (C2H2), ethane (C2H6), carbon monoxide (CO), and carbon dioxide (CO2). The ratio between the observed and the no-surface abundances of these species, can help distinguish the existence of a shallow surface (Psurf < 10 bar), an intermediate surface (10 bar < Psurf < 100 bar), and a deep surface (Psurf > 100 bar). This framework can be applied together with future observations to other sub-Neptunes of interest.

Figure 1: Selected criteria and a flowchart of possible steps to identify the existence of the surface and the surface pressure for a hydrogen-dominated exoplanet with properties similar to K2-18b.


When X = single species, f [X] = [X]/[X]no-surface
When X = species A/species B, f [X] = [A]/[B]
Abundance Ratio (f [X])
f [CO/CH4]
f [CH4]
f [HCN]
f [NH3]
f [C2H2]
f [CO/H2O]
Surface Level (bar)
(a)
(b)
Atmospheric characterization
f [NH3] < 1
f [HCN] <1
f [NH3] ~ 1
f [HCN] ~ 1
f [CH4] < 1
f [C2H2] < 1
f [CO/CH4] > 1
f [CO/H2O] > 1
f [CH4] ~ 1
f [C2H2] ~ 1
f [CO/CH4] < 1
f [CO/H2O] < 1
Deep surface
(p > 100 bar)
Shallow surface
(p < 10 bar)
Intermediate surface
(10 bar < p < 100 bar)