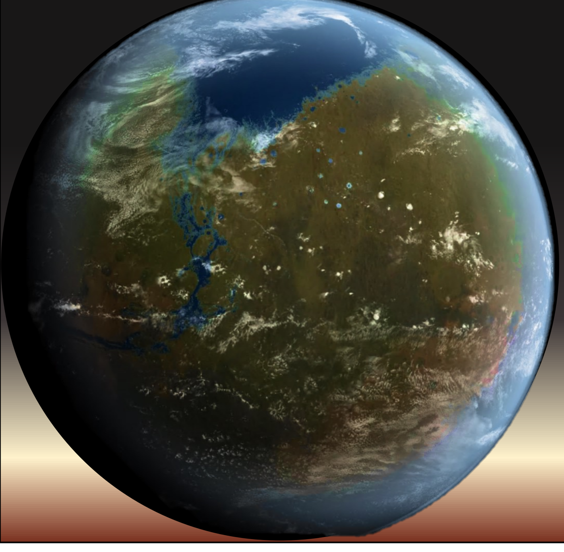

Challenges of Utilizing Mars' Resources to Warm Mars

*Edwin Kite [1,2](edwin.kite@astera.org), **Alex Kling**[1](alex.kling@astera.org), M. I. Richardson[3], S. Ansari[4], R. Ramirez[5], H. Mohseni[4], M.A. Mischna[6], M.H. Hecht[7], L. J. Steele[2,8], A. S. Braude[1], A. L. Bamba[4], T. Nakagawa[1,9]*

[1] Astera Institute . [2] U. of Chicago. [3] Aeolis Research. [4] Northwestern. [5] UCF. [6] JPL, Caltech. [7] MIT Haystack Observatory. [8] ECMWF. [9] U. of Colorado.

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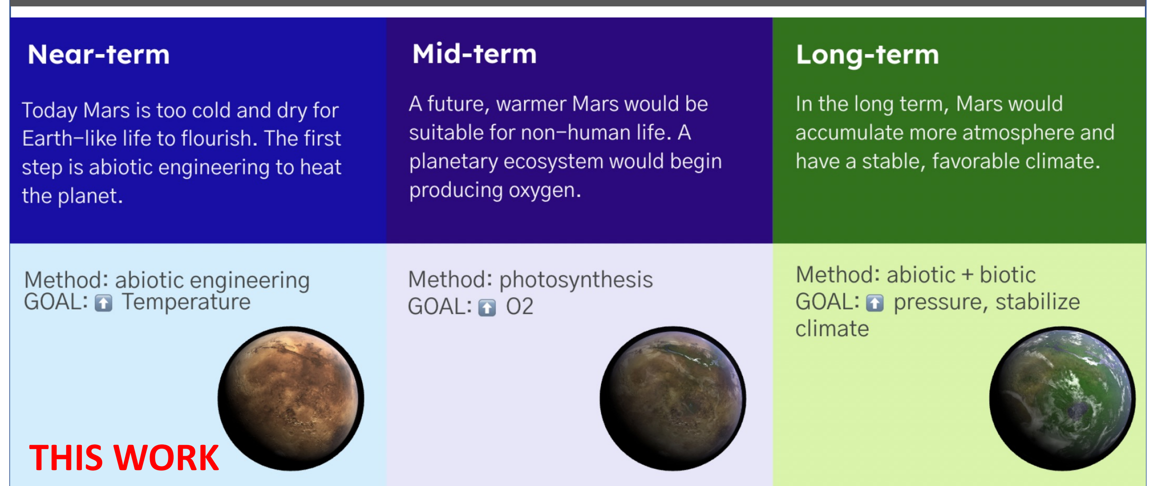
3 –step approach to terraforming



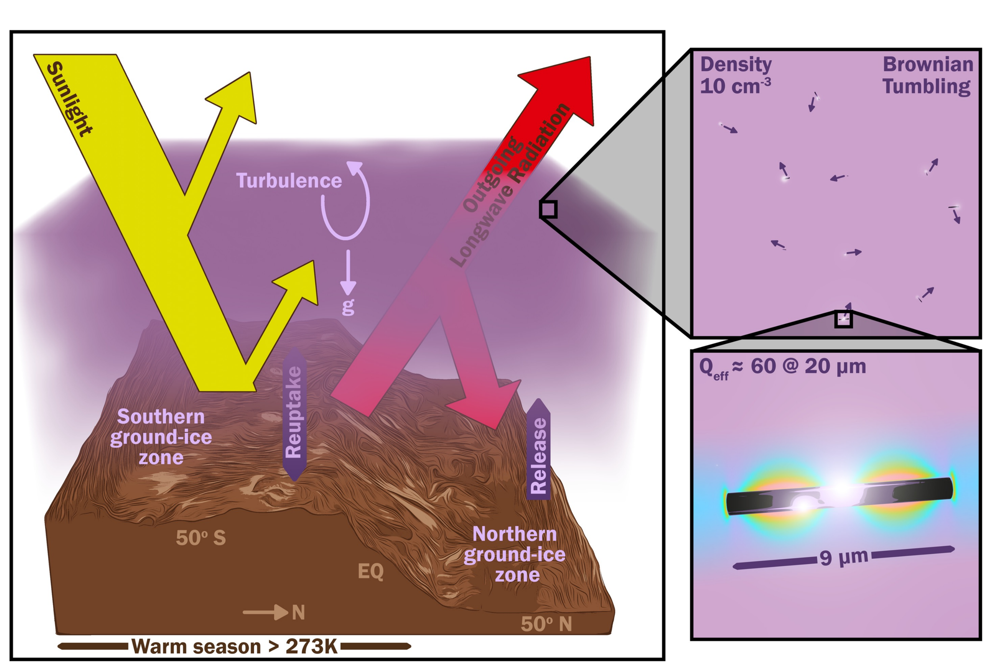
Warming Mars could be a step toward making it suitable for life, but would represent a major challenge for planetary science and engineering. Recent work suggests physically feasible methods [1,2,3], including engineered-aerosol warming [4,5]. However, before we can assess whether warming Mars is worthwhile, relative to the alternative of leaving Mars as a pristine wilderness, we must confront the practical requirements, cost, and possible risks. [6]

Approaches to warming Mars

The technological challenge of warming Mars can be approached from multiple angles. [7]

- Greenhouse gas, (e.g. CFC *chlorofluorocarbons*)
- Reflect energy from orbit mirrors, particles
- Diverting volatiles from asteroids
- Release CO_2 ice trapped in the caps (not sufficient by itself [8])
- Silica aerogel tiles [1]
- Engineered aerosols – x 5000 more efficient per unit mass than gas [4]

Engineered aerosols provide favorable absorption and scattering of visible light and trap the thermal radiation from the surface.



***Overview of the engineered-aerosol warming.** Figure: A.M. Geller, Northwestern, CIERA + IT-RCDS. From [4].*

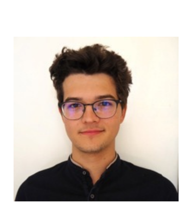
Who we are

Astera Institute is a nonprofit research institute for public good based in Emeryville, in the San Francisco Bay area. Astera has a strong focus on open-science: we are working with partners at leading universities and institutions.


Edwin Kite

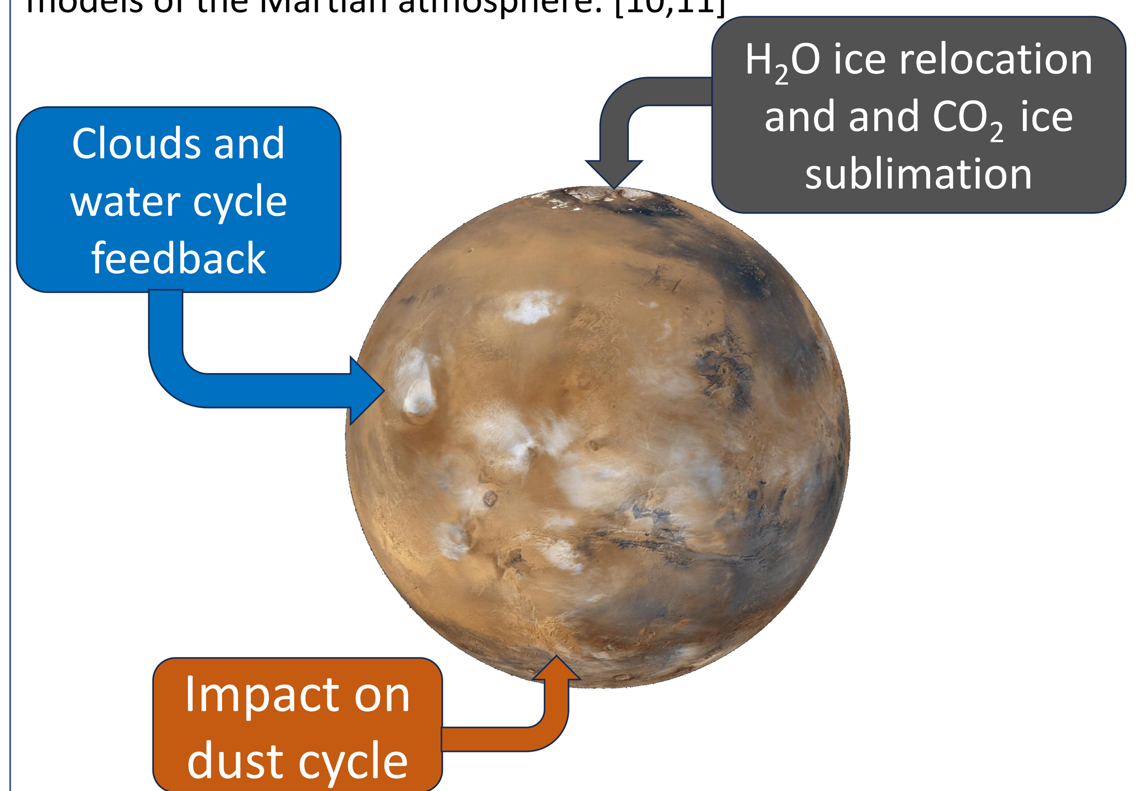

Alex Kling

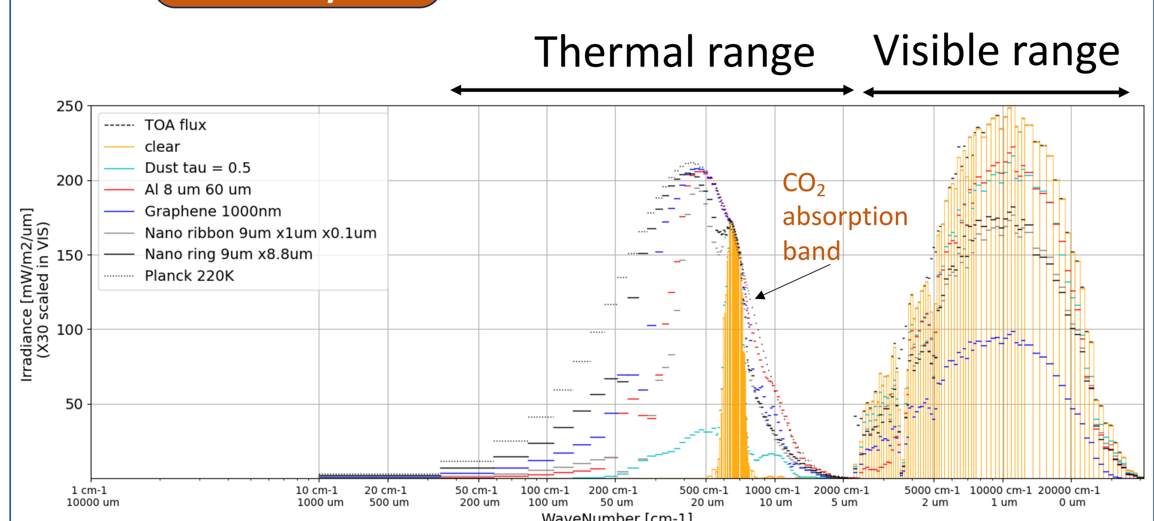

Ashwin Braude


Adrian Dumitrescu

Research

Understanding the **climate feedbacks** [9] due to the response of engineered aerosols is critical and best explored using 3D numerical models of the Martian atmosphere. [10,11]



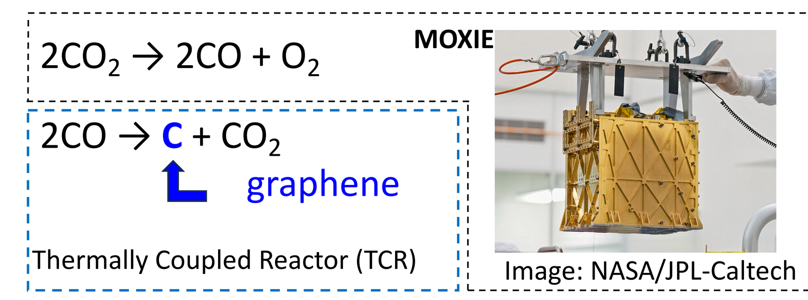


***Our open-source particle screening tool** calculates solar and thermal energy available at the surface for a clear atmosphere (orange), or with aerosols. github.com/alex-kling/TerraScreen*

Open question: aerosol ISRU production

Example feedstock production for:

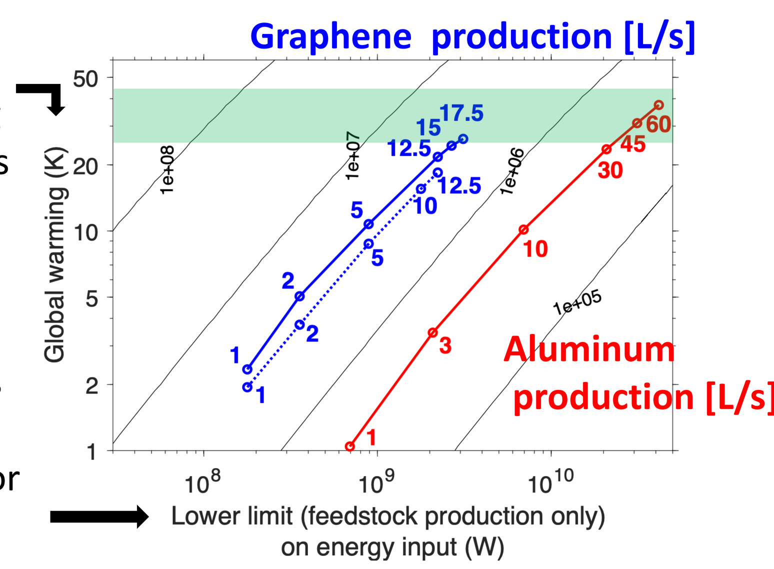
- Metallic nano-structures such as **Aluminum nano-rods.** Aluminum is **mined from the regolith.**
- **Graphene** (i.e carbon) which is extracted from the CO_2 atmosphere through **solid oxide electrolysis** (SOE) [12,13,14,15]



Production of graphene through Solid Oxide Electrolysis (notional)

MarsWRF GCM output, excluding climate feedbacks

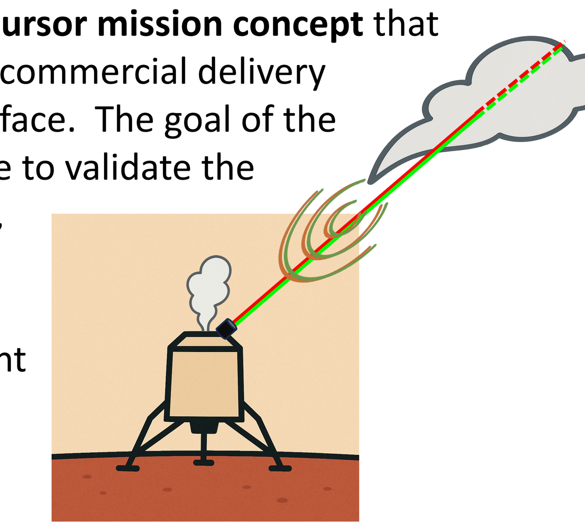
Conversion from production rates [L/s] to energy (fission reactor or solar)



***Steady-state temperature response** as a function of energy required to produce feedstock, for a mix of graphene disk of different diameters (blue), and for thin Al rods (red). Black contours show energy gain.*

Upcoming work

- We are actively investigating **particle designs and trade-off** in terms of warming efficiency per unit mass and in-situ production at scale. Examples of other particles being assessed are:
  - ⌀=9 µm nano ring (high efficiency, difficult production)
  - 9x1x0.1 µm nano ribbons (suitable for roll-to-roll production)
  - Coated particles (e.g. enhanced scattering properties)
  - Porous spheres (calculations from A. Raman's group, UCLA)
- **Particle manufacturing and validation**. We are in the process of manufacturing particles at a small scale (mg) to validate the simulated optical properties in a substrate using Fourier transform infrared spectroscopy (FTIR)
- **Particle dispersion tests.** We are setting-up a test chamber to characterize the deployment and clumping behavior of free floating nano-particles. The effort involves developing a backscatter differential absorption lidar (DIAL) to retrieve particles' position and size using remote sensing.
- We are investigating a **precursor mission concept** that would leverage upcoming commercial delivery services to the Martian surface. The goal of the precursor mission would be to validate the release of a small (<100 kg, non-climate -altering) amount of nano-particles to validate their deployment and dispersion in Martian conditions.

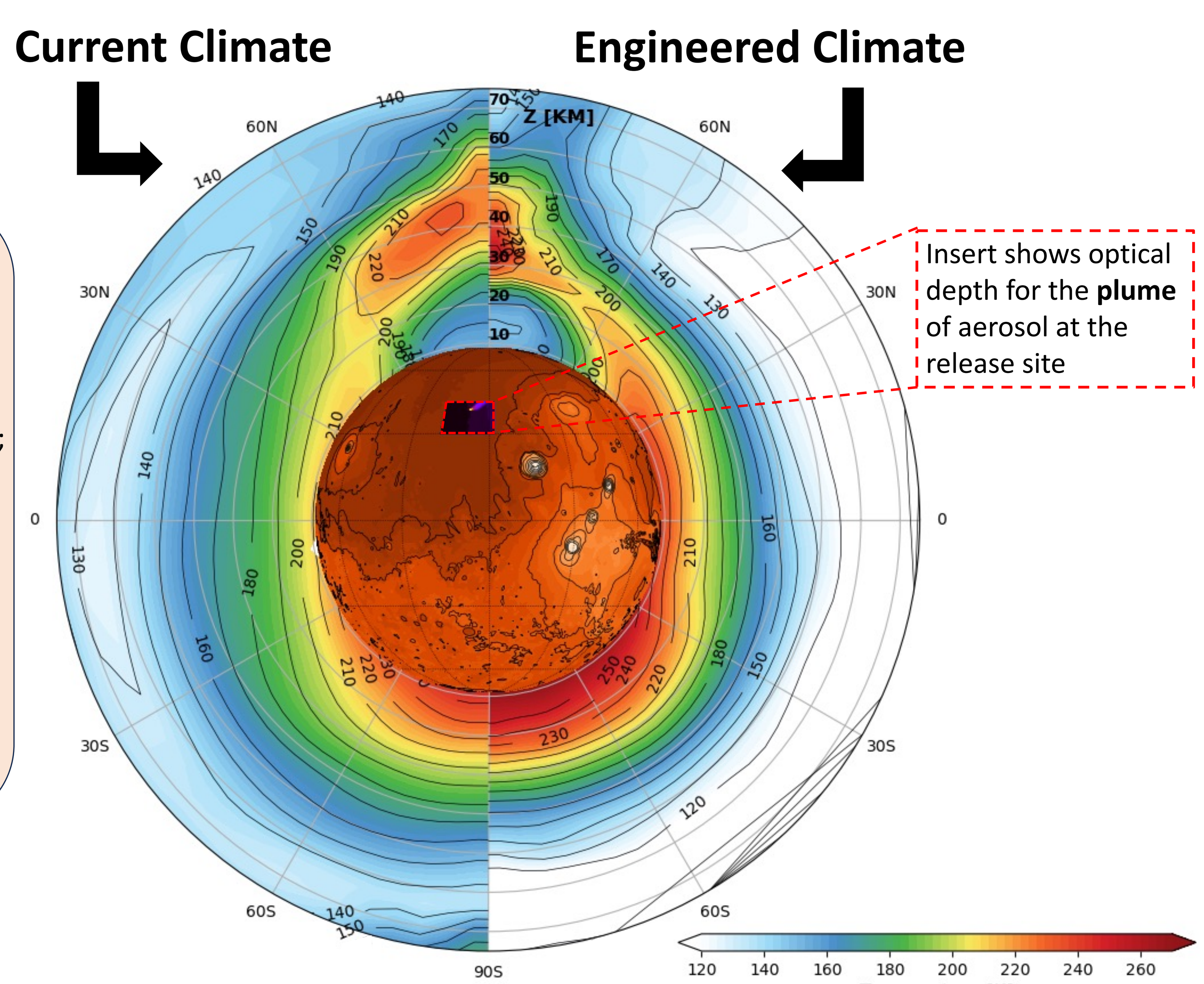


***Precursor mission study** to test the dispersal and tracking of particles using a backscatter lidar (notional)*

Initial results

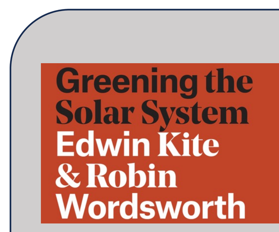
- **Global aerosols production rates of 10's L/s provide ~30K of warming within a few Earth years. [4,5]**

In order for engineered aerosol global warming of Mars to start to melt the ice, basic challenges include that particles must be made on (or transported to) Mars; be released without clumping together; disperse globally; increase the warm-season average temperature of parts of Mars with shallow ground ice by >35 K; and degrade gracefully. Moreover, making Mars' surface suitable for life would involve many more steps beyond initial warming, for example, soil chemistry and suitability for biology.



***Atmospheric temperature 3D climate simulation without (left) and with (right) engineered aerosols.** Colors and solid contours on the globe show topography*

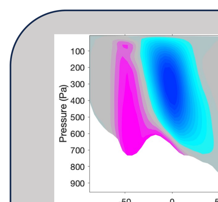
Learn more



Asterisk essay, 2025

Pilot study: Ansari et al., *Science Advances*, 2024

Perspective paper: DeBenedicts et al. *Nature Astronomy*, 2025



Atmosphere Dynamics Impacts: Richardson et al. 2025

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