

Parametric Modeling of Stellar Winds

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Background

A planet's magnetic field is caused by electrically conducting fluid within the planet's interior being converted into electric and magnetic energy. This is also known as the **dynamo effect**. (1) The magnetic field (i.e. the **magnetosphere**) of a planet protects it from harmful radiation from deep space as well as its star in the form of **stellar winds**. (2) Stellar winds are supersonic bursts of plasma that are produced. From the star's outer atmosphere (i.e. the corona). These winds form a bubble around the planet(s) in the system known as an **astrosphere**. (3) The way we measure these bursts and other electrically conducting fluids is with the **Magnetohydrodynamics (MHD) Model**. (4)

Proxima Centauri, our closest stellar neighbor, is an active M-dwarf star characterized by intense magnetic activity. **Proxima Centauri b** is the Earth-sized planet that orbits it

Research/Methodology

Objective

Model the astrosphere around Proxima Centauri - Using Earth's space environment for comparison, analyze whether a planet at a specific orbital radius (**R = 68.5 stellar radii, R_***) can sustain a magnetosphere. Additionally, quantify the plasma risks (i.e. charging, radiation, erosion) for future interstellar probes and space technology

Methodology

Use the Space Weather Modeling Framework (SWMF) to solve the MHD equation. Additionally, use observed magnetic field data to describe the time evolution of plasma density and pressure.

- From this, parameters are extracted
 - Plasma density (ρ)
 - Magnitude of velocity ($|u|$)
 - Magnitude of magnetic field ($|B|$)
 - Plasma temperature (T)

Stellar Wind Dynamic Pressure: $P_{sw} = \rho u^2$

- Determines the level of force being push upon an object by stellar wind. Higher dynamic pressure = less stable magnetosphere

Magnetic Topology: How the magnetic field is "shaped" and moves

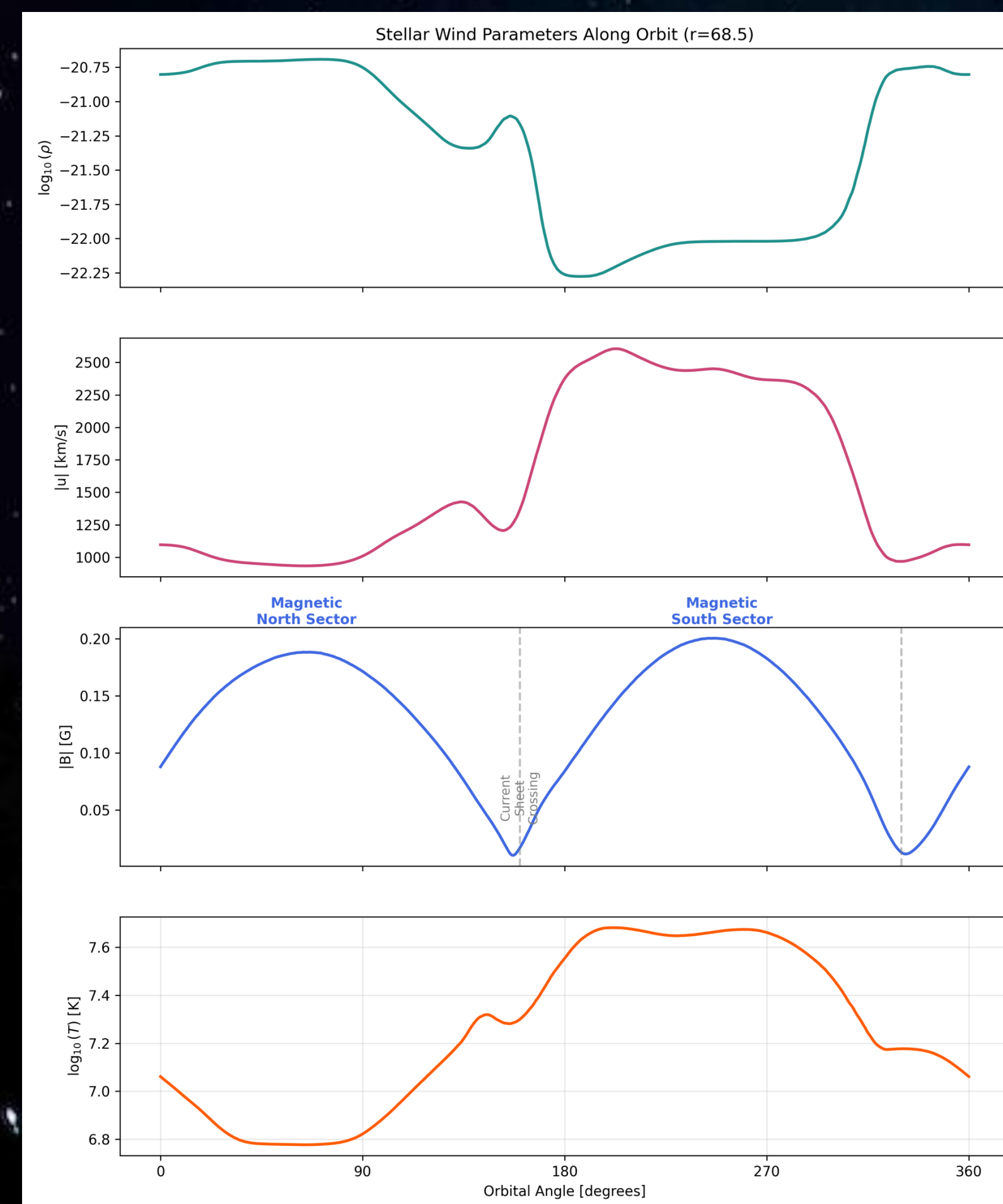
Results

Line Plots

As the Proxima b travels, the stellar wind speed ($|u|$) more than doubles between 1000 and 2500 km/s , as it enters high-speed stellar wind streams. These velocity jumps correlate with a drop in density (ρ) and a spike in temperature (T) exceeding $10^7 K$. Most importantly, the magnetic field ($|B|$) reveals a 'two-sector' environment; the planet crosses the star's magnetic equator twice per orbit (at 160° and 330°). These **Current Sheet crossings** represent total magnetic reversals, suggesting a volatile magnetosphere that may struggle to protect the planet's atmosphere over billion-year timescales.

Contour Maps

These contour maps show the star's magnetic field twisting into a **Parker Spiral**—much like a rotating garden sprinkler. As Proxima b orbits (the dotted circle), it must plow through these alternating 'arms' of dense and thin plasma, explaining the constant shifting in space weather we see in our line plots. This structure shows that the planet isn't just sitting in a steady wind; it is constantly transitioning between different magnetic zones as the star rotates.



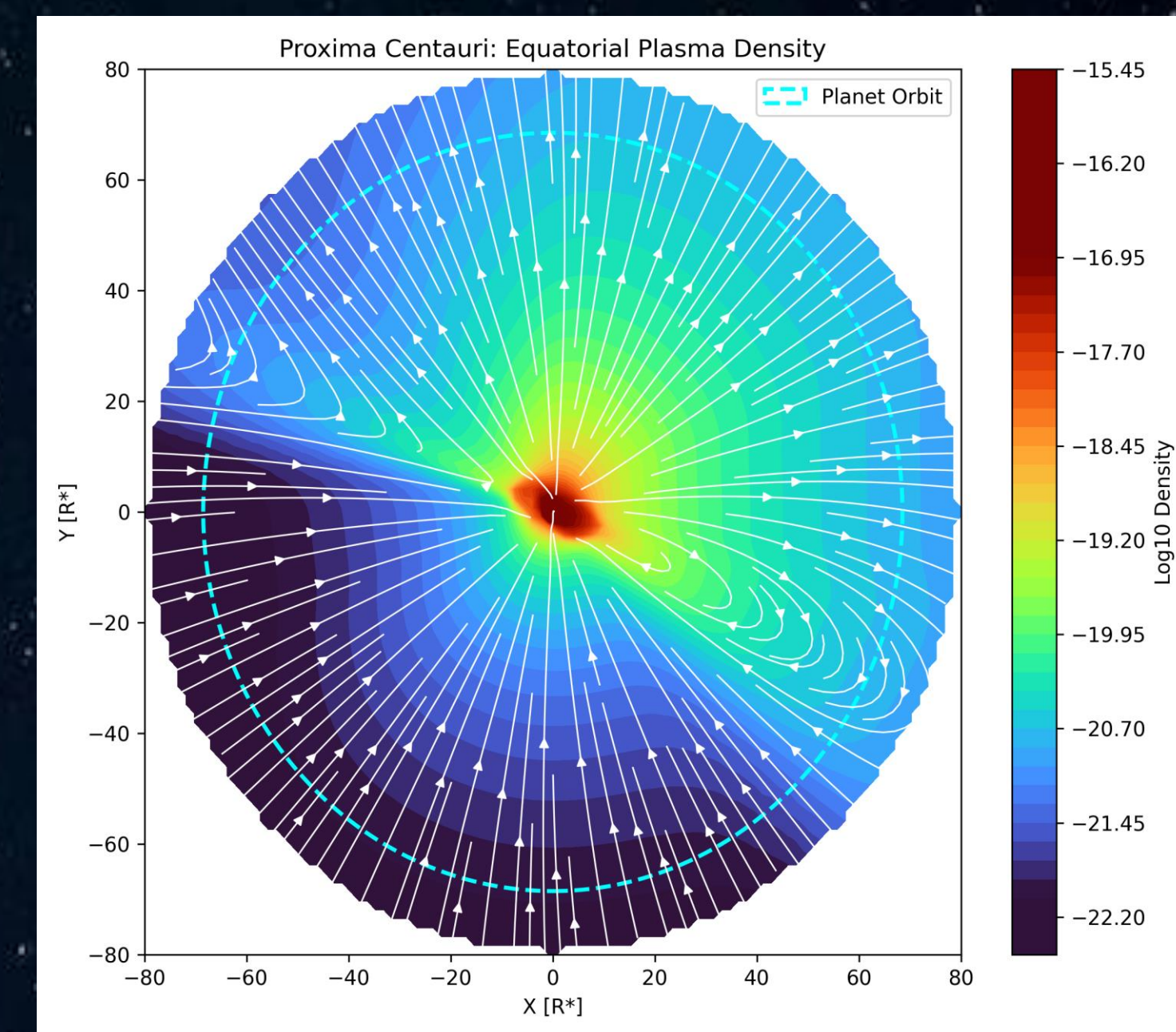
Time-series plots extracted from 3D SWMF Magnetohydrodynamic (MHD) coordinates; illustrate the environmental variability experienced by the planet over a single orbital period.

The sectors of higher and lower density, velocity, and temperature indicate that the dynamic pressure is highly fluctuating. The velocity plot shows a radial gradient, indicating the stellar winds speed up as they approach the orbital radius.

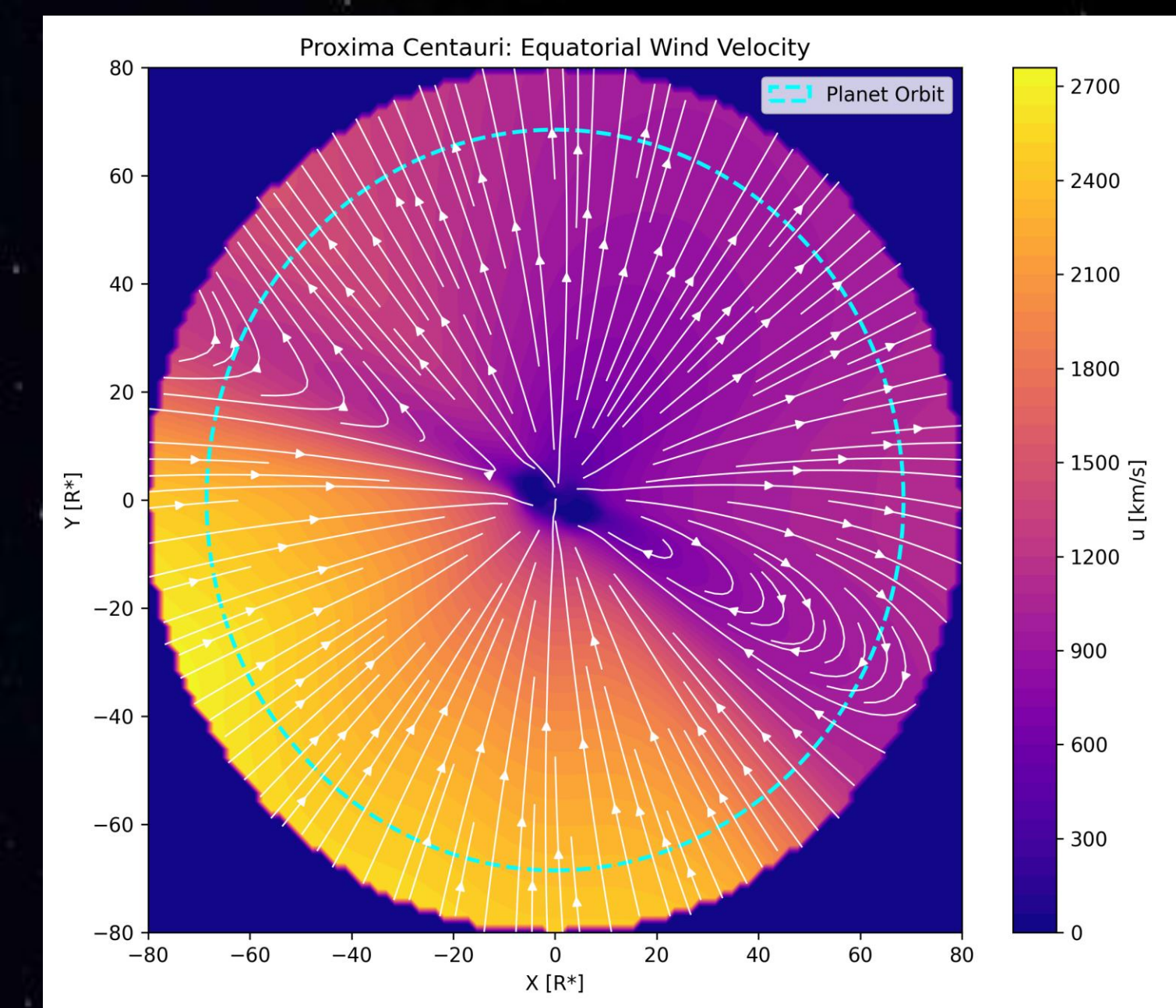
The stellar wind dynamic pressure is calculated to be $P_{sw} \approx 2000 km/s$

Comparison to our system

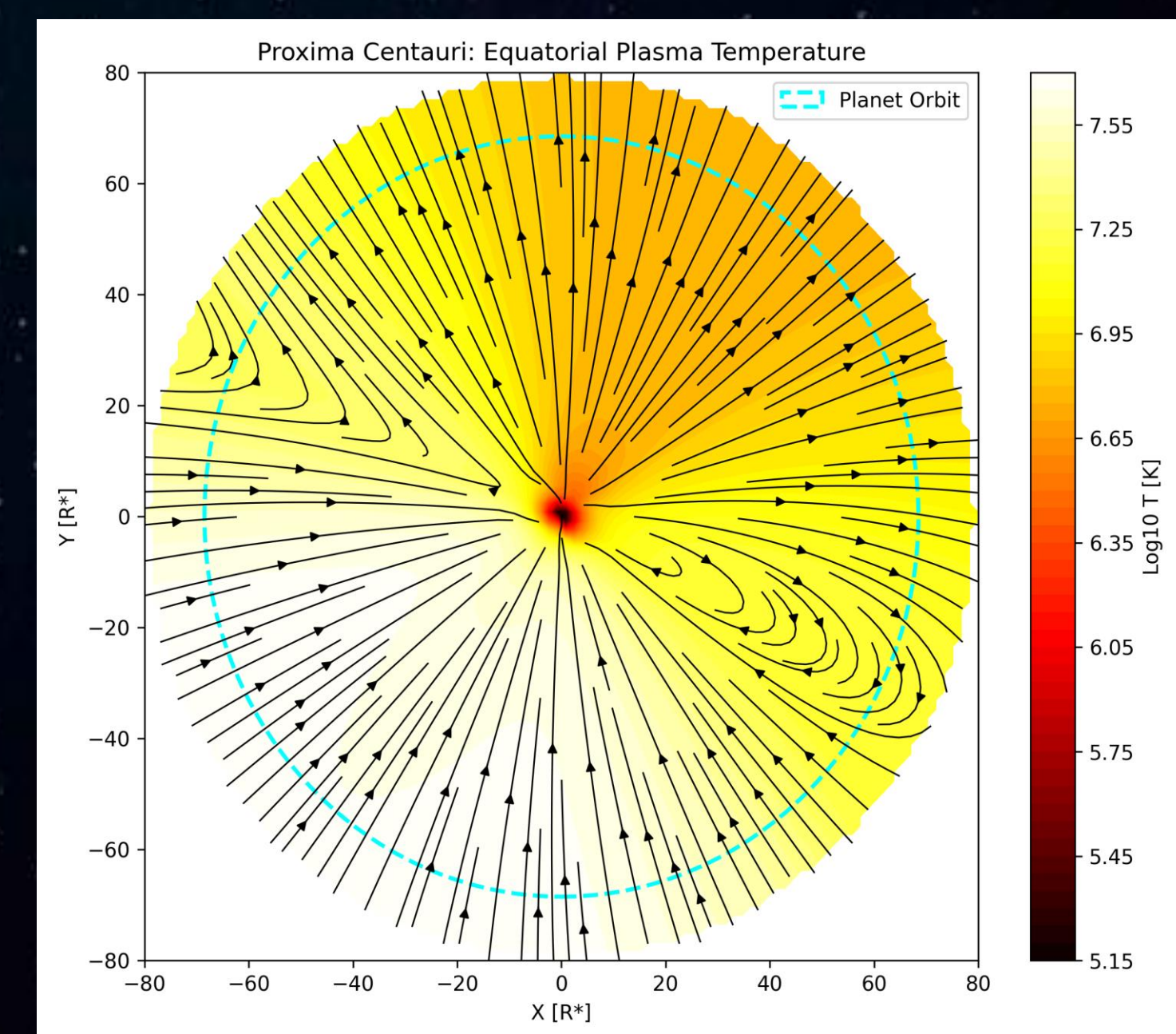
For reference, the stellar wind Earth is hit with is steady for the most part. Additionally, the stellar wind dynamic pressure is a mere $P_{sw} \approx 400 km/s$, only 1/5 of the strength of Proxima b's dynamic pressure.



Illustrates the logarithmic mass distribution ($log_{10}(\rho)$). Note the sector-like structures that the planet traverses during its orbit.



Displays the wind speed magnitude (km/s). High-velocity streams are visible, indicating regions of high dynamic pressure.



Shows the thermal distribution ($log_{10}(T)$) with overplotted black streamlines representing the equatorial magnetic field (B_x, B_y).

So What?

The code helps give us a tool for measuring the radiation levels experienced by any planet, aiding in the search for habitable worlds. It can also help with accounting for the parameters that cause radiation damage in space-bound equipment (i.e. satellites, spaceships, etc.) so we can better protect them from the harsh radiation. Helps us determine that Proxima Centauri b cannot sustain a stable magnetosphere, and is by that metric **not** habitable.

References

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- Bagenal, F.** (2018). *The Solar Wind* (Chapter 3). Laboratory for Atmospheric and Space Physics (LASP), University of Colorado Boulder. <https://lasp.colorado.edu/mop/files/2018/08/Chapter-3.pdf>
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