Maestro: a new python framework for orchestrating ray tracing simulations of radio frequency plasma waves in the magnetosphere

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Abstract

We are studying the generation and propagation of whistler-mode waves from the upper ionosphere into the magnetosphere. We are using a ray-tracing approach to solve the wave propagation problem, which enables low computational-cost, rapid parameter scans. This approach also gives insights into the physics of wave propagation, through the use of simplified models. We have developed a new python framework called Maestro. It is designed to orchestrate the ray tracing simulations, making them easier to setup, run, and analyze once complete. Maestro ray tracing results will be shown for whistler waves in simplified plasma geometries, illustrating the physics of whistler propagation, ionospheric ducting of VLF waves, and magnetospheric reflection. Results will also be shown for rays propagated in a more realistic ionospheric model, as computed by the SAMI2/3 code. This research is supported by the DARPA Defense Science Office

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ABSTRACT

The propagation of whistler-mode waves are important for space weather, radiation belt dynamics, and as a diagnostic for the SMART program[1]. We are developing a new code to compute this using ray tracing. Maestro is quick and flexible; we have used it for **quantitative predictions** in **realistic plasma** backgrounds, and also used it to **discover** and study linear **mode conversion** in a reduced model.

METHODS

1. Ray tracing is used to compute the dynamics of plasma waves
2. A new python framework is under development to facilitate this modeling
3. This has been applied to realistic and simplified models

RESULTS AND DISCUSSION

- Calculations underway to predict **whistler wave intensity** that will be produced by the SMART project
- Linear **mode conversion** of lower-hybrid waves has been discovered in reduced model of ionosphere/magnetosphere boundary
- Could this mode conversion be involved in: ionospheric and plasmaspheric hiss, lightning generated whistlers, lower hybrid ducting…

[1] See "SA33C-3166 - Space Measurements of A Rocket-Released Turbulence (SMART) an Experiment to Study Turbulence" on Wednesday afternoon

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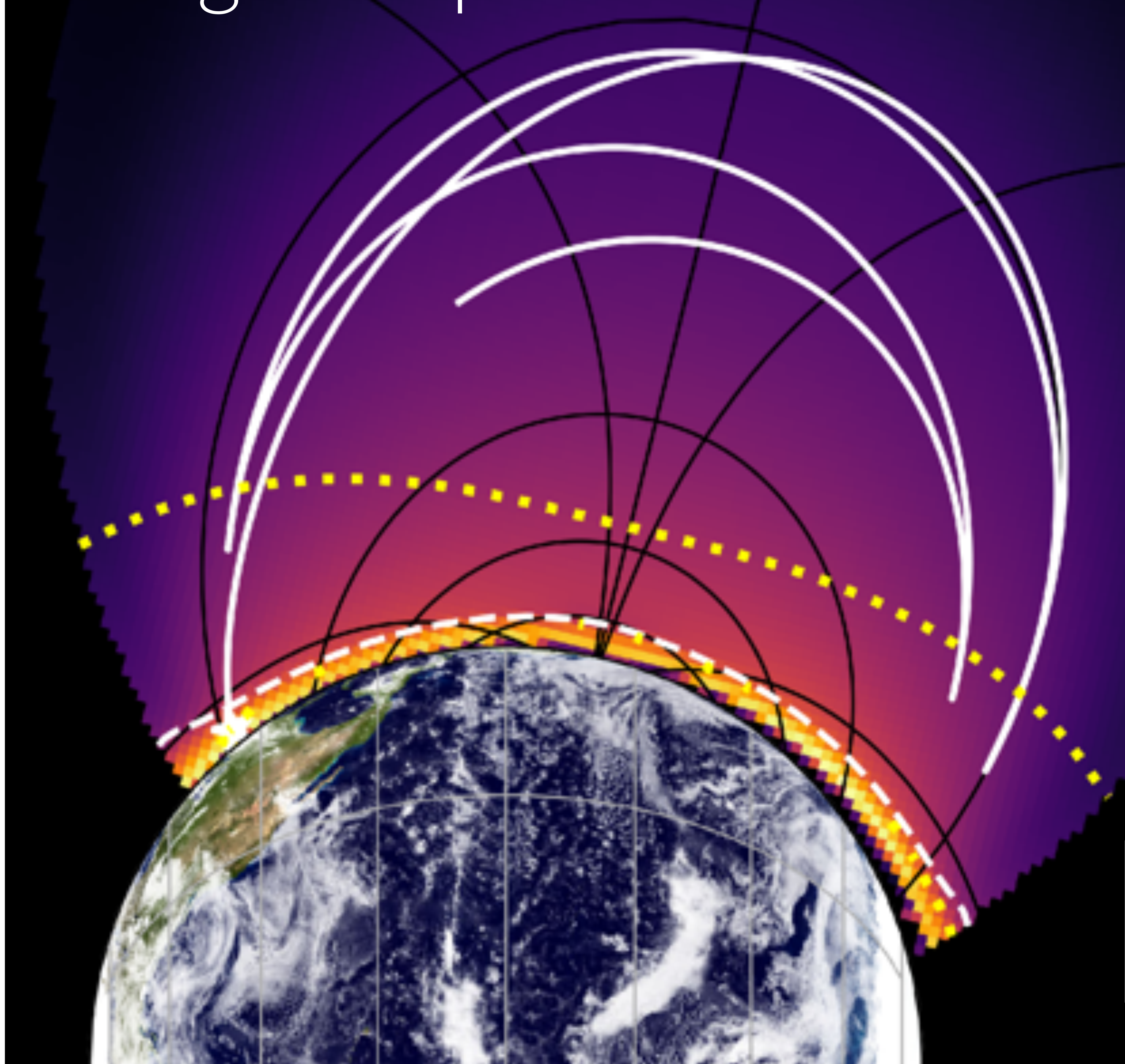
Using Maestro, we are **developing new insights** into the **dynamics of plasma waves** in the magnetosphere



SPACE MEASUREMENT OF A ROCKET-RELEASED TURBULENCE
SMART
ONR · NRL · DARPA

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Supplemental Material

Ray tracing for plasma waves

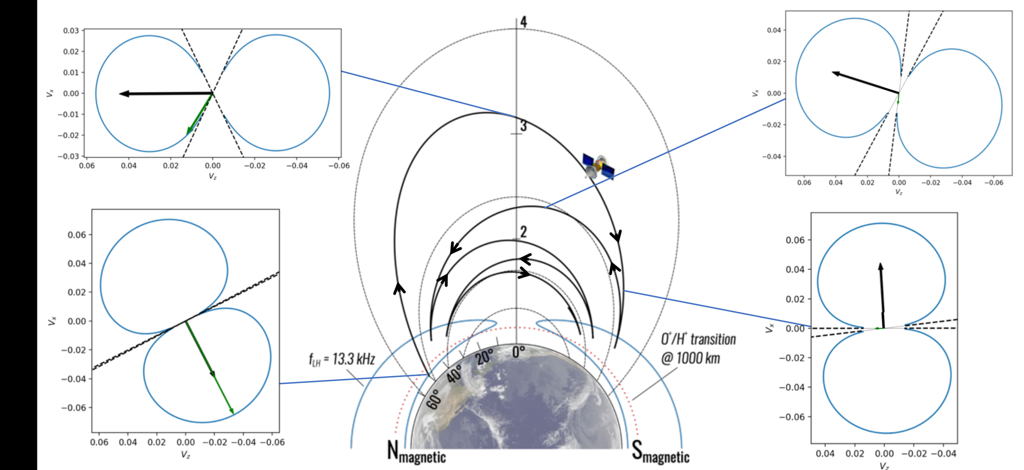
Ray Equations:

$$\frac{d\mathbf{x}}{d\tau} = \frac{\partial D}{\partial \mathbf{k}}$$
$$\frac{d\mathbf{k}}{d\tau} = -\frac{\partial D}{\partial \mathbf{x}}$$
$$\frac{dt}{d\tau} = -\frac{\partial D}{\partial \omega}$$
$$\frac{d\mathbf{x}}{dt} = -\frac{\partial D/\partial \mathbf{k}}{\partial D/\partial \omega} = \frac{\partial \omega}{\partial \mathbf{k}} = \mathbf{v}_g$$

Cold Plasma Dispersion Model:

$$D = An^4 - Bn^2 + C = 0$$
$$A = S\sin^2\theta + P\cos^2\theta$$
$$B = RL\sin^2\theta + PS(1+\cos^2\theta)$$
$$C = PRL$$

Functions S, P, R, L depend on plasma properties and magnetic field strength



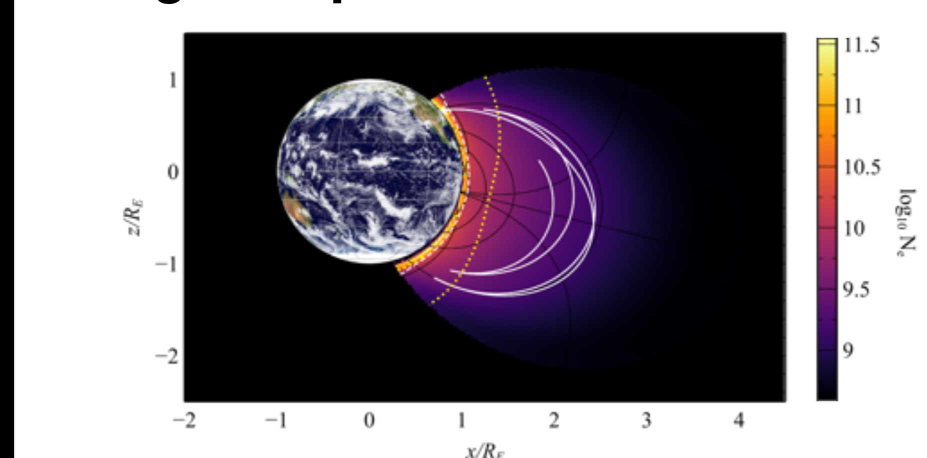
Python class structure in Maestro

Plasma System
- Geometry
- Species
- Density
- Magnetic Field

Dispersion Model
- Dispersion model
- Wave modes
- Derivatives of D

Wave Model
- Wave parameters
- Frequency
- Ray initial conditions
- Ray tracing output

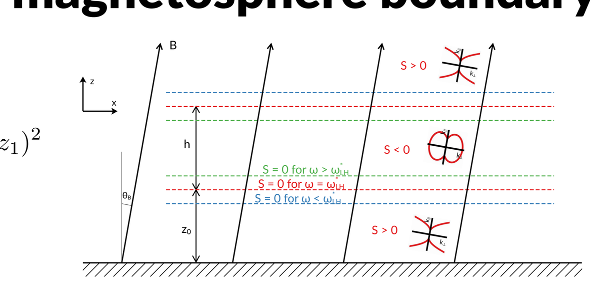
Wave dynamics in a SAMI2-computed background plasma

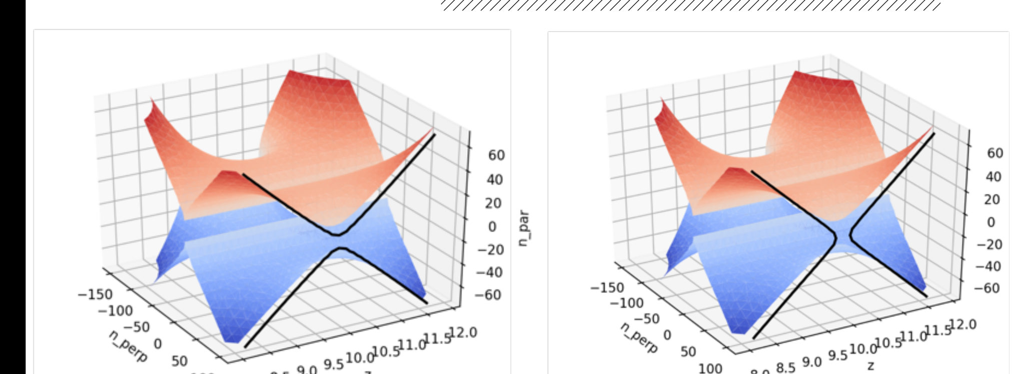


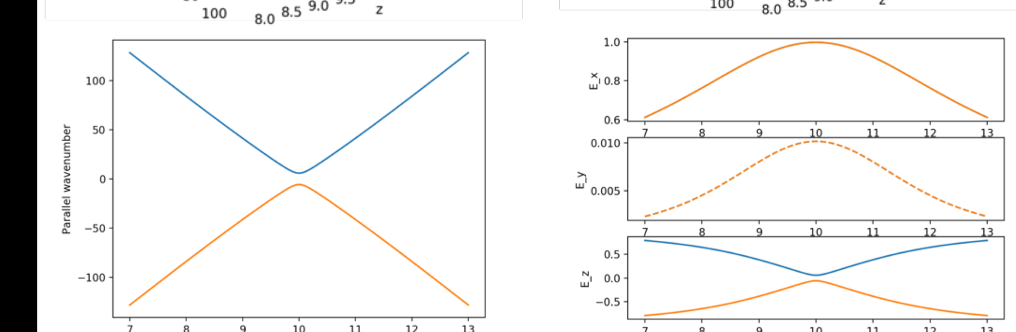
Result from a ray-tracing simulation of the propagation of whistler waves into the magnetosphere. The color background shows the electron density, as computed by the code SAMI2. The white dashed curve shows the location where the ionospheric oxygen plasma gives way to the magnetospheric hydrogen plasma. The white curve shows the trajectory that the whistler wave takes through the magnetosphere, nearly following the field lines between the northern to southern hemispheres, and reflecting after it passes the lower hybrid cutoff (yellow dashes).

Mode conversion in reduced model of ionosphere / magnetosphere boundary

$$D > 0; \quad D = \text{const.}$$
$$P < 0; \quad P = \text{const.}$$
$$S(z;\omega) = S_0(\omega) + S_1(z - z_1)^2$$
$$z_1 = z_0 + \frac{h}{2}$$
$$S_0(\omega) = -a + b(\omega - \omega_0)$$







$$|\eta|^2 \equiv \frac{|\tilde{\eta}|^2}{|\mathcal{B}|} = -\frac{1}{2}\frac{h_*}{(-\det\mathcal{H}_*)^{1/2}} \qquad \tau = e^{-\pi|\eta|^2}, \qquad \beta(\eta) \equiv \frac{(2\pi\tau)^{1/2}}{\eta\Gamma(-i|\eta|^2)}.$$

[1] E. R. Tracy, A. N. Kaufman, and A. J. Brizard. Ray-based methods in multidimensional linear wave conversion. Physics of Plasmas, 10(5):2147–2154, 2003.
[2] E. R. Tracy, A. N. Kaufman, and A. Jaun. A ray-based algorithm for multi-dimensional linear conversion. Physics Letters A, 290(5):309 – 316, 2001.