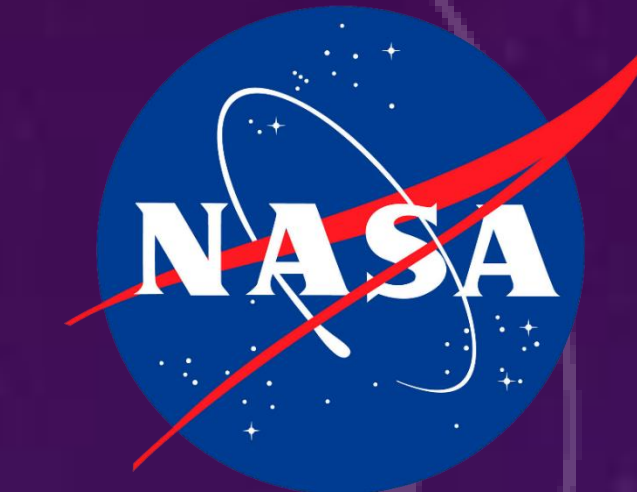




Modeling Spectroscopy to Understand Alfvén Waves and Turbulence

in the Solar Corona
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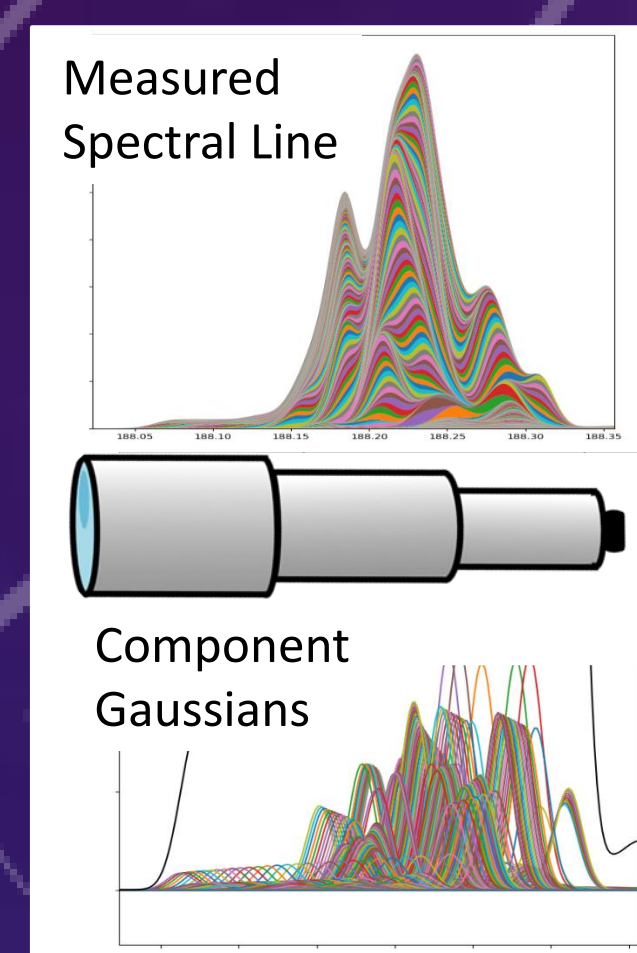
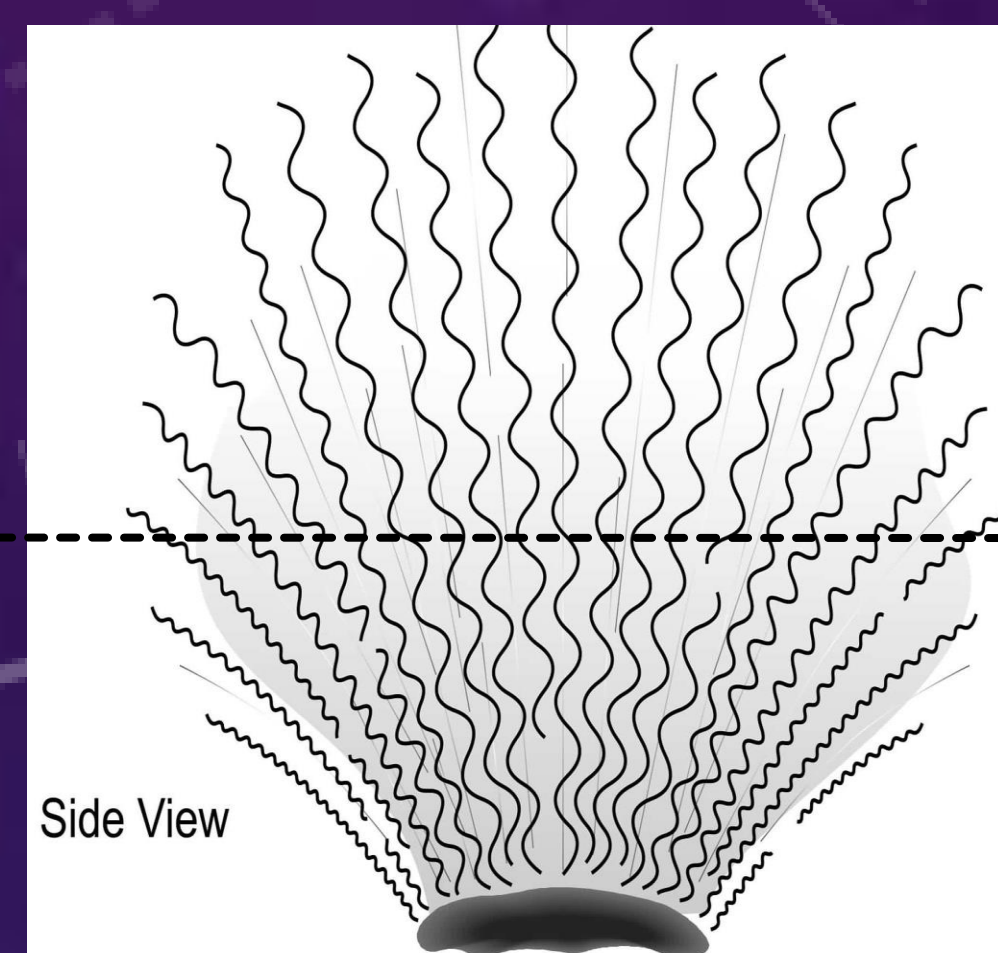
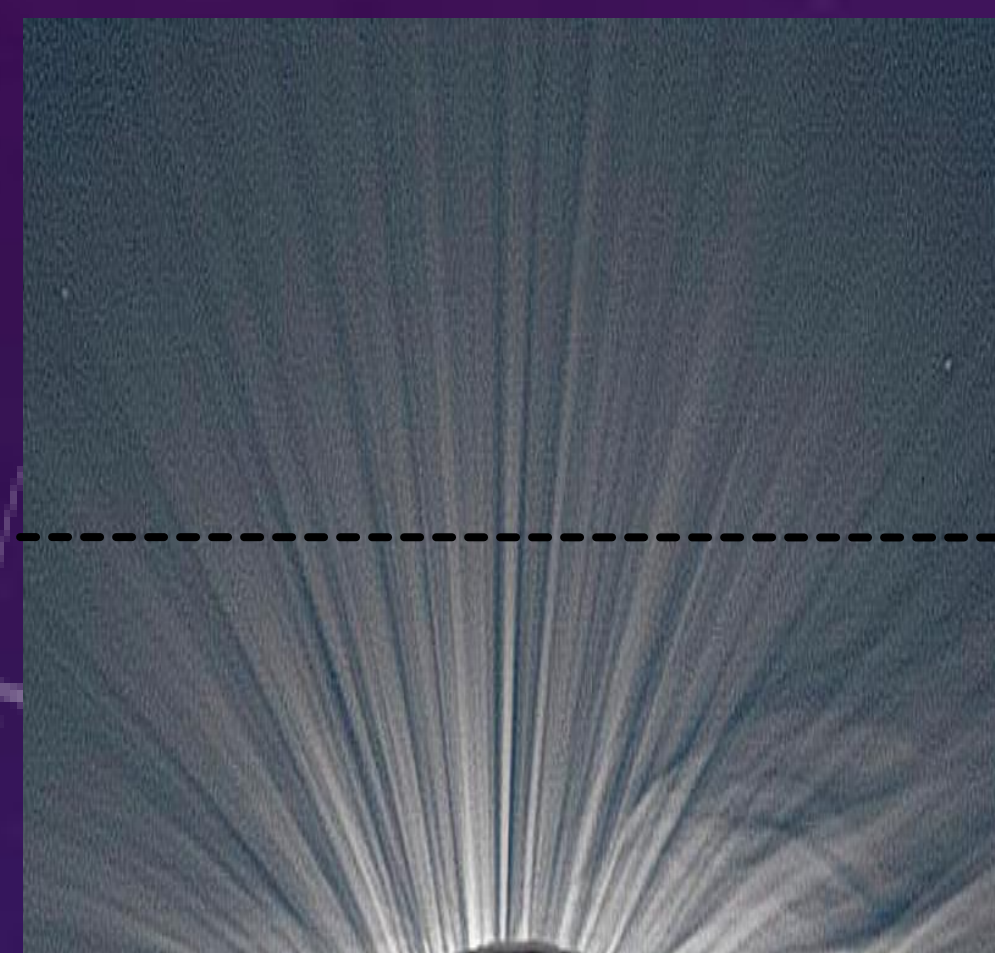


Abstract

There is much debate in the solar community regarding the precise mechanism by which the corona is heated to millions of Kelvin. Alfvén waves, driven by fluid motion in the photosphere and propagating upwards to dissipate in the corona, are one of several popular hypotheses for the source of the thermal energy. Observations of off-limb spectral lines are in theory able to constrain some properties of these waves (e.g., amplitudes and phase speeds) as a function of heliocentric altitude, but in practice the interpretation of these measurements is difficult due to the optically-thin nature of the corona. In this work, a forward model (GHOSTS) is developed and refined so that it can be used to generate realistic simulated observations of the Solar Corona. Recent improvements to the model include the addition of resonantly scattered light, refinements in the treatment of photon scattering, and the self-consistent calculation of non-equilibrium ionization states in the corona (ongoing work).

Measuring Alfvén Waves in the Corona

Above the poles of the Sun, open magnetic field lines define **magnetic plumes** which are being **shaken by photospheric convection**. Because these oscillations are transverse, they cause a slight **Doppler shift in the spectral lines** they produce. But because there are many such flux tubes along a line of sight, measurements are the sum of many individual Doppler-shifted spectral lines.

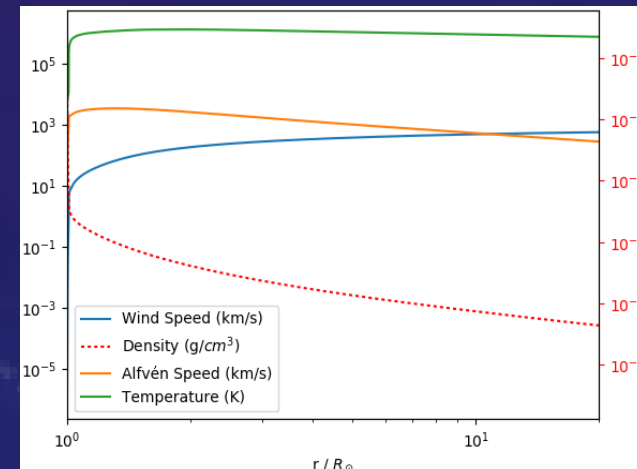


It is not immediately obvious exactly how to extract the properties of the waves from such a profile. One method often used, but little verified, is to simply fit the line with a Gaussian and then **relate the line width to the RMS amplitude**. Care must be taken to subtract out the thermal width to get the true non-thermal (wave/turbulence) width of the line. [3,5,7,8] Usually the remaining width is then assumed to represent the plasma in the Plane of the Sky (POS), which may be misguided. The purpose of this work is to try to better understand how the shape of the spectral lines is related to the Alfvén waves in the corona.

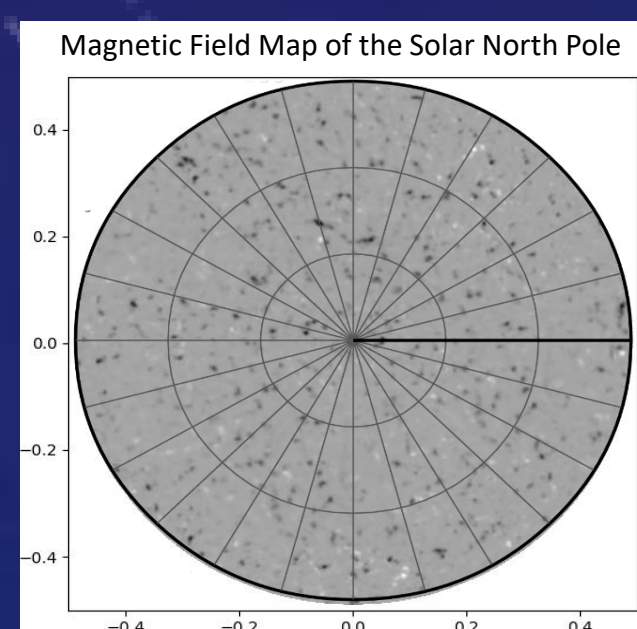
Simulating Coronal Measurements

In order to simulate the spectral lines, three kinds of input are needed:

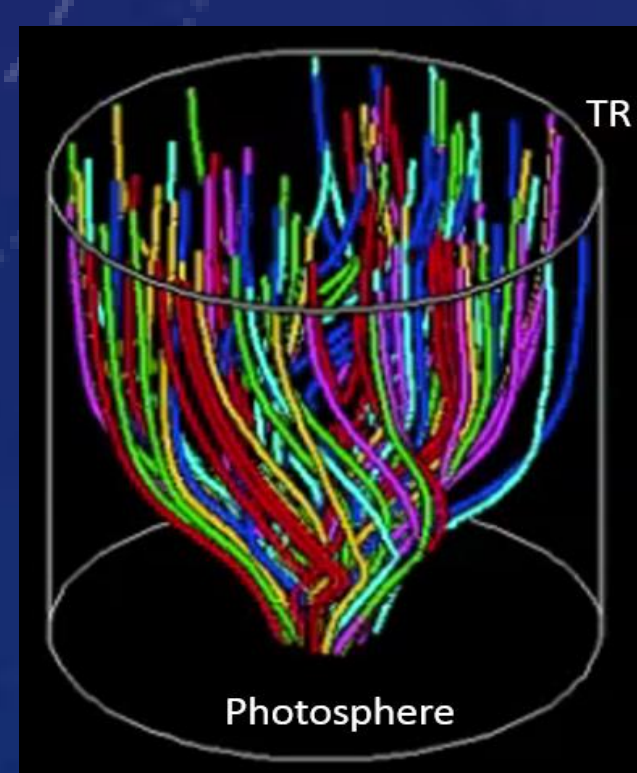
Coronal Plasma Properties: The **ZEPHYR** code is a 1- dimensional code that simulates the time-independent plasma properties of the corona as a function of altitude. [2] It produces tabulated output of the following variables, which are read into the GHOSTS model: **Density, Wind Speed, Alfvén Speed, Temperature**. These values are used as the average background values inside the coronal hole, which are then modified by the magnetic field strength.



Polar Magnetic Field Map: This creates the polar plumes. Because we don't have a line of sight to the solar poles, these maps must be partially synthesized. The magnetic field maps from **SOLIS/VSM** [4] magnetograms taken of large coronal holes between 2010 and 2013 were stitched together to yield polar maps. The magnetic field strength modulates a variety of plasma parameters in the overlying corona, such as density and solar wind velocity.



Alfvén Wave Profiles: The **BRAID** code is a simulation of a bundle of flux tubes expanding in the chromospheric network. [1] From that simulation, we are able to draw an average x and y velocity as a function of time. This gives us a **wave profile** that we can draw from in the GHOSTS model. For future work, a distribution of wave speeds will be drawn from BRAID, instead of a single profile.

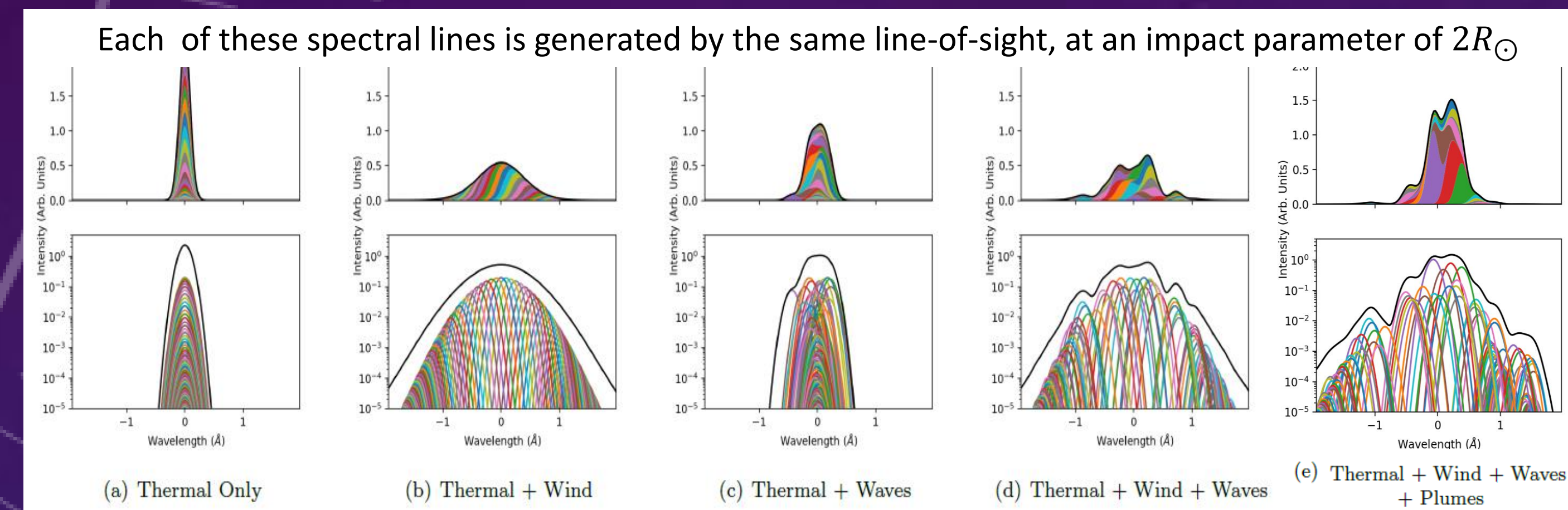


References

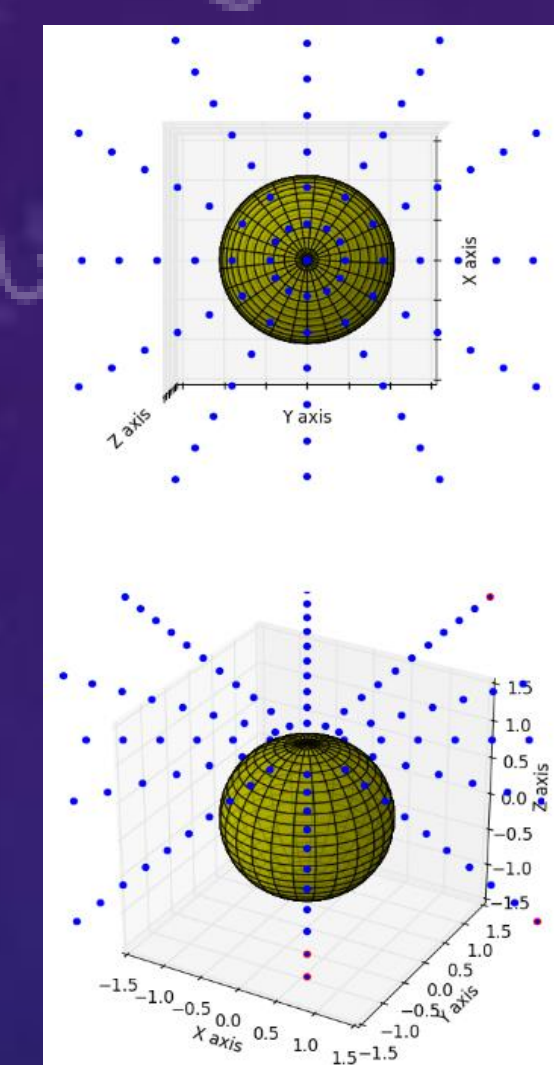
- [1] van Ballegoijen, et. al. 2011, ApJ, 736, 3
- [2] Cranmer, S. R., et. al. 2007, ApJS, 171, 520
- [3] Esser, R., 1990, JGR, 95, 10261
- [4] Henney, C. J., et. al. 2009, ASP Conf. 405, 47
- [5] Landi, E, Cranmer, S.R., 2009, ApJ, 691, 794
- [6] Owocki, S., et. al. 1983, ApJ, 275, 354-366
- [7] Seely, J. F., et. al. 1997, ApJ, 484, L87
- [8] Tu, C. Y., et. al, 1998, ApJ, 503, 475

The GHOSTS Model Generating Spectral Lines

GHOSTS is the **G**lobal **H**eliospheric **O**ptically-thin **S**pectral **T**ransport **S**imulation. This is a semi-empirical forward model which simulates spectral lines coming from the corona. A sightline is established, and the light produced by each point along the sightline is determined based on the local plasma parameters. Because the corona is optically thin, all of this light can simply be summed. Different physics can be turned on and off individually, as shown in this plot:



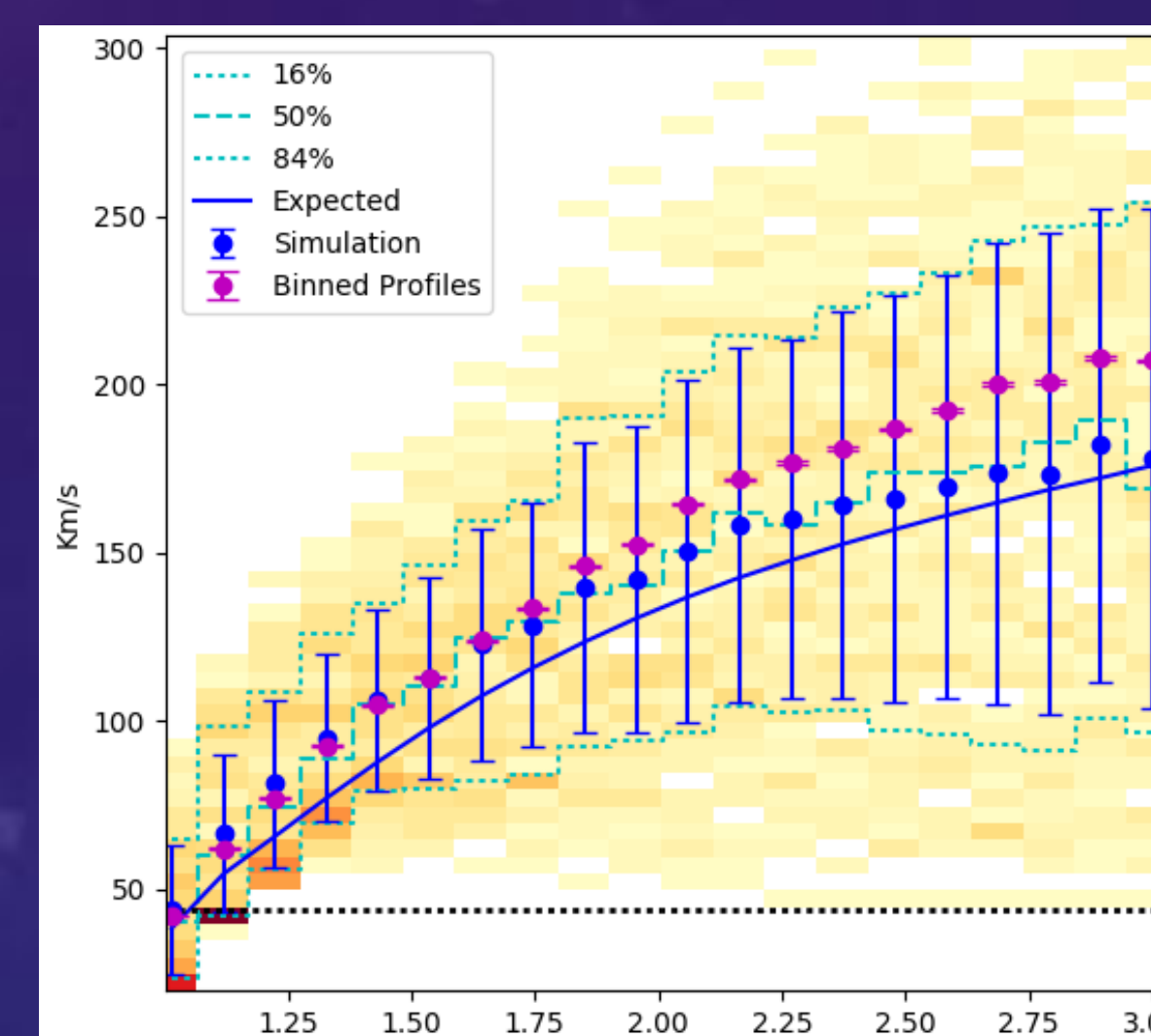
Analyzing Spectral Lines



GHOSTS **generates many sightlines** at a given impact parameter, and **fits them with Gaussians** to find their width.

A typical run generates about **100 sightlines** at each impact parameter, using **6 magnetic field maps**, creating **10 different ion lines** each, with about **200 seconds of time integration** per line.

These ensembles of lines can then be studied with respect to the known input parameters.



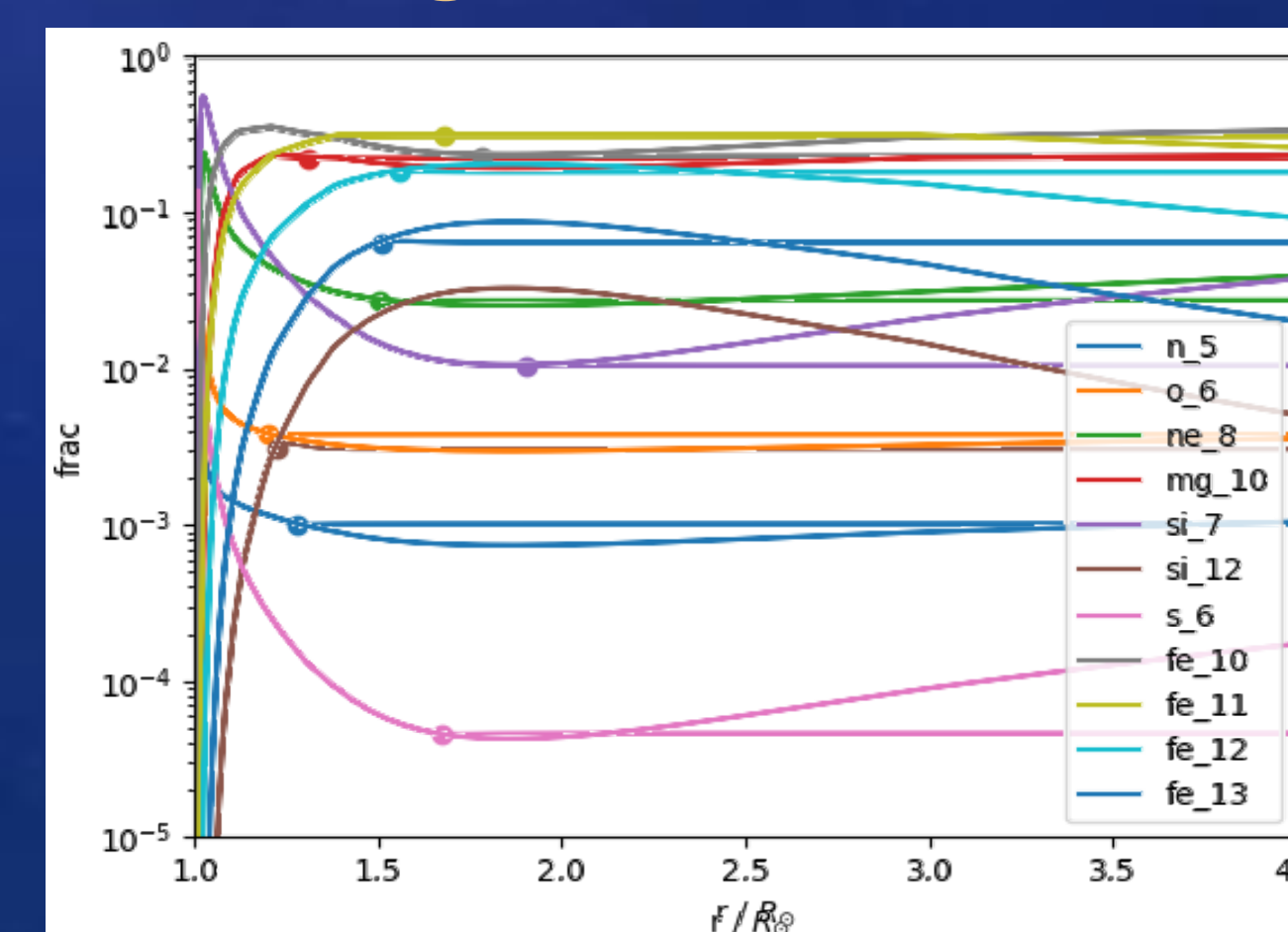
Pending Upgrades Two Types of Light

Two different sources of light are now handled by the code: **collisionally excited lines**, and **resonantly scattered** photons from the bright solar disk below, provided by the SUMER Spectral Atlas.

The resonant light has just been implemented. Most of the analysis done so far has been only with the collisional light. I am looking forward to exploring the way that the resonantly scattered light changes the measurements, especially in the in the middle/upper corona where it is dominant.

Ionization and Freezing-In

CHIANTI is a database of quantum mechanical information, which provides coronal elemental abundances A_p , and temperature dependent ionization fractions $f(T)$. A caveat: the **ionization fraction stops being dependent on temperature** when the **collision rate gets too low**: If $\tau_{collision} > \tau_{expansion}$ then the particles are **unable to reach a collisional equilibrium** before they are swept out by the solar wind, and the **ionization state becomes frozen-in**. This must be accounted for to properly model the spectral lines that would be produced. Currently, the code does this manually by comparing the times, as seen on the right.



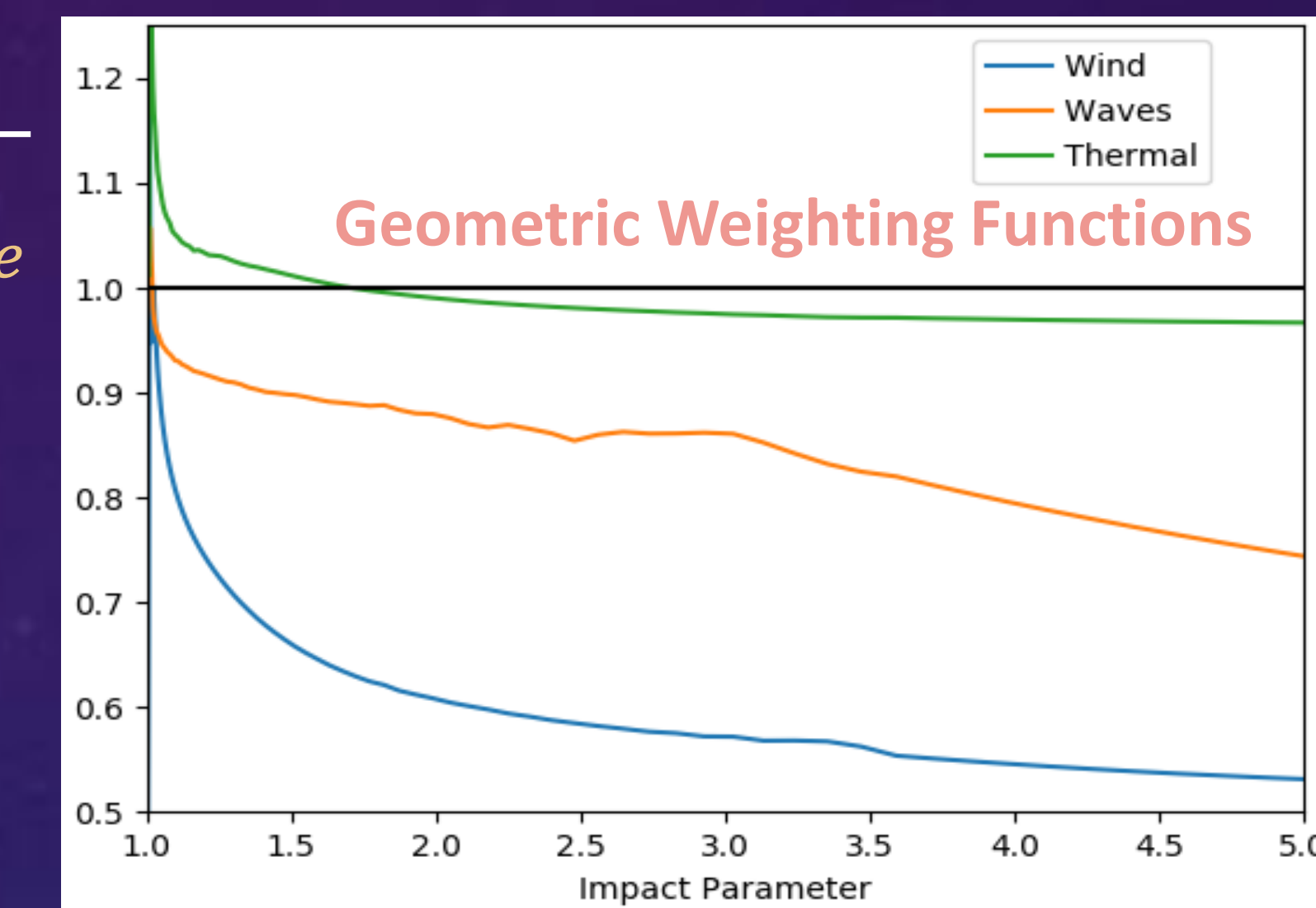
A more rigorous method, currently being implemented: The system can be described by the following equation [6], which can be iterated numerically to find the true, self-consistent non-equilibrium ionization states for each ion of each element. C and R are the temperature dependent collision and recombination rates.

$$0 \frac{\partial n_i}{\partial t} + \frac{1}{r^2} \frac{\partial}{\partial r} (r^2 n_i u_i) = n_{i-1} C_{i-1} + n_{i+1} R_{i+1} - n_i (C_i + R_i) \Rightarrow \frac{\partial n_i}{\partial r} = RHS$$

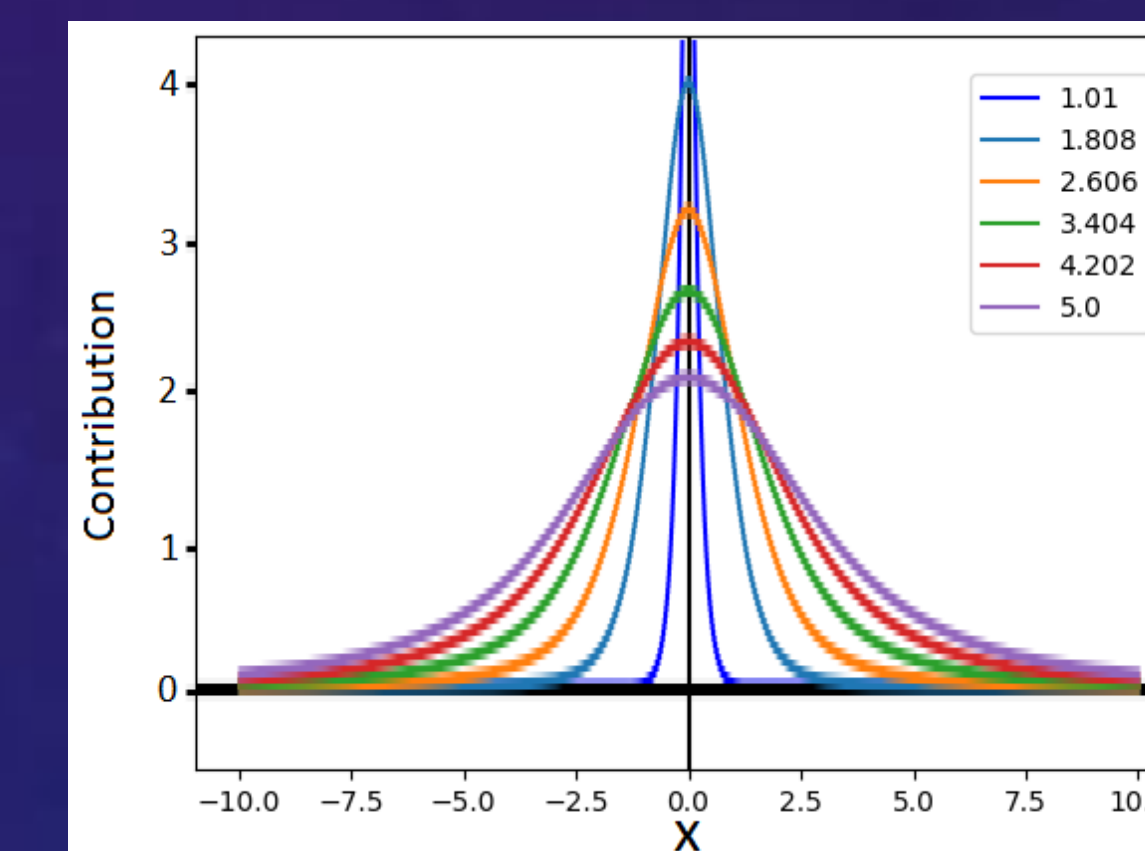
Understanding the Contributions to the Non-Thermal Line Width

The **width of a spectral line can be decomposed** into three components. Those components can be written as functions of the Plane of the Sky (POS) values of various plasma parameters. The known plane-of-sky values are multiplied by a derived **geometric weighting function**, which accounts for the fact that all the light is not produced in the POS:

$$\Delta V(b) = \sqrt{V_{thermal}^2 + V_{wind}^2 + V_{wave}^2}$$
$$V_{wind} = W_{wind}(b) \times U_r(b)$$
$$V_{wave} = W_{wave}(b) \times V_{rms}(b)$$
$$V_{thermal} = \sqrt{W_{th}(b) \times T(b)} \sqrt{\frac{2k_b}{m_i}}$$

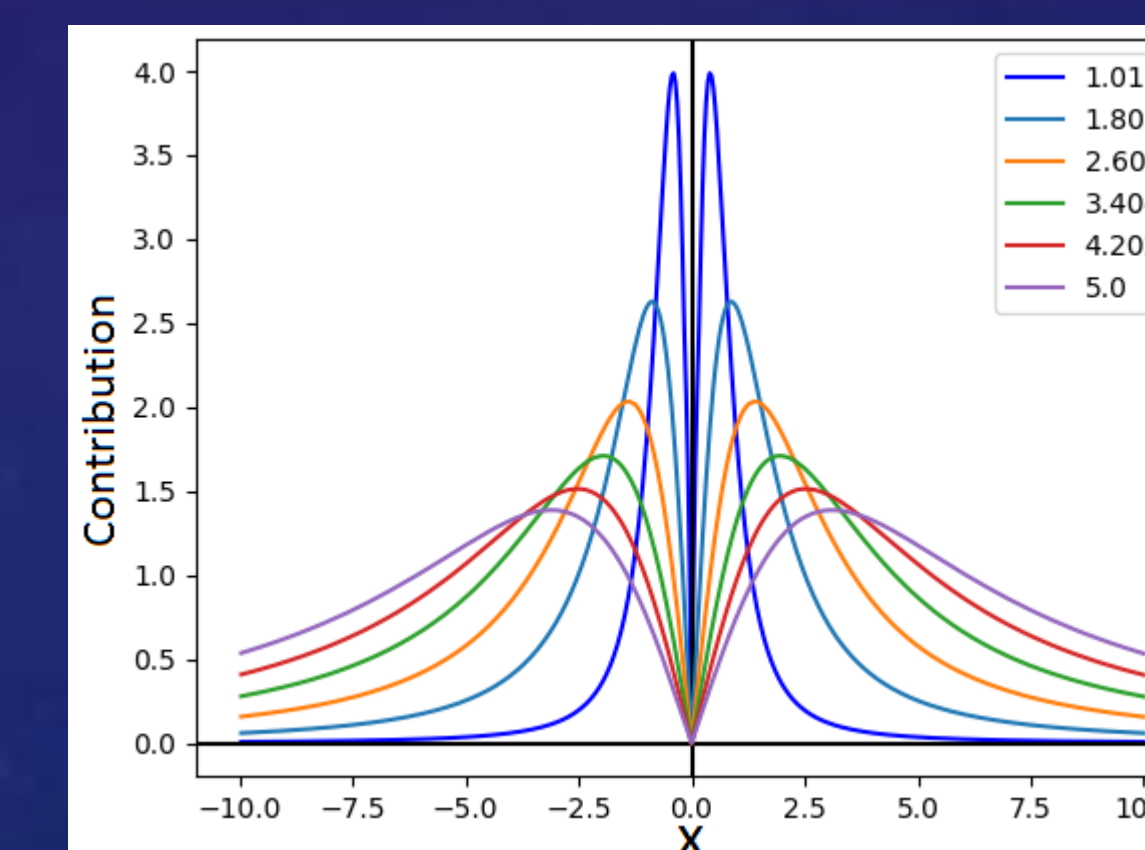


Because we know the plasma properties everywhere, we can determine these weights with the following integrals. The plots on the left show the normalized integrands. Waves contribute in the plane of the sky, but the solar wind contributes in front of and behind it.



Alfvén Waves

$$v_{||,waves}^2(b) = \frac{\int_{-\infty}^{\infty} (v_{rms} \times \cos(\phi))^2 \rho^2 dx}{\int_{-\infty}^{\infty} \rho^2 dx} \Big|_{y=0, z=b}$$
$$W_{wave}(b) = \frac{v_{||,waves}(b)}{v_{rms,pos}(b)}$$



Solar Wind

$$v_{||,wind}^2(b) = \frac{\int_{-\infty}^{\infty} (v_w \times \sin(\phi))^2 \rho^2 dx}{\int_{-\infty}^{\infty} \rho^2 dx} \Big|_{y=0, z=b}$$
$$W_{wind}(b) = \frac{v_{||,wind}(b)}{v_{wind,pos}(b)}$$

Early Result: The Wind Affects the Widths!

Perhaps the more important question is: Given a **measured line width**, how much do each of the broadening sources contribute?

$$\frac{V_i(b)}{\Delta V(b)} = P_i(b) = \frac{W_i v_{i,pos}}{\sqrt{\sum_i (W_i v_{i,pos})^2}} \quad \text{For } i \text{ in (Wind, Waves, Thermal)}$$

