Semi-Empirical Analyses of Alfvén Wave-Driven Winds from Red Giants and Supergiants

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COOL STARS 20.5 ... virtually cool

Cool Evolved Star Outflows

Understanding the mechanisms that drive outflows (winds) from non-dusty cool evolved stars remains one of the outstanding challenges in stellar astrophysics. Current progress is being driven by observations made at the highest spectral and spatial resolutions, and instrumental sensitivities. In this Poster we highlight three semi-empirical projects that address potential mass-loss mechanisms, and derive robust mass-loss rates.

Alfvén Wave-Driven Winds?

A leading candidate for driving winds from non-dust, non-pulsating, cool stars is Alfvén waves. **Here we seek to determine whether a "steady wave-driven wind" is viable.** Non-coronal red giants provide the most stringent test, because the low densities and implied heating suggests coronal temperatures [1].

Using measured wind acceleration, turbulence, mass-loss rates, and thermal constraints inferred from UV line profiles and VLA radio observations, we can examine the energy and momentum requirements of damped Alfvén waves in radially diverging (thin flux-tube) geometries.

For known stellar parameters and wind acceleration and geometric properties, the wave energy density, $\epsilon(r) = \rho\langle\delta v(r)^2\rangle$ (δv =wave amplitude), can be derived along with the wave-damping length, $L(r)$, gas heating rate, $Q(r)$, and T_{gas}.

Results:
(1) Derived $\langle\delta v^2(r)\rangle$ exceed empirical measures of wind turbulence.
(2) For ζ Aurigae, $L(r)$ are significantly greater than previously published [2].
(3) Wind T_{gas} for red giants are not consistent with radio continuum observations of non-coronal star [3].
(4) Turbulence-driven winds are also problematic for red giants.

References

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Acknowledgements

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New Mass-loss Rates for Arcturus and Aldebaran

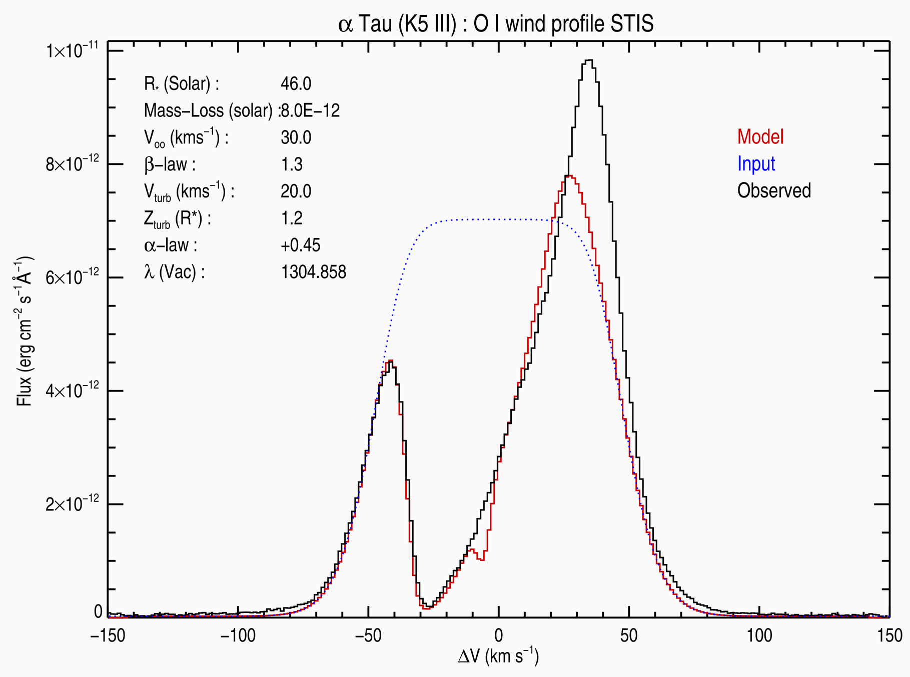
In this HST project, in collaboration with Thomas Ayres, we have improved upon previous UV line profile wind scattering models by using an exact solution for the accelerating wind scattering problem with *complete redistribution* and **v**ariable microturbulence [4]. We adopt a form, where $1.2R_*$ is the adopted inner wind radius boundary condition,

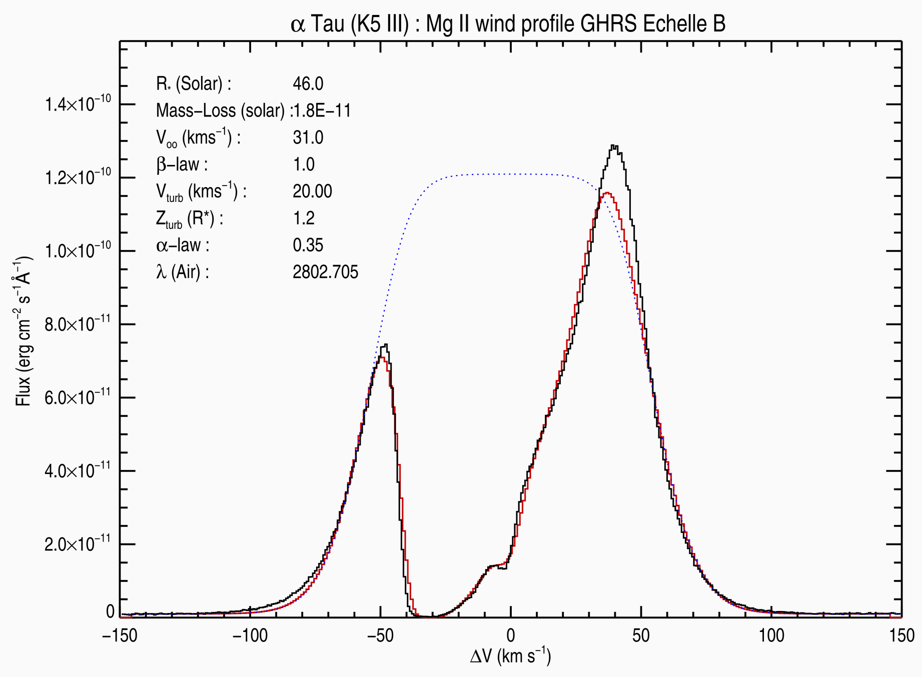
$$V_{turb}\,(R) = V_{turb}\,(1.2R_*)\left(\frac{R_*}{R}\right)^{\alpha}$$

and associate magnetic/shock wave amplitudes to the microturbulence through $\langle\delta v^2\rangle = CV_{turb}$.

- More lines: Si III 1206Å, O I 1303Å triplet, C II 1335Å, and Mg II h& k 2976 and 2802Å, leads to more robust mass-loss rates.
- Examine *First Ionization Potential* (FIP) effect in stellar winds, i.e., is Mg II (Mg I FIP 7.6 eV) overabundant compared to O I (FIP 13.6 eV)? [5].
- Mass-loss rate for Arcturus is substantially smaller than published 2×10^{-10} $M_\odot yr^{-1}$ [6].
- Profiles of 1206Å, from thermally ionized Si III, compared to dominant Mg II/O I/C II lines gives first direct T_{gas} constraints of acceleration region.
- $V_{turb}(r)$ gives estimate of shock/wave amplitude growth/decay throughout the stellar outflow.

Two example profile computations are shown below for α Tau.





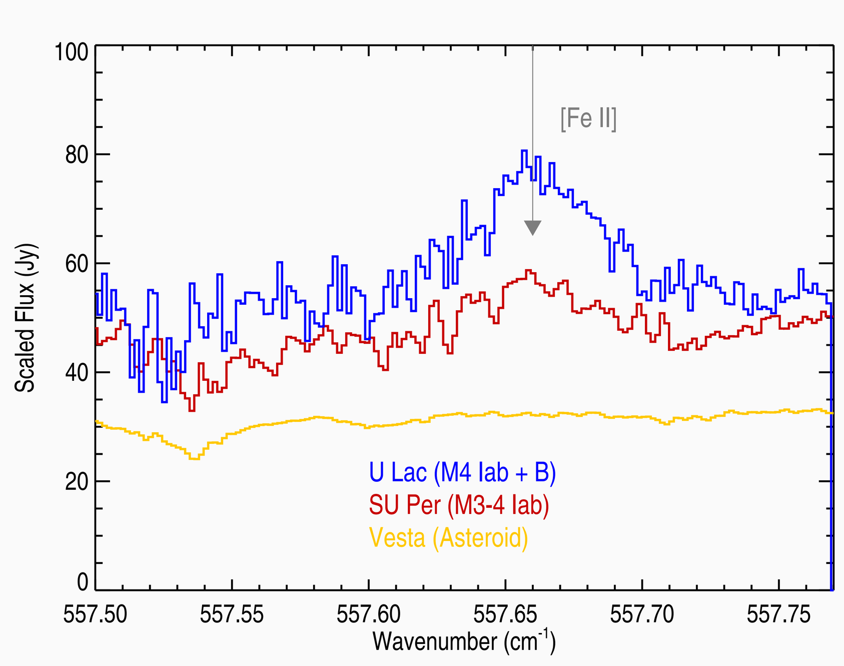
A Novel Mass-Loss Rate Estimator for Non-Dusty RSGs

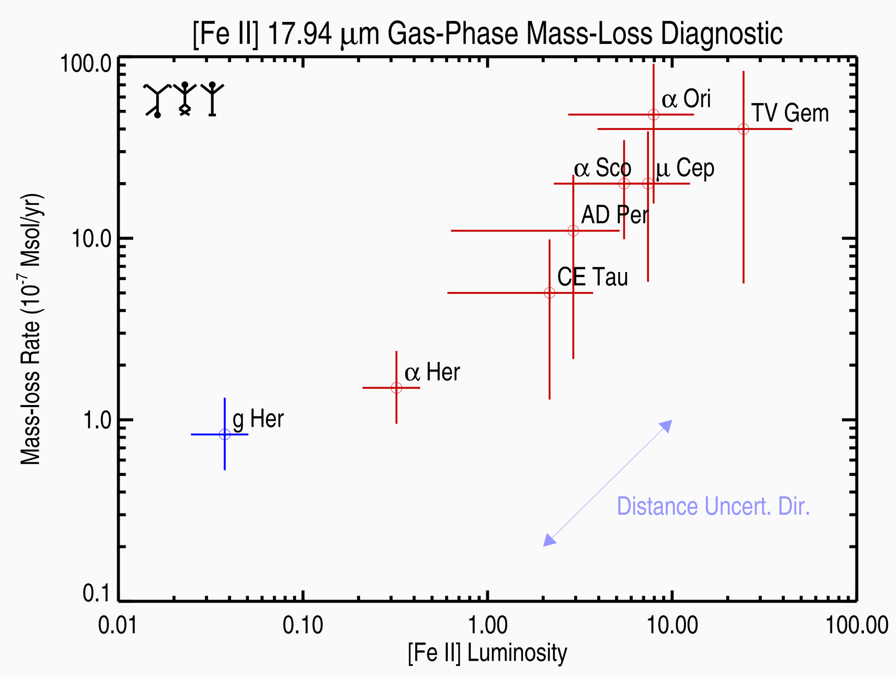
Estimating mass-loss rates from K and early- mid-M supergiants is notoriously difficult and uncertain (sometimes orders of magnitude). Empirically, this is because, in part, molecules (CO, SiO) are not fully associated, and the gas-to-dust mass fraction is high (and not well determined) – with less silicate dust formation compared to later, dustier, spectral-types.

There is no standard model for mass-loss from RGSs to accurately estimate mass-loss rates for galactic evolution studies, so we are exploring a new mass-loss rate estimator that uses empirical evidence of the required wave/shock heating associated with the outflow acceleration zone. [Fe II] 17.94 μm emission appears to be a good diagnostic

1. Optically-thin emission from magnetic dipole transitions between levels of excited $a\,{}^4$F term.
2. Fe II is the dominant ionization state, Fe I is easily ionized by chromospheric plasma.
3. Mid-IR flux is insensitive to contributions from pockets of hot chromospheric gas.
4. Empirically and theoretically, wind heating: [Fe II] luminosity $\propto \dot{M}^{\gamma}$.

First observations of a large sample of RSGs were obtained with the TEXES on NASA's IRTF in Semester 2019B with examples shown below (left, poor weather), and are ongoing. Right Fig. shows existing measurements for stars with independent mass-loss rate estimates available.





This study is in collaboration with Matthew Richter (PI TEXES), Thomas Greathouse, Edward Guinan, Edward Monteil, & Anita Richards.