Toward Mitigating Granulation RV Noise with GRASS: The GRanulation And Spectrum Simulator

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https://github.com/palumbom/GRASS

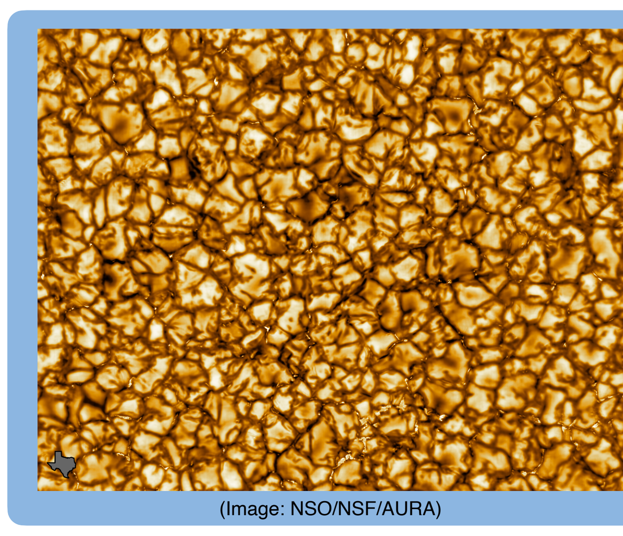
1. Granulation is a source of RV noise

Background: The radial velocity method is one of the most widely-used techniques to detect exoplanets and measure their masses.

Problem: Convective cells known as "granules" in stellar atmospheres perturb the shape of spectral lines and introduce radial velocity noise, obscuring signals from low-mass planets with Doppler semi-amplitudes of order 10 cm/s.

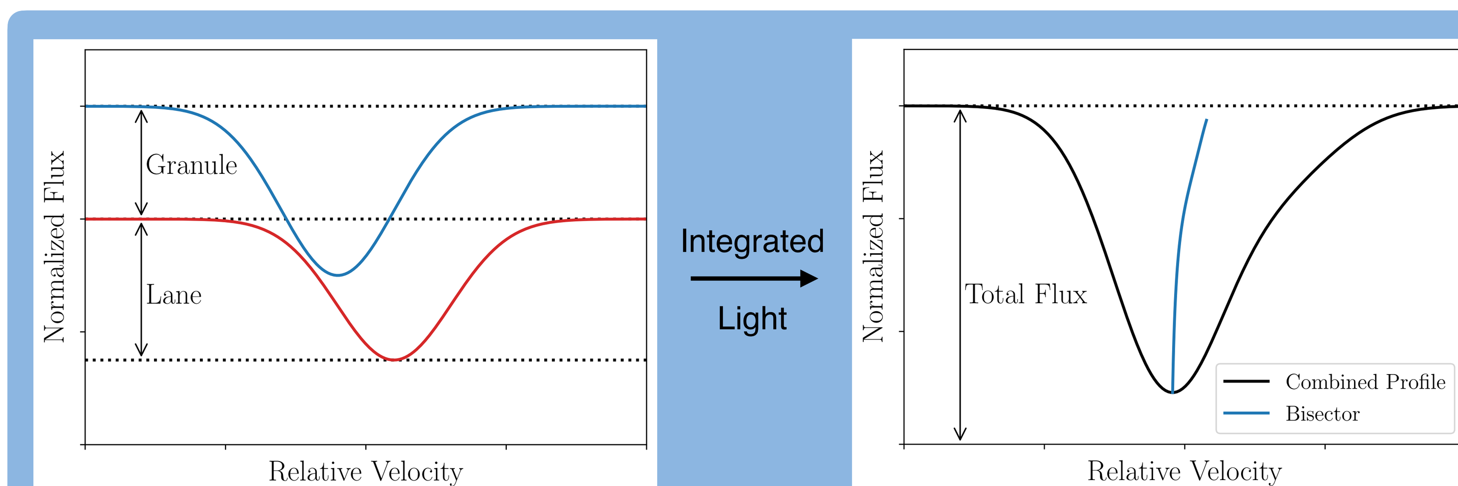
Goal: We use high-resolution observations of the Sun to create the first empirical model of spectral variability due to granulation in the quiet Sun. We call our tool the GRanulation And Spectrum Simulator (GRASS)[1].

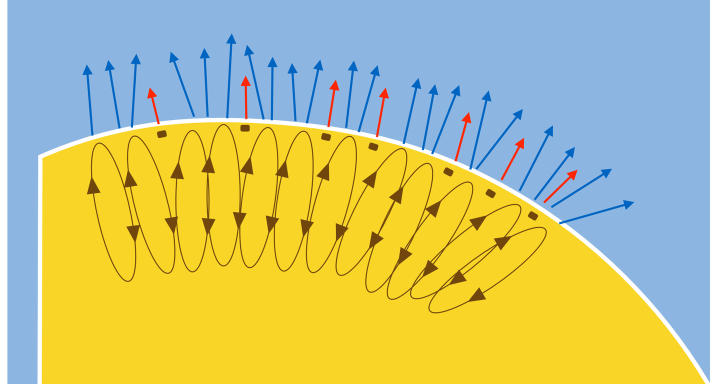
Importance: GRASS is a valuable test bed for evaluating analysis techniques and machine learning models that account for and mitigate stellar RV noise.



(Image: NSO/NSF/AURA)

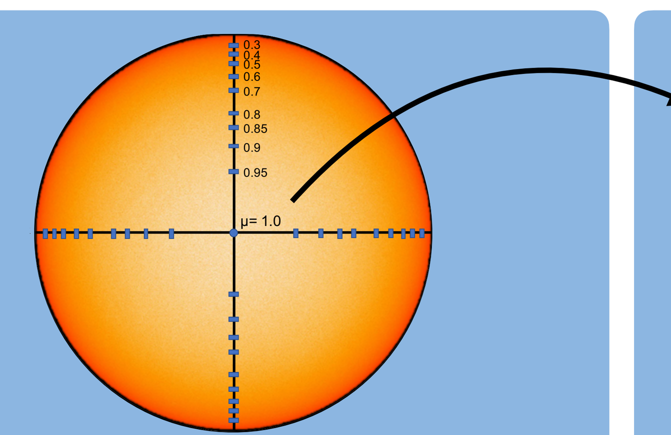
In white light, granules appear as roughly Texas-sized (~1 arcsecond[2]) convective cells in the solar atmosphere. The collective motion, formation, and dissipation of these cells creates the photometric "flicker" observed for distant stars.



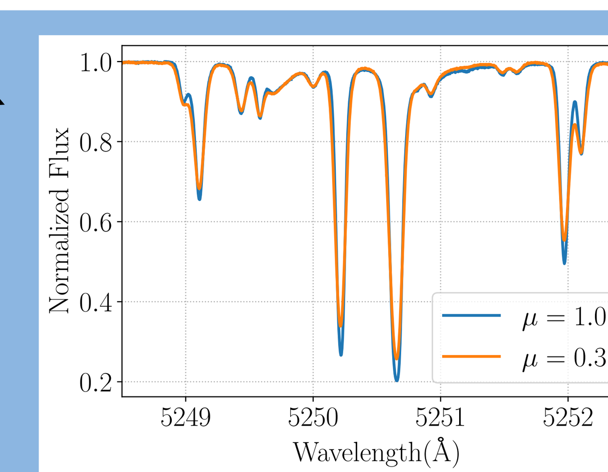


The differing intensities and Doppler shifts within individual granules also alter the shape of absorption lines, introducing asymmetry that is quantified in a line "bisector." These asymmetries become a source of noise when interpreted as COM Doppler shifts.

2. Solar observations encode granulation

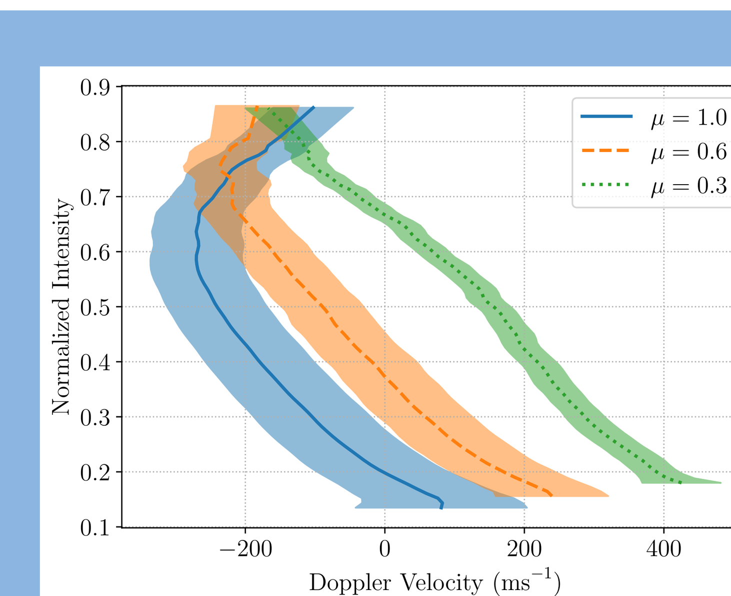


As the only star whose surface we can resolve in detail, and whose center of mass motion is precisely known, the Sun is an important test bed for understanding stellar RV variability.



To study convection in the solar atmosphere, Löhner-Böttcher et al.[2,3] observed high spectral resolution (R ~ 700,000) time series of many solar absorption lines at many spatially resolved disk positions.

These observations encode the spatial (differently colored lines) and temporal (shaded regions) variability of line shapes at the m/s level. We use these shape variations as a model to construct synthetic spectra with observationally informed granulation signatures.



3. Synthesizing observationally informed spectra

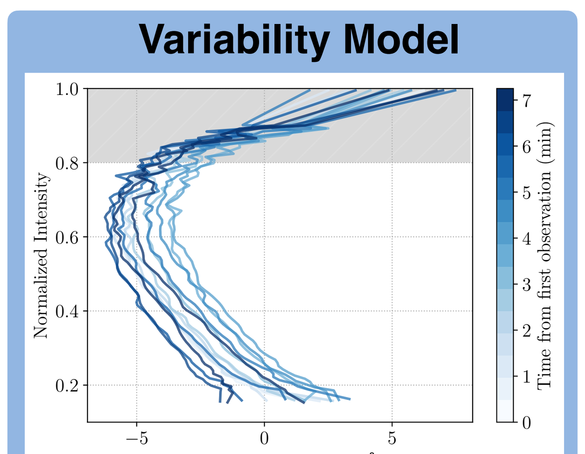
Differential Rotation

$$\omega(\phi) = A + B\sin^2\phi + C\sin^4\phi$$

Limb Darkening

$$\frac{I_\mu}{I_0} = 1 - u_1(1-\mu) - u_2(1-\mu)^2$$

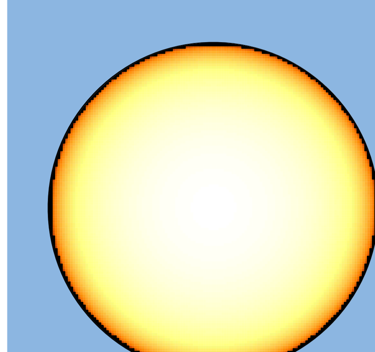
Variability Model



Line List

VALD3

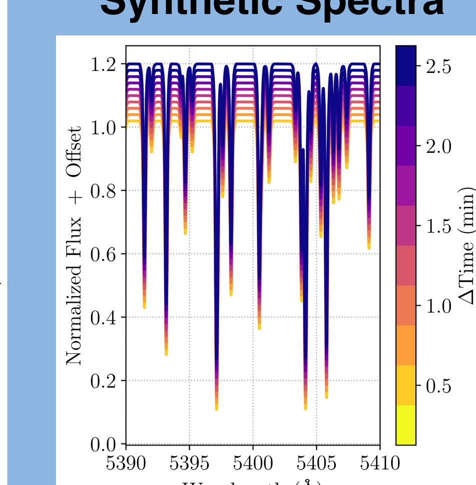
Model Grid of Stellar Surface



$I(t, \lambda, x, y)$

Using the input solar observations, GRASS computes flux values on a model stellar disk…

Time Series of Synthetic Spectra

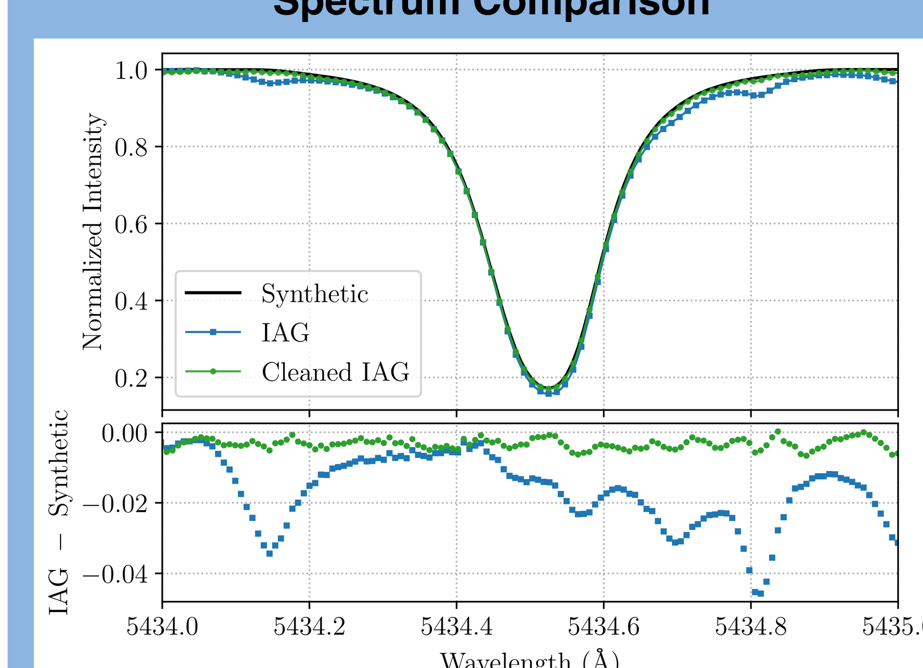


$I(t, \lambda)$

…and then sums over the spatial dimensions, producing time series spectra for a point source.

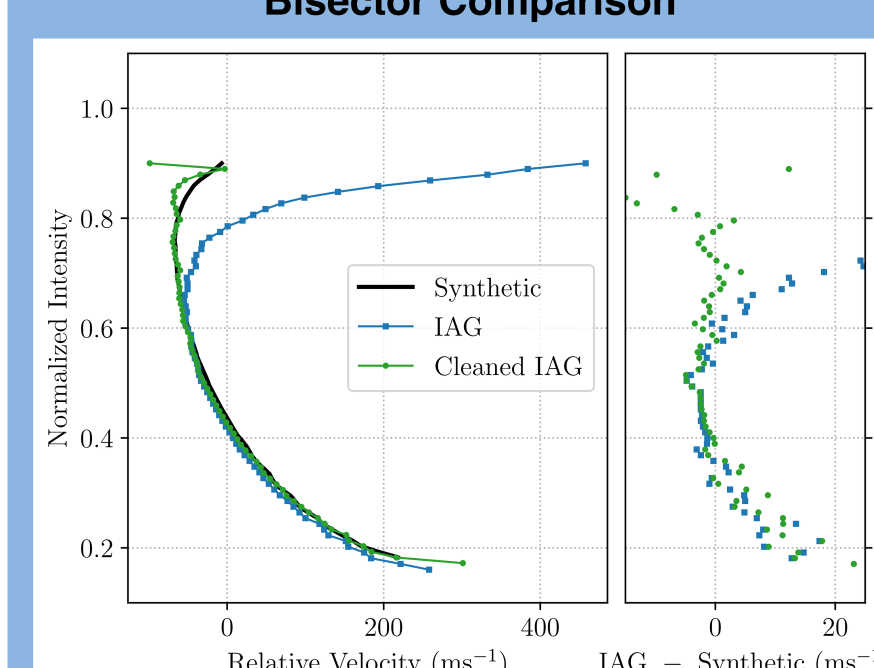
4. GRASS accurately reproduces solar line shapes

Spectrum Comparison



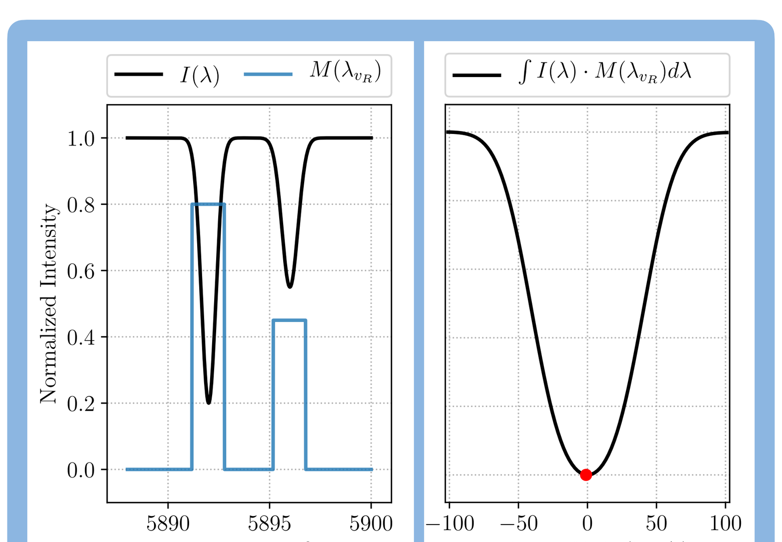
Our model disk-integrated line profile (black) closely match the IAG Solar Atlas[4] (blue), especially when shallow line blends are modeled out of the Atlas (green). As evident in the residuals (bottom panel), all discrepancies between the synthetic and cleaned IAG line profiles are below the 2% level.

Bisector Comparison



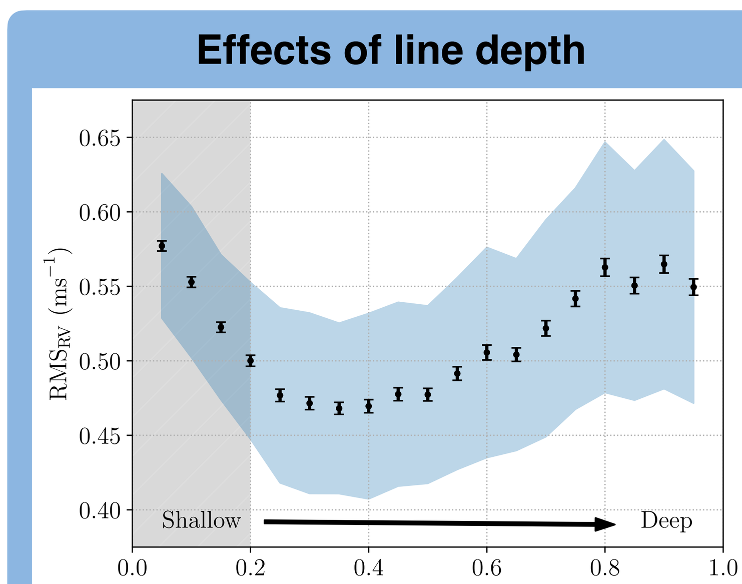
Our synthetic disk-integrated bisectors (black) similarly closely match the IAG bisector (blue). When shallow line blends are modeled out of the IAG line profile (green), the agreement is much greater, especially above 60% of the continuum level.

5. Probing line-by-line variability with GRASS



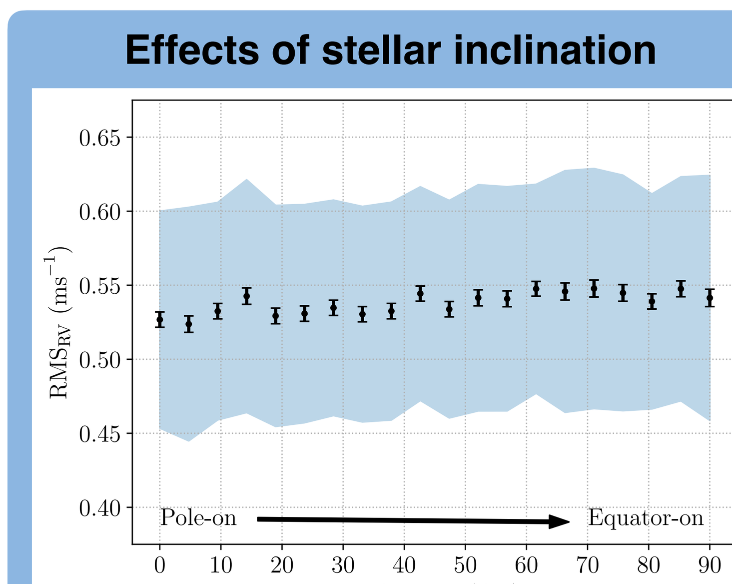
To probe line-by-line RV variability, we measure velocities from cross-correlation functions (CCF's) computed from our synthetic spectra. Although there are no "true" Doppler shifts in the spectra, the line-shape variations produce apparent Doppler variability.

Effects of line depth



When interpreting line-shape changes as Doppler velocities, the resulting RV variability (black points) is larger for deeper lines by as much as ~10 cm/s. For shallower lines (hatched region), the larger RMS may be an artifact of the data processing[1].

Effects of stellar inclination

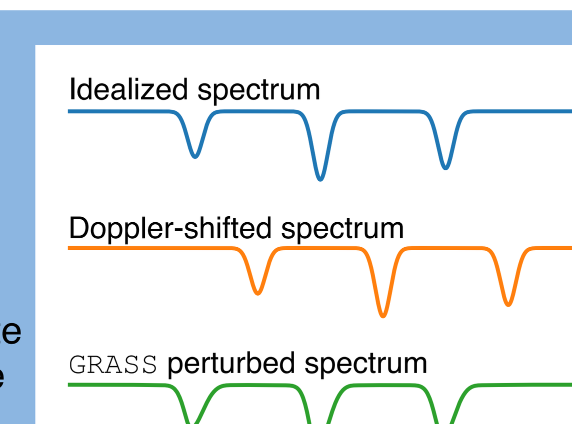


Conversely, stellar inclination does not appear to dramatically affect the observed RV variability.

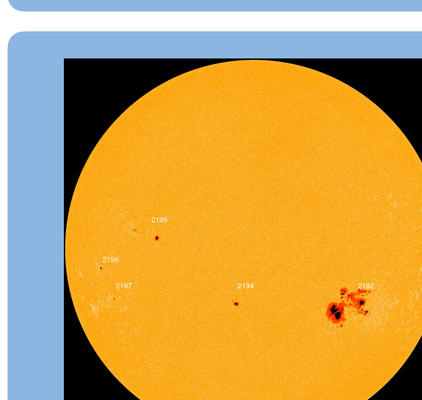
6. Future prospects for GRASS

Key takeaway

GRASS is a test-bed for RV noise mitigation methods. By default, it produces spectra free from COM Doppler shifts and other activity signatures (e.g., spots). By injecting Doppler signals, we can then evaluate methods for recovering planets in the presence of granular variability.



What's next



(Image: NASA)

Other forms of activity beyond granulation also preclude the RV detection of Earth-sized planets. Future versions of GRASS could use observations of sunspots to empirically model changes in line shapes within these regions. GRASS should also be used to evaluate new models for disentangling true Doppler shifts from stellar variability.

References

1. Palumbo et al. (2022), AJ, 163, 1, 11
2. Löhner-Böttcher et al. (2018), A&A, 611, 4
3. Löhner-Böttcher et al. (2019), A&A, 624, 57
4. Reiners et al. (2016), A&A, 587, A65

Acknowledgments

This research was supported by Heising-Simons Foundation Grant #2019-1177. This work was supported by a grant from the Simons Foundation/SFARI (675601, EBF). EBF acknowledges the support of the Ambrose Monell Foundation and the Institute for Advanced Study. MLP acknowledges the support of the Penn State Academic Computing Fellowship. The Center for Exoplanets and Habitable Worlds and the Penn State Extraterrestrial Intelligence Center are supported by the Pennsylvania State University and the Eberly College of Science. Computations for this research were performed on the Pennsylvania State University's Institute for Computational and Data Sciences' Roar supercomputer.

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