University of Warwick
Matt.Godfrey@warwick.ac.uk

Spatial Mapping of Atmospheric Winds and Sodium Absorption on HD 189733b Using *TERMINATOR*

Matt Godfrey, Peter J. Wheatley, Tom Louden

Introduction

Exoplanet atmospheres are fundamentally 3D, shaped by complex interactions between stellar irradiation, planetary rotation, and atmospheric dynamics. These processes drive strong winds, thermal contrasts, and chemical gradients, especially at the terminator region. Yet, most transmission spectroscopy studies treat planets as 1D, symmetric absorbers, averaging out the spatial information present at the limb. With high-resolution and time-resolved spectroscopy, we can now better probe the true spatial structure of atmospheres, resolving:

- Zonal winds (e.g., super-rotating equatorial jets)
- Day-to-night circulation flows
- Signatures of atmospheric escape, such as extended helium or sodium tails

These developments require new models capable of capturing atmospheric inhomogeneities, beyond the capabilities of traditional light curve models.

Current Modelling Landscape

Over 50 retrieval codes exist for exoplanet atmospheres[1], most designed to recover 1D, globally-averaged from spectra. These approaches typically lack sensitivity to atmospheric asymmetries and dynamics present at the planetary terminator.

To address this gap, a complementary 'family' of geometric forward models has evolved; *batman*[2] (fast transit light curve generator, symmetric planets and limb-darkened stars; photometry-focused), *spiderman*[3] (maps planetary brightness distributions for phase curves and secondary eclipses; emission-based), and *catwoman*[4] (models asymmetric transits using two semi-circular planet halves).

Despite these advances, many existing models either lack the spectral resolution or geometric flexibility to directly map wind-driven Doppler shifts and spatially-varying transmission spectra across the planetary limb.

Model

TERMINATOR is a fast, geometric code designed to spatially resolve exoplanet atmospheres during transit using time-resolved, high-resolution spectroscopy.

The planet is modelled as an opaque core surrounded by customisable atmospheric annulus sectors, each with independent transmission spectra, heights, or velocity fields. The code uses an analytical geometric algorithm (adapted from *spiderman*[3]) to calculate the exact overlap between each planetary annulus sector and each stellar annulus at every timestep, making it fast and numerically efficient. These intersected regions are then used to compute the flux decrement and transmission spectrum throughout the transit.

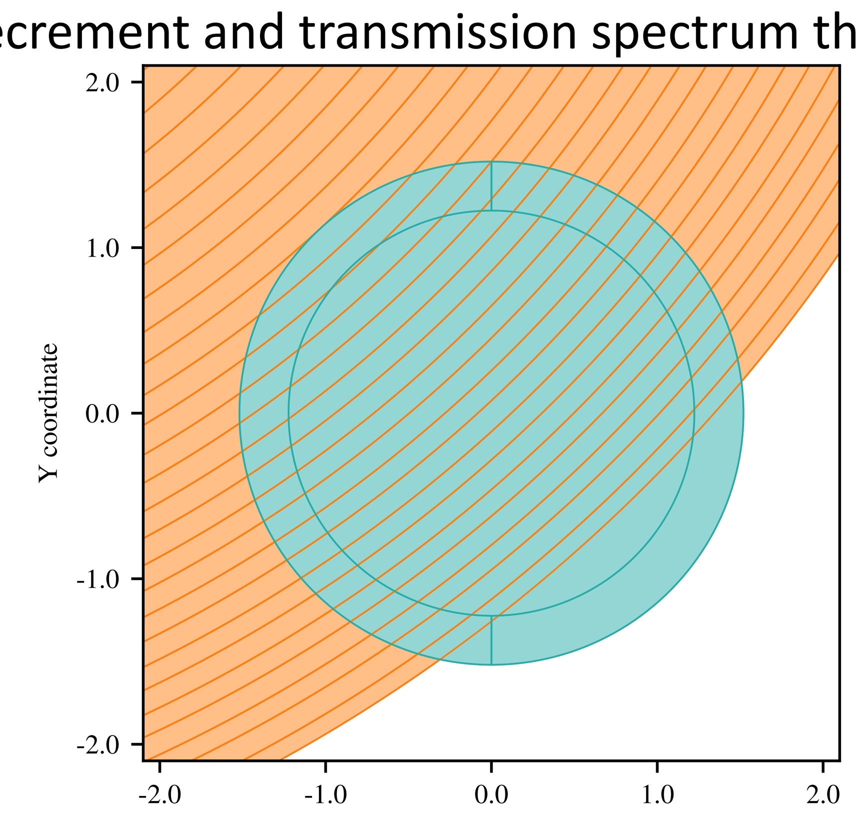

Figure 1. The geometry used by the terminator code. The coordinate system is centred on the planet, which is shaded in blue.

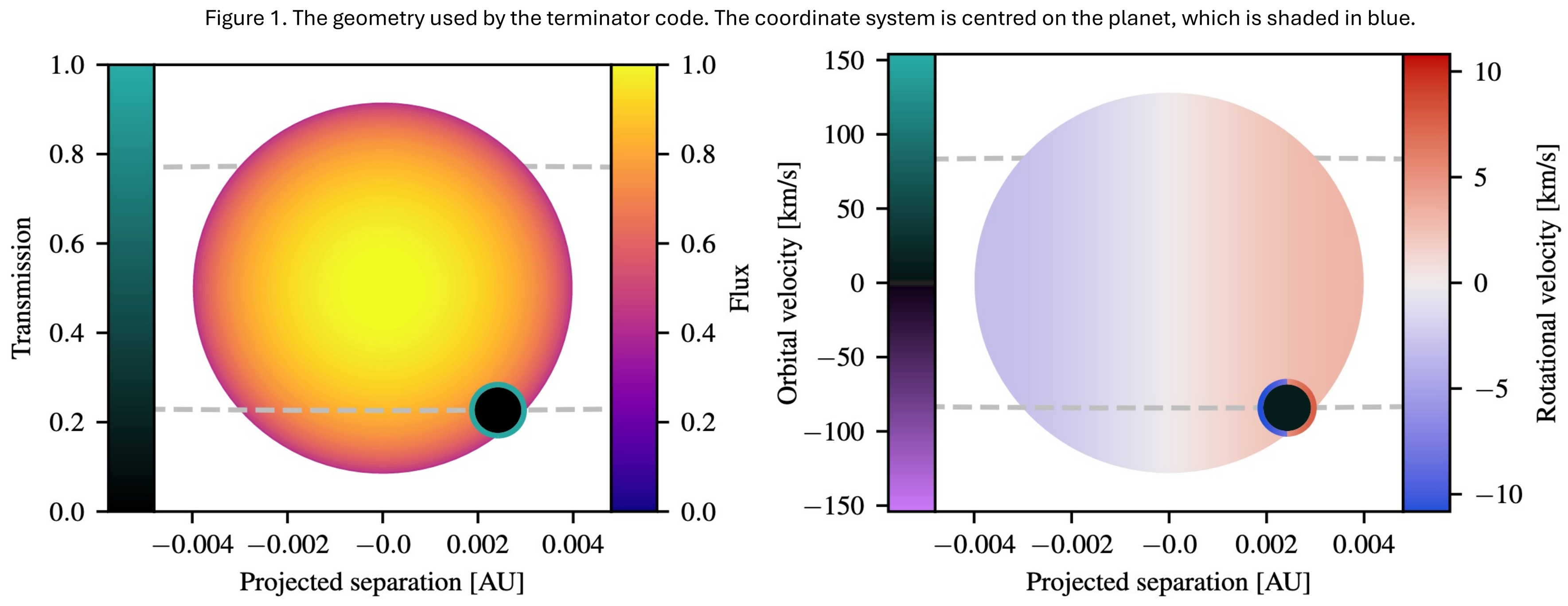

Figure 2. Model output for example system in flux (left) and velocity (right) space. Transmission and velocity structure are shown across the star–planet system.

We use full Bayesian retrievals via MultiNest, allowing robust exploration of parameter space (e.g., wind velocities, absorption depths, scale heights) and quantification of model uncertainties. The model is also resolved, such that it implicitly accounts for limb-darkening, centre-to-limb variations, and the Rossiter-Mclaughlin effect.

Future work

- Finalise benchmarking of *TERMINATOR* against previous studies to ensure model fidelity.
- Extend beyond sodium to include other tracers of atmospheric dynamics: Metastable helium - sensitive to escape in irradiated atmospheres, Neutral atomic species (e.g., Fe, Ti) common in ultra-hot Jupiters where molecular dissociation dominates.
- Apply *TERMINATOR* to new datasets, including JWST observations, to probe asymmetries during ingress and egress.

Application to HD 189733b

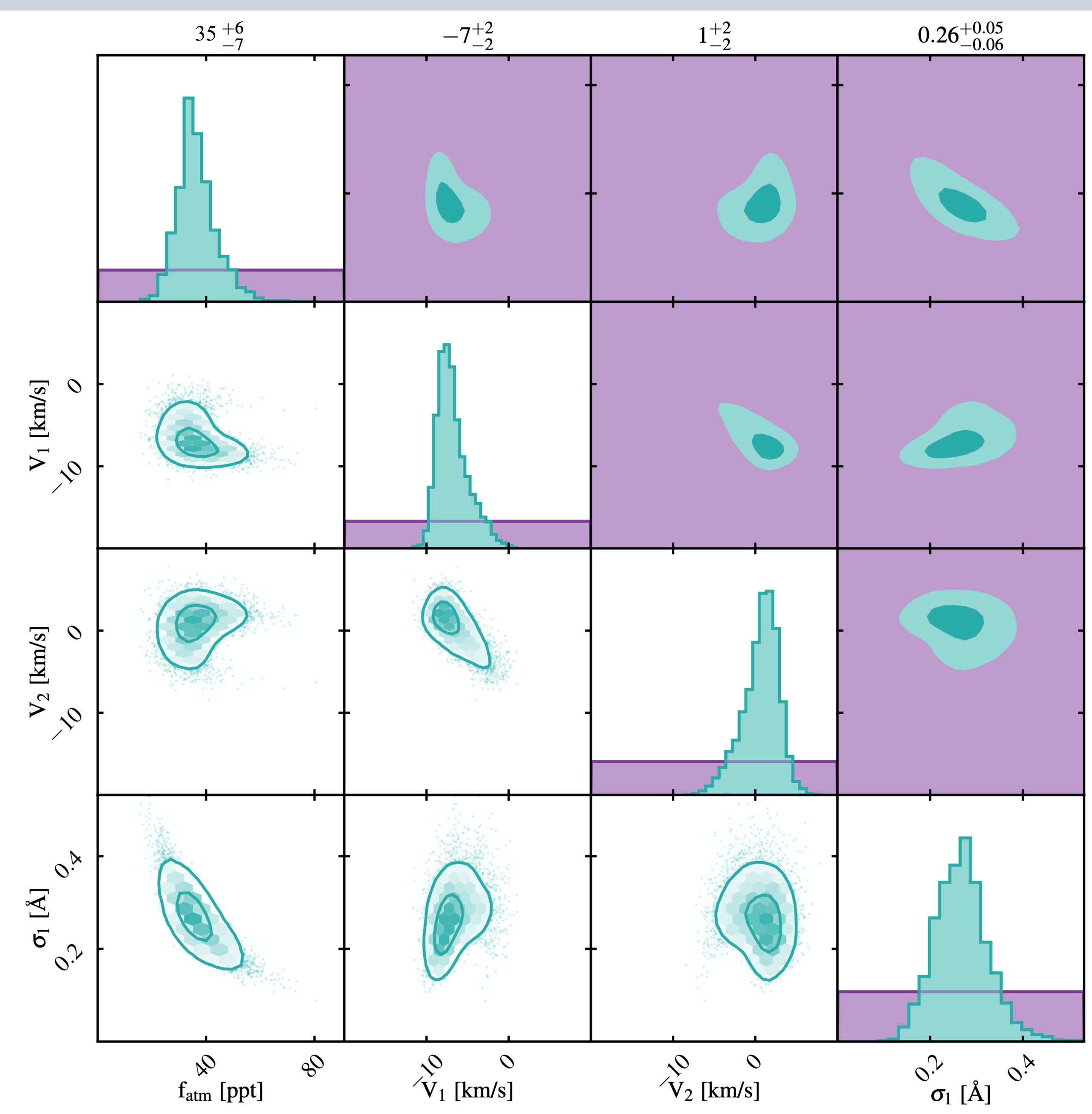

Figure 3. Posterior distributions for the HD 189733b model fit. Green shows the retrieved posteriors; purple shows priors. Median values and 68% intervals are listed above. Velocities include offsets beyond the expected tidally-locked rotation.

Applied TERMINATOR to HARPS sodium data for HD 189733b, detected spatially-resolved wind velocities:

- Trailing limb (V_1): -7 ± 2 km/s → consistent with super-rotating jet on the evening terminator.
- Leading limb (V_2): 1 ± 2 km/s → consistent with tidally-locked rotation on the morning side.
- Line width ($\sigma_1 = 0.26 \pm 0.05$ Å) narrower than previous estimates, reflecting improved resolution of atmospheric velocities and RM effect.

Results are in line with GCM predictions of equatorial jets on hot Jupiters, and match Louden & Wheatley (2015)[5] but with improved uncertainty quantification thanks to MultiNest.

Conclusions

- *TERMINATOR* provides a fast, flexible model to spatially resolve exoplanet atmospheres during transit, capturing winds, cloud asymmetries, and escape signatures.
- Validated using HARPS sodium observations of HD 189733b, detecting a super-rotating equatorial jet and confirming wind asymmetries.
- The model's Bayesian-ready performance enables robust parameter retrievals and is adaptable to a variety of datasets (e.g., JWST, ultra-hot Jupiters).

References

[1] MacDonald, R. J., & Batalha, N. E. (2023). *A catalogue of exoplanet atmospheric retrieval codes*. Research Notes of the AAS, 7(3), 54.
[2] Kreidberg, L. (2015). *batman: BAsic Transit Model cAlculatioN in Python*. Publications of the Astronomical Society of the Pacific, 127(957), 1161–1165.
[3] Louden, T., & Kreidberg, L. (2018). *SPIDERMAN: An open-source code to model exoplanet phase curves and secondary eclipses*. Monthly Notices of the Royal Astronomical Society, 477(2), 2613–2627.
[4] Espinoza, N., & Jordán, A. (2015). *catwoman: A Python tool to model asymmetric exoplanet transit light curves*. Monthly Notices of the Royal Astronomical Society, 450(2), 1879–1885.
[5] Louden, T., & Wheatley, P. J. (2015). Spatially resolved eastward winds and rotation of HD 189733b. *The Astrophysical Journal Letters*, 814(2), L24.