Atmospheric retrieval of M dwarfs as planet hosts with an auto-differentiable spectral model

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Overview

- We developed **ExoJAX**, a tool for fitting differentiable spectral models with the HMC, to be applied to **M dwarfs**.
- We confirmed that we can directly fit the near-infrared high-resolution spectra of M dwarfs using simultaneously the **atmospheric structure (T-P profiles)** and the **mixing ratios of both molecules and atoms** as free parameters.
- Best-fit spectra **reproduced well the absorption features of molecules and atoms** simultaneously in some regions.
- **Layer-by-layer temperature-pressure structure** is well constrained only around the photosphere.

Backgrounds

M dwarfs are the favorable targets for the Earth-like planet search.

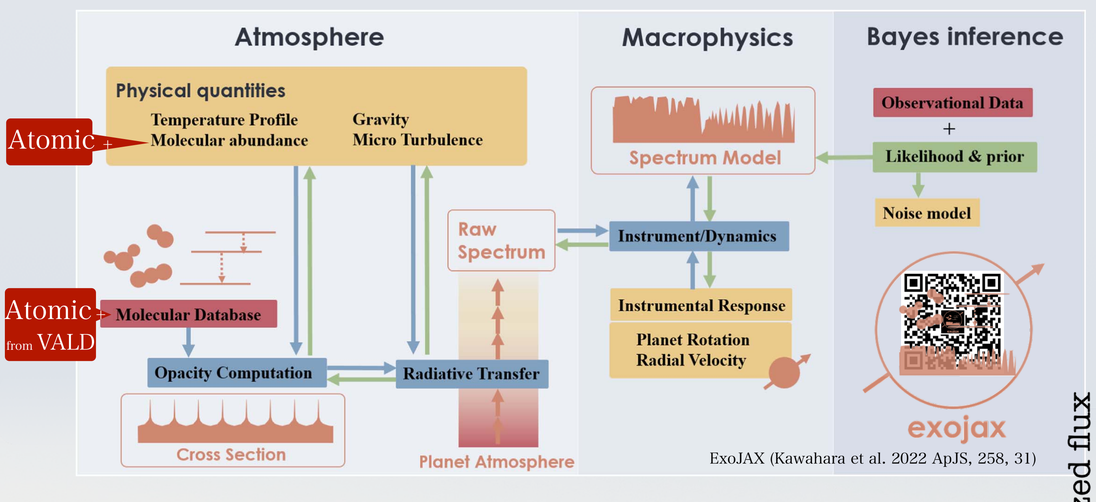
T_{eff} ~ 2300-3900 K → Peak flux on Near-IR

$M_* < 0.6\ M_\odot$, $R_* < 0.7\ R_\odot$ → Advantageous to detect small-planets

- The nature of M dwarfs is crucial as a planet-hosting environment.
- Due to the effects of low temperatures, such as a large number of molecular lines, there are known differences between observed spectra and models, or even between several state-of-the-art models.

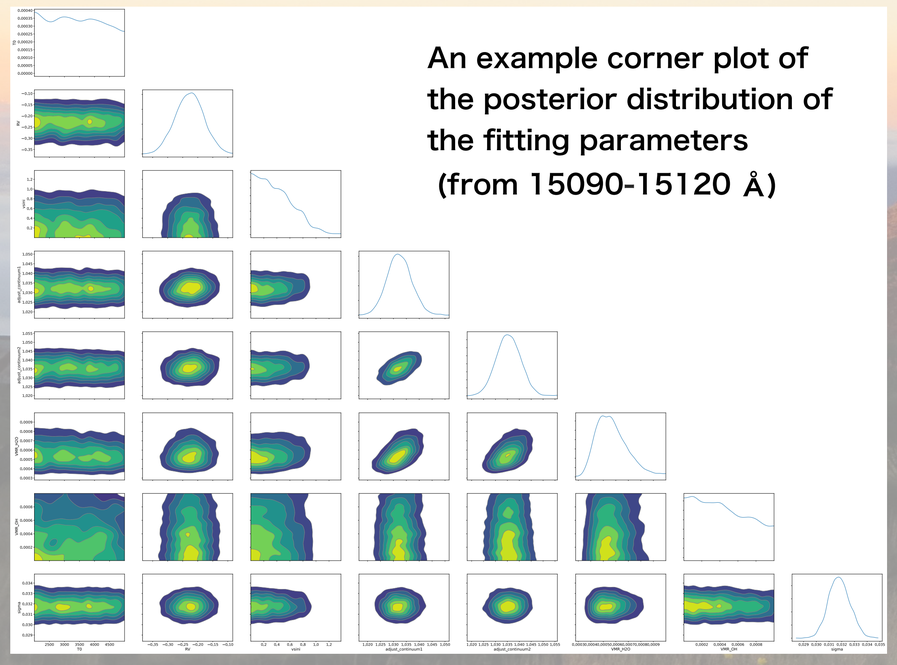
Methods

- **ExoJAX** (https://github.com/HajimeKawahara/exojax) is an open source code for Bayesian inference of atmospheric parameters by fitting differentiable spectral models to observational spectra using **HMC-NUTS** (Hamiltonian Monte Carlo + No-U-Turn Sampler) which was developed for planetary mass objects (Kawahara et al. 2022).
- It is written in Python with **GPU**/TPU compatible package for auto-differentiation and accelerated linear algebra, JAX (Bradbury et al. 2018)
- We enhanced ExoJAX to apply it to M dwarfs high-R spectra.



ExoJAX (Kawahara et al. 2022 ApJS, 258, 31)

- We developed a module for working with **atomic line data** in the Vienna Atomic Line Database (VALD; Kupka et al. 1999).
- This made it possible to fit M-dwarf spectra, **considering a huge number of both atomic and molecular lines simultaneously**

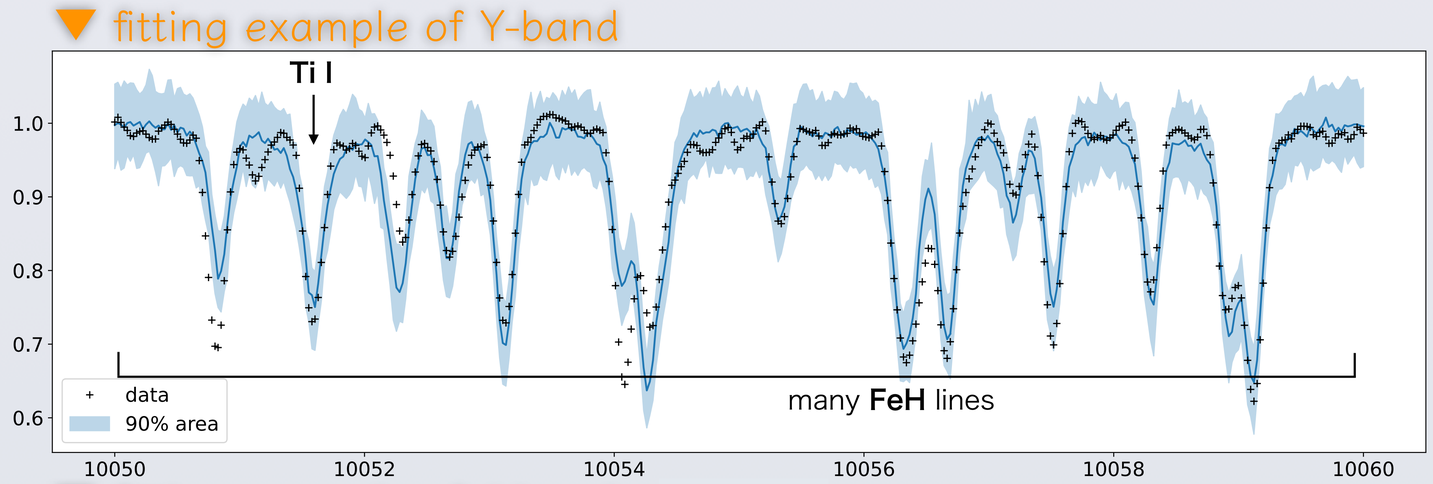


An example corner plot of the posterior distribution of the fitting parameters (from 15090-15120 Å)

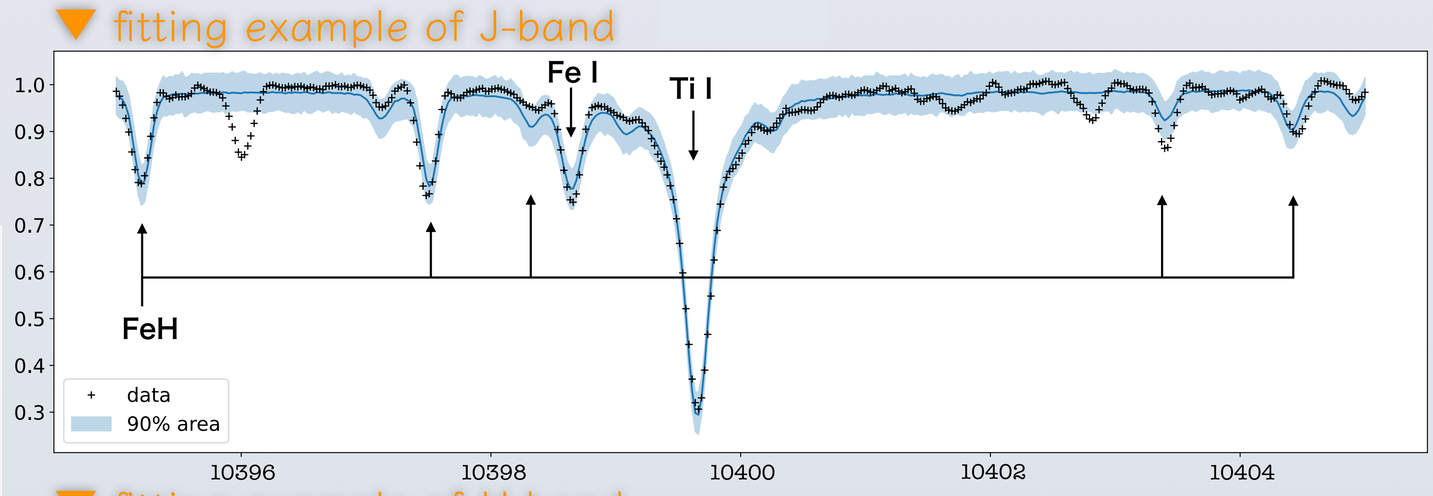
Results

- The **near-infrared spectra (R~80000)** of **Barnard's star (T_{eff} ~3200 K)** obtained with **Subaru/IRD** are successfully fitted within the 90% credible interval.
- It is the first time that the complex spectra of M dwarfs have been directly fitted with a spectral model using the **T-P profile of the atmosphere** and **the mixing ratios of individual chemical species** including H_2O as free parameters.
- Deviations from the observed spectra, such as near 10396 Å, may be due to defects in the line list. Further investigation of the selection of molecular species and line database is needed.

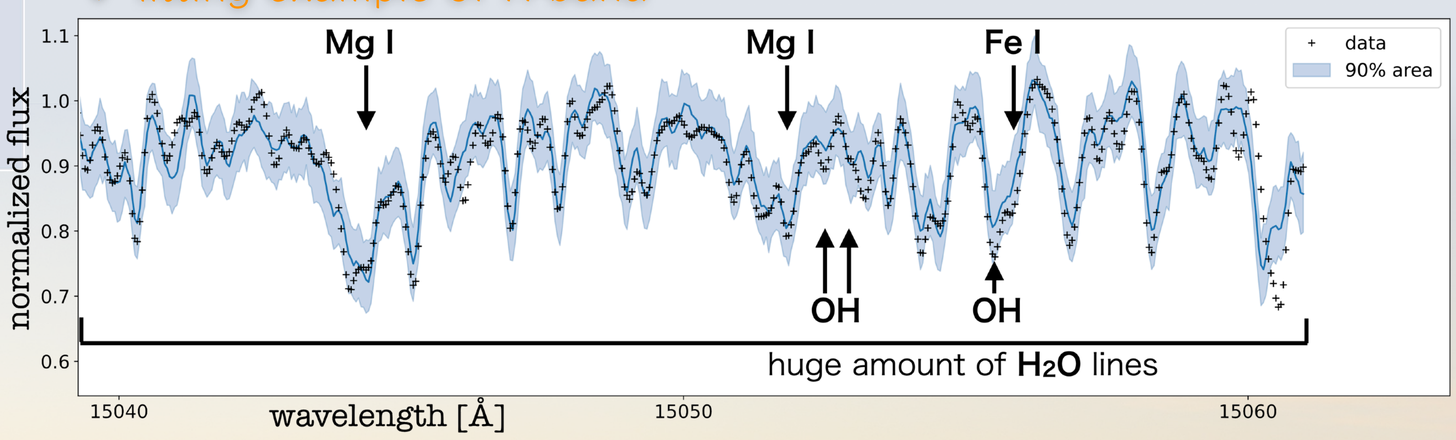
▼ fitting example of Y-band

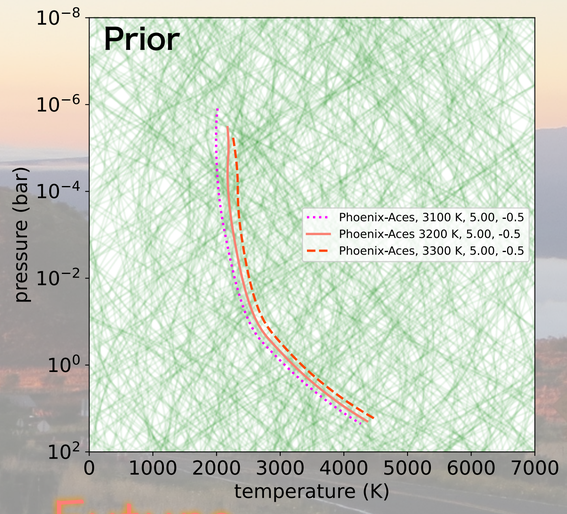


▼ fitting example of J-band

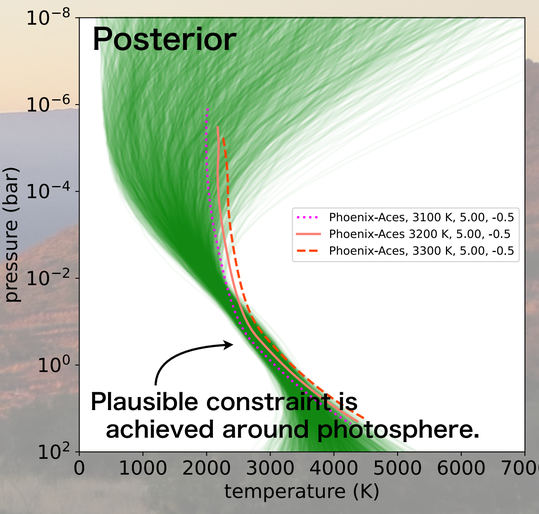


▼ fitting example of H-band





- **Layer-by-layer T-P profile** can be determined agnostically to prior assumptions (smoothness is ensured using a Gaussian process).



Future

- Soon publish a **spectral atlas that includes the accuracy of line data** at each wavelength range.
- Planning more detailed chemical analysis, possibly with effects of **dust/clouds**.