Constraining Atmospheric Mixing in Gas Giants with *JWST*

Thematic Areas (Check all that apply):

☒ (Theme A) Key science themes that should be prioritized for future JWST and HST observations
☐ (Theme B) Advice on optimal timing for substantive follow-up observations and mechanisms for enabling exoplanet science with HST and/or JWST
☐ (Theme C) The appropriate scale of resources likely required to support exoplanet science with HST and/or JWST
☐ (Theme D) A specific concept for a large-scale (∼500 hours) Director's Discretionary exoplanet program to start implementation by JWST Cycle 3.

Summary: Atmospheric vertical mixing remains one of the least understood and least constrained atmospheric processes in gas giant exoplanets and brown dwarfs. It is typically parametrized with the K_{zz} parameter and is the key process which drives the chemical and aerosol properties of the observable atmosphere in these objects. The K_{zz} parameter is presently uncertain by 6-8 orders of magnitude for gas giant exoplanets and brown dwarfs. This uncertainty inevitably seeps in our chemical and cloud modeling of exoplanet atmospheres risking our interpretation of spectroscopic data from *JWST*. Studies have shown that *JWST* can directly probe K_{zz} in the atmospheres of exoplanets with high SNR transmission and emission spectroscopy of a large sample of warm to hot Jupiters and Saturns. Such studies have already been ongoing with samples of brown dwarfs with *JWST* and *Spitzer* and have proven that working with just theoretical estimates of K_{zz} can lead to incorrect interpretation of atmospheric chemical composition. Therefore, we outline the need to leverage the wavelength coverage and excellent precision of *JWST* to obtain high SNR transmission/emission spectroscopy of a large sample of gas giant planets across a range of planetary effective temperatures to constrain K_{zz}.

Anticipated Science Objectives: The gas giant exoplanet and brown dwarf community has identified a key unconstrained parameter that is a key driver in various atmospheric processes and can make interpreting the spectra and atmospheres of gas giant planets difficult – atmospheric vertical mixing. Vertical mixing is typically parametrized with the K_{zz} parameter [1, 2, 3, 4] which remains uncertain by 6-8 orders of magnitude in giant planet atmospheres [5, 6, 7, 8]. Uncertainty in K_{zz} translates directly to uncertainty in our understanding of atmospheric chemistry of exoplanets because vertical mixing can alter the photospheric abundance of atmospheric gases like CH_4, CO, NH_3, etc by several orders of magnitude (see panels (a)-(d) Figure 1) [9, 10, 11]. The upper atmosphere photochemistry of gas giant planets is also sensitive to K_{zz}[12, 13, 11]. K_{zz} is further responsible for keeping the cloud/haze particles aloft in the atmosphere, controlling the sizes of cloud particles and their vertical extents in the atmosphere [14, 15, 16, 17] (see panel (g)-(h) Figure 1). Both chemical abundances and cloud properties are sensitive to K_{zz} and also influential in shaping the transmission and emission spectra of these gas giant exoplanets (see (e)-(f) Figure 1). So, an uncertainty in K_{zz} is ultimately an uncertainty in all our models of atmospheres. These models are directly compared with data from instruments like *JWST* to infer key planetary properties like atmospheric metallicity, internal heat fluxes, and elemental ratios like C/O which are all markers of planet formation and evolution . However, Figure 1 shows that *JWST* observations of transmission and emission spectra of gas giant planets are sensitive to K_{zz} when both photochemistry and vertical mixing is taken into account. We propose that this sensitivity of *JWST* data to K_{zz} be leveraged as an opportunity to constrain K_{zz} for a large sample of warm/hot Jupiters and Saturns.

Urgency: With high SNR brown dwarf spectra, it is now clear that to meaningfully understand brown dwarf atmospheres and evolution, one simply cannot ignore observationally constraining K_{zz} [18, 6, 8, 7, 19, 16]. Therefore, understanding K_{zz} is extremely important for gas giant planets as well to take the next step beyond identifying important gases in their atmospheres to leveraging those gases to understand their interior physics, evolutionary history, and formation.

Risk/Feasibility: Figure 1 and studies like [9] show that this to be feasible but high SNR must be achieved in spectroscopy with multiple transits/eclipses of planets, if required.

Cannot be accomplished in the normal GO cycle: The science outlined here requires a survey of transmission/emission spectra of a large sample of gas giant planets across a large range of T_{eff} values with high SNR.

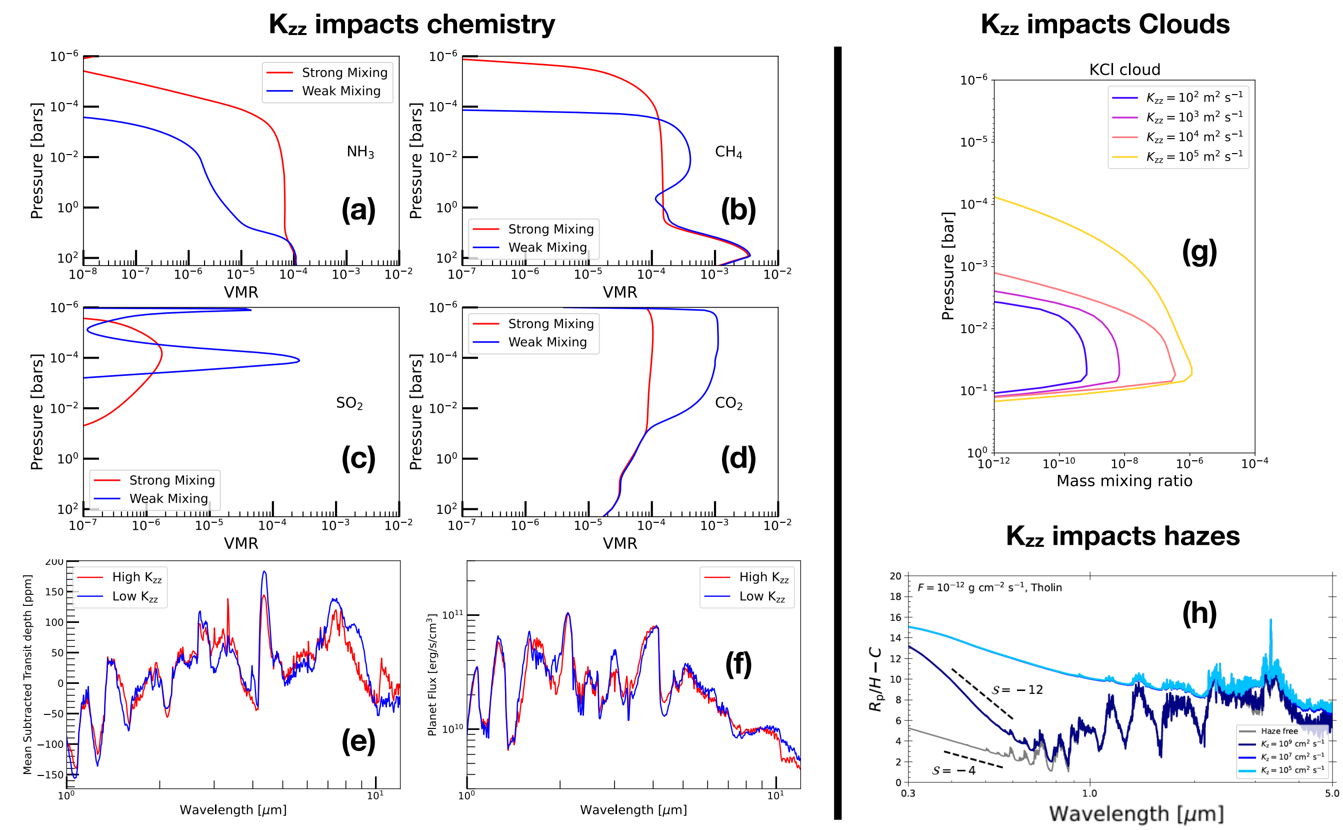

Figure 1: The impact of K$_{zz}$ on atmospheric chemistry, atmospheric mineral clouds, and photochemical hazes is shown here. Panel (a), (b), (c), and (d) show the impact of high and low K$_{zz}$ on the molecular abundance profile of NH_3, CH_4, SO_2, and CO_2, respectively, in the presence of atmospheric vertical mixing and photochemistry for an example warm sub-Saturn HAT-P-11b. Panels (e) and (f) show the transmission and emission spectra calculated from this high and low mixing scenarios, respectively. These models were computed using the `PICASO` and VULCAN atmospheric models [20, 12]. This shows the opportunity to leverage *JWST* observations to constrain the highly uncertain K$_{zz}$ by measuring precise chemical abundances from gas giant planet spectra with *JWST*. Panel (g) shows the large impact of K$_{zz}$ on the mass mixing ratio and vertical profile of mineral clouds in gas giant planet atmospheres. Panel (h) shows the impact of K$_{zz}$ on the transmission spectra of planets with photochemical hazes. These models are from [21] and [22].

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