Mapping Jupiter's Mischief

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Key Points:

- Recent *Juno* results provide updated latitudinal abundance profiles that map the distribution of several key atmospheric species on Jupiter.
- Mapping key gases in Jupiter's troposphere characterizes the chemical and dynamical processes responsible for Jupiter's banded appearance.
- Chemistry in Jupiter's troposphere is tied to element abundances in the deep atmosphere, providing constraints for Jovian formation models.

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Abstract

New results (Grassi et al., 2020) from analysis of *Juno* Jovian Infrared Auroral Mapper (JIRAM) 4-5 μm observations provide updated latitudinal abundance profiles and measurements of the spatial distribution of H_2O, NH_3, PH_3, GeH_4, and AsH_3 in Jupiter's troposphere near the 3-5 bar level. The observed compositional variations provide new constraints on processes shaping chemical abundances in the cloud-forming region of the troposphere, including vertical and horizontal atmospheric mixing, meteorology and cloud formation, transport-induced quenching, and photochemistry. Along with recent results from the *Juno* Microwave Radiometer (MWR) for NH_3 and H_2O abundances far below the clouds, the JIRAM measurements of key disequilibrium tracer species can also be used to explore the coupled dynamics, chemistry, and bulk composition of Jupiter's deep atmosphere. The heavy element abundance inventory on Jupiter is a key constraint for the development and assessment of giant planet formation models. Combined with prior ground-based, spacecraft, and *in-situ* observations, the *Juno* results suggest near-uniform ($\sim$2-4$\times$) enhancements over protosolar abundances for several heavy elements in Jupiter's atmosphere, giving new clues about the composition of the material accreted, the timing and location of formation, and the internal evolution of Jupiter over the history of the Solar System.

Plain Language Summary

New results from the *Juno* spacecraft provide high-resolution measurements of the distribution of several key gases in Jupiter's atmosphere, and show how their abundances vary with latitude. The observed abundance distributions result from a complex tangle of chemical and physical processes, including atmospheric circulation, chemical reactions, and cloud formation that together shape the abundances of chemical species in the troposphere. Recent infrared and microwave measurements also provide key clues about the chemistry and composition of Jupiter's atmosphere below the clouds and into the deep interior. The new results from the *Juno* mission thus represent a major step toward completing its goal of providing an accurate elemental inventory of Jupiter's deep atmosphere, and deliver new insights into Jupiter's formation and chemical evolution: what is Jupiter made of, and how did it get that way?

Prelude to *Juno*

Jupiter is the most massive planet in the Solar System, and played a central role in shaping the formation history, architecture, and composition of the planets. Important clues about early planetary history can thus be found in our understanding of Jupiter's structure and chemical composition. For example, Jupiter consists mostly of hydrogen with a bulk composition roughly similar to that of the Sun, suggesting that Jupiter (and other H-rich giant planets) formed while there was still enough H and He gas in the protoplanetary disk available for significant accretion (for reviews, see Lunine et al., 2004; Taylor et al., 2004). Moreover, observations of exoplanetary systems showing evidence of planetary migration, along with modern dynamical models, suggest that Jupiter drove planetesimal migration and accretion throughout the early Solar System (e.g., see Gomes et al., 2005; Tsiganis et al., 2005; Helled et al., 2014; D'Angelo & Lissauer, 2018; Raymond et al., 2018, and references therein). Jupiter thus provides a record of the formation and earliest evolution of our own planetary system, and serves as a prototype for similar formation processes in exoplanetary systems.

Theoretical models and infrared observations also show that Jupiter emits nearly twice as much energy as it absorbs from the Sun, suggesting a hot, convective interior. For this reason, gas abundances in the troposphere of Jupiter have generally been considered (while accounting for cloud formation) indicative of its bulk composition. A key constraint for Jovian formation models is thus the comparison of model results to the

Figure 1. Jupiter near 56° N as seen by *Juno* from a distance of 15,500 km during its 13th perijove encounter. The bright clouds are inferred to be high clouds of NH_3, with darker cloud material located deeper in the atmosphere. JunoCam visible light image with colors exaggerated. Image credit: NASA/JPL-Caltech/SwRI/MSSS/Gerald Eichstädt/Seán Doran (CC NC SA).

observed abundances of compounds such as CH_4, NH_3, H_2S, and H_2O, etc., taken to represent the planetary elemental abundances of the "heavy elements" C, N, S, and the majority of planetary O, respectively. For example, *in-situ* measurements of Jupiter's troposphere by the *Galileo* Probe Mass Spectrometer (GPMS; e.g., Mahaffy et al., 2000; Wong et al., 2004) showed enhancements in heavy-element-to-H_2 ratios for several elements (C, N, S, Ar, Kr, Xe) and depletions in others (e.g., Ne, O) relative to the original (or "protosolar") element inventory of the Solar System. In this context, the success of planetary formation and evolution models are measured by their ability to reproduce the observed enrichments and/or depletions. An accurate determination of Jupiter's global element inventory has thus become a major goal of planetary research.

However, efforts to determine some representative Jovian composition have posed a challenging task. Jupiter is not a *tame* planet. High clouds of icy NH_3 or storm-driven H_2O clouds obscure deeper atmospheric levels (e.g., see Figure 1). And recent observations suggest an atmosphere as variable and tumultuous as the swirling clouds suggest (e.g., de Pater et al., 2016; Bolton et al., 2017; Li et al., 2017; Fletcher, 2017; Antuñano et al., 2019; Fletcher et al., 2020). Although the *Galileo* Probe provided crucial measurements of Jupiter's troposphere, it descended into an anomalously dry "hot spot" region (features found along the boundary between the equatorial zone and the north equatorial belt) characterized by low cloud opacity, low abundances of cloud-forming species, high thermal (5 μm) emission, and a water abundance that was still increasing with depth

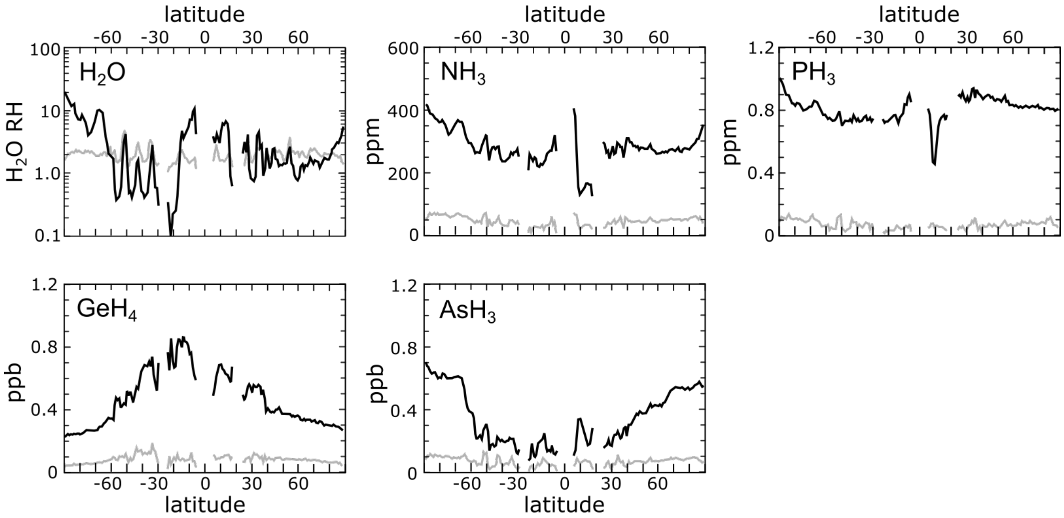

Figure 2. Averaged latitudinal profiles for H_2O (relative humidity), NH_3, PH_3, GeH_4 and AsH_3 (mole fractions) from Grassi et al. (2020) using *Juno* JIRAM observations from the first 15 perijove encounters (PJ1-PJ15). The black curves represent mean abundance values and the gray curves represent the standard deviation over all PJ1-PJ15 profiles. Gaps in the abundance profiles occur at latitudes with high aerosol opacity (corresponding with cloud-thick zones), where measurements of the gas composition are difficult to obtain. See Grassi et al. (2020) for details.

when the probe signal was lost at the 22-bar level (e.g., Wong et al., 2004; Orton et al., 1998; Niemann et al., 1998). So the question remained to what extent the GPMS results for H_2O could be taken as representative of some deep, well-mixed oxygen inventory for Jupiter as a whole. The *Juno* mission was designed to remotely sound the deep atmosphere to hundreds of bars, far beneath the upper veil of clouds, to address such global questions about Jupiter's interior structure and bulk composition – and, in turn, its formation and chemical evolution.

Juno at Jupiter

Launched in the summer of 2011, *Juno* entered an eccentric polar orbit of Jupiter in the summer of 2016, swooping closely past the planet (less than 5000 km above the cloud tops) every 53.5 days. The major scientific products of these encounters are now coming to light. New results by Grassi et al. (2020) map the distribution of key atmospheric gases in Jupiter's atmosphere using data collected by the Jovian Infrared Auroral Mapper (JIRAM) over the first two years of *Juno*'s orbit (August 2016 to September 2018). The JIRAM observations at 4-5 μm are sensitive to thermal emission from the cloud-formation region near $\sim$3-5 bar (with clouds in silhouette against a bright background), along with spectral features from several tropospheric gases. Grassi et al. (2020) performed retrieval analysis on a subset of available JIRAM data, using spectra selected for relatively high radiance, low emission angle, and high resolution. The *Juno* spacecraft measurements provide two key advantages over previous observations: very high resolution (courtesy of its close proximity to Jupiter), and coverage at high latitudes using similar viewing geometries as for low latitudes (courtesy of its polar orbit).

Grassi et al. (2020) provide new latitudinal abundance profiles (summarized in Figure 2) and map the distribution of H_2O, NH_3, PH_3, GeH_4, and AsH_3 in the cloud-forming region of Jupiter's troposphere. The results also allow for new analysis of persistent correlations of gas abundances within discrete regions on Jupiter (e.g., belts and polar regions), and – in the case of water vapor relative humidity – possible associations with zonal wind patterns (Grassi et al., 2020). The observed tropospheric abundances result from a tangle of closely coupled chemical, dynamical, and radiative processes, including vertical and horizontal mixing, meteorology and cloud formation, thermochemical kinetics and disequilibrium, and photochemistry. The *Juno* results thus provide new constraints for a range of models exploring how such processes conspire to shape the chemical composition of Jupiter's troposphere. The new results also represent another major step toward completing *Juno's* goal of mapping key species (including disequilibrium species) to provide an accurate elemental inventory of Jupiter's deep atmosphere.

Chemical Connections to the Deep

A number of the minor species observed in Jupiter's troposphere (including CO, PH_3, GeH_4, and AsH_3) are present in abundances that far exceed those expected from thermodynamic equilibrium. As was first demonstrated for CO (Prinn & Barshay, 1977), this behavior represents vertical mixing from deeper, denser, warmer levels where the species in question has a higher abundance at an equilibrium maintained by fast reaction kinetics (i.e., chemical timescales are short relative to mixing timescales, $\tau_{\text{chem}} < \tau_{\text{mix}}$). However, departures from equilibrium can occur at higher, cooler altitudes where convective vertical mixing occurs faster than chemical reactions can maintain equilibrium (i.e., $\tau_{\text{chem}} > \tau_{\text{mix}}$), effectively "quenching" the abundance of a molecular species at a fixed value throughout the upper troposphere. For most disequilibrium species, the "quench level" for this transition (i.e., $\tau_{\text{chem}} \approx \tau_{\text{mix}}$) is typically near 600−1000 K (Fegley & Prinn, 1985; Fegley & Lodders, 1994; Visscher & Moses, 2011; Wang et al., 2016). The observed tropospheric abundances of tracer species such as CO, PH_3, GeH_4, and AsH_3 thus provide a window to the dynamics, chemistry, and composition of Jupiter's deep atmosphere down to $\sim$ kilobar levels (e.g., Giles et al., 2017a; Grassi et al., 2020).

For example, PH_3 is expected to be the dominant P-bearing phase at high temperatures in Jupiter's deep atmosphere, but is subject to removal by oxidation and/or condensation at lower temperatures ($<$ 500 K). There has been some debate regarding the identity of the lower temperature P-bearing phase, mostly due differences in thermodynamic data adopted for phosphorus oxides such as P_4O_6 (for discussion, see Fegley & Lodders, 1994), and various compounds have been considered to replace PH_3 at lower temperatures, including: P_4O_6 (Fegley & Lodders, 1994; Visscher et al., 2006), P_4O_{10} (Borunov et al., 1995), H_3PO_4 (Wang et al., 2016) and/or $NH_4H_2PO_4$ (Fegley & Lodders, 1994; Visscher et al., 2006; Morley et al., 2018). In any case, there is consensus that disequilibrium PH_3 observed in the troposphere comes from a deep atmospheric source representative of Jupiter's elemental P inventory. However, the observed PH_3 abundance – possibly including the deep abundance – varies as a function of latitude in both 5 μm (e.g., Drossart et al., 1990; Giles et al., 2015, 2017a; Grassi et al., 2020) and mid-infrared (e.g., Irwin et al., 2004; Fletcher et al., 2009, 2016) observations. Notably, mid-infrared PH_3 values have typically been $\sim 2\times$ higher than the 5 μm values, and show an equatorial maximum as high as $\sim$2 ppm PH_3 (e.g., see Fletcher et al., 2009, 2016) in the same location as the NH_3 maximum (de Pater et al., 2016; Li et al., 2017). Both PH_3 and NH_3 also show minima near 10°N in the JIRAM data (see Figure 2), suggestive of similar dynamical influences. Adopting the $\sim$1 ppm PH_3 abundance maximum observed by JIRAM (near the south pole, see Figure 2; Grassi et al., 2020) as a lower limit for the deep PH_3 abundance yields a Jovian phosphorus inventory of at least $1.3\times$ the protosolar value.

Germane (GeH_4) is also subject to removal by condensation at temperatures below 700 K yet survives at $\sim$ ppb disequilibrium concentrations into Jupiter's upper troposphere. Because Ge is distributed among several Ge-bearing species at high-temperatures (Fegley & Lodders, 1994), GeH_4 cannot be taken as representative of Jupiter's bulk Ge inventory (note that 1 ppb GeH_4 corresponds to $0.1\times$ the protosolar Ge abundance). Nevetheless, quenched GeH_4 is expected to show strong sensitivity to the convective mixing rate compared to PH_3 or AsH_3 (Fegley & Prinn, 1985; Fegley & Lodders, 1994; Wang et al., 2016). Noting that convective mixing will be stronger at low latitudes on a rotating planet such as Jupiter (Flasar & Gierasch, 1977; Visscher et al., 2010), Wang et al. (2016) demonstrated that higher GeH_4 abundances would be expected near the equator than near the poles, in agreement with the latitudinal trends observed by JIRAM (e.g., see Figure 2 and Grassi et al., 2020; Giles et al., 2017a, for discussion and comparison of observed trends).

On the other hand, the AsH_3 abundance is expected to be less sensitive to the rate of mixing (Fegley & Lodders, 1994; Wang et al., 2016) and the latitudinal profile of tropospheric AsH_3 is enigmatic, with an abundance that *increases* toward the poles (see Figure 2; Giles et al., 2017a; Grassi et al., 2020). Although the chemical scale height for each disequilibrium species differs depending upon reaction kinetics and quench conditions, each is presumably subject to the same convective transport. The unexpected AsH_3 profile thus suggests that the chemical processes shaping the AsH_3 abundance remain incompletely understood. As suggested by Giles et al. (2017a), the observed distribution is plausibly explained by photolytic destruction of AsH_3 in Jupiter's upper troposphere (analogous to NH_3 and PH_3 photochemistry near 200 mbar; Strobel, 1977; Kaye & Strobel, 1983), where higher photolysis rates toward the equator yield less AsH_3. Assuming that AsH_3 is the dominant As-bearing in Jupiter's deep atmosphere (Fegley & Lodders, 1994), the maximum AsH_3 abundance of 0.7 ppb measured by Grassi et al. (2020) suggests an enhancement of $\sim$1.3$\times$ the protosolar value, similar to that observed for PH_3.

Jupiter's deep atmospheric water abundance (and more generally, Jupiter's oxygen inventory) is critical to our understanding of Jupiter's formation as well as dynamical and chemical processes (such as cloud formation) in Jupiter's troposphere. Prior to *Juno*, however, the obscuring presence of clouds and other opacity sources have long limited our ability to determine the H_2O abundance below the clouds. Earth-based infrared observations must contend with telluric H_2O contamination (e.g., see Bjoraker et al., 2016, 2018) whereas centimeter measurements must account for synchroton emission from Jupiter's radiation belts (e.g., de Pater et al., 2016). Moreover, as noted above, it is unclear to what extent near-infrared observations (most sensitive to hot spot regions) or the GPMS measurement ($X_{H_2O} = 420 \pm 140$ ppm, corresponding to $\sim 0.5\times$ the protosolar H_2O/H_2 ratio) can be taken as representative of the bulk planetary inventory.[1]

Given these challenges, several investigators turned to chemical models to estimate the H_2O abundance by considering how water in the deep atmosphere influences the observed behavior of other species (in particular CO) mixed into the upper troposphere. For example, the $\sim$1 ppb CO observed in Jupiter's troposphere (e.g., Bézard et al., 2002; Bjoraker et al., 2018) is far greater (over 20 orders of magnitude) than the equilibrium abundance predicted near the 6-bar level, suggesting rapid vertical mixing from deeper in the atmosphere where CO is more abundant and forms via net reactions such as $CH_4 + H_2O \rightleftarrows CO + 3H_2$. For a given carbon inventory (characterized by CH_4), the observed (quenched) abundance of CO thus depends upon the rate of reactions that interconvert $CO \rightleftarrows CH_4$, the strength of convective vertical transport, and the abundance of water in the deep atmosphere: more H_2O yields more CO.

Following the approach pioneered by Prinn and Barshay (1977) and Fegley and Prinn (1988), modern numerical studies of H-C-O chemistry in Jupiter's atmosphere use extensive reaction networks to estimate the H_2O abundance based upon CO quench kinetics (e.g., see Visscher et al., 2010; Visscher & Moses, 2011, who estimated 420-2160 ppm

[1] For reference, a "protosolar" atmospheric water abundance is defined here as $X_{H_2O} = 830$ ppm or $X_{H_2O}/X_{H_2} = 9.61\times10^{-4}$ using elemental abundances from Lodders (2010) and accounting for the removal of some oxygen into rock (e.g., Visscher et al., 2010). For conversion between mole fraction abundances and element-to-H_2 mixing ratios on Jupiter, a hydrogen abundance of X_{H_2}=0.864 is adopted based upon *Galileo* measurements of the He abundance (Niemann et al., 1998; von Zahn et al., 1998).

H_2O). More recently, Wang et al. (2015) showed that for a narrower range of rapid mixing rates expected near equatorial latitudes, the kinetic schemes of Visscher and Moses (2011) and Venot et al. (2012) give 85-640 ppm H_2O and 2500-9300 ppm H_2O, respectively. Full resolution of model differences (caused by differences in adopted rates of key reactions in the $CO \rightleftarrows CH_4$ reaction scheme) may require improved understanding of the dynamical behavior of Jupiter's deep atmosphere and/or new studies that explore whether the reaction networks adapted from H-C-O combustion experiments under oxidizing conditions will behave consistently in hydrogen-rich planetary environments (e.g., see Moses et al., 2011; Venot et al., 2012, 2020; Moses, 2014; Wang et al., 2015, for further discussion). In the meantime, chemical models of the deep atmosphere will also be improved by new observational constraints on Jupiter's composition far below the clouds.

Looking Below the Clouds

The spatial distribution of cloud-forming species such as NH_3 and H_2O mapped by JIRAM provide information about the meteorological processes that affect their abundances in the cloud-forming region of Jupiter's troposphere ($\lesssim$ 10 bar). For example, the observed H_2O relative humidity is highly variable with latitude (see Figure 2), with local enhancements in water vapor that appear to be associated with cyclonic regions consistent with models of moist convection (e.g., see Dowling & Gierasch, 1989; Roos-Serote et al., 2000; Ingersoll et al., 2004; Fletcher et al., 2017; Giles et al., 2015; Grassi et al., 2020). The distribution of NH_3 likewise shows abundance variations (see Figure 2) shaped by vertical and horizontal mixing, including an enhancement along the edges of the equatorial zone, a strong depletion near 10°N (consistent with microwave measurements; see Li et al., 2017, and discussion below), and longitudinal variations (including NH_3-rich plumes) near hot spot latitudes (e.g., see de Pater et al., 2016; Giles et al., 2017b; Li et al., 2017; Fletcher et al., 2016, 2020; Grassi et al., 2020).

While the JIRAM results provide new abundance estimates in the cloud-forming region of Jupiter's atmosphere, recent results from *Juno* Microwave Radiometer (MWR) measurements provide complementary estimates of the NH_3 and H_2O abundances well below the clouds (e.g., see Janssen et al., 2017). Because NH_3 absorbs more strongly than H_2O, MWR determinations of the water abundance require an accurate estimate of the NH_3 abundance profile, which is best constrained in the equatorial zone (e.g., Li et al., 2017). Using this approach (for 351 ppm NH_3 or 2.5× protosolar N), Li et al. (2020) obtain a deep H_2O abundance of 2500^{+2200}_{-1600} ppm (or $3.0^{+2.6}_{-1.9}\times$ protosolar H_2O) in the equatorial zone, confirming that the GPMS measurement (420 ppm) was not representative of Jupiter's deep water inventory. Combined with prior ground-based, spacecraft, and *in-situ* observations, the *Juno* results thus suggest roughly uniform (∼2-4×) enhancements over protosolar abundances for several heavy elements in Jupiter's atmosphere.

The deep abundance measurements of the major cloud-forming species (Li et al., 2020) along with disequilibrium abundances (Grassi et al., 2020) can also be used to identify connections between the upper troposphere and the deep atmosphere, and to explore related questions about which chemical pathways, atmospheric motions, and meteorological processes are shaping the observed abundances of tropospheric chemical species: how deep does chemical variability extend? To what extent do deep atmospheric abundances represent bulk element inventories? For example, the MWR results show spatial variations in NH_3 extending to at least the ∼50 bar level (e.g., see Li et al., 2017; Bolton et al., 2017; Ingersoll et al., 2017) with a deep abundance (∼360 ppm) less than that observed by GPMS (570 ppm; Wong et al., 2004). In addition, high-resolution *Juno* measurements of Jupiter's gravity field suggest the presence of a diluted core and the possibility that the heavy element inventory is not uniformly mixed throughout the planet as a whole (e.g., see Wahl et al., 2017; Debras & Chabrier, 2019), presenting new challenges for inferring the chemical consequences of Jupiter's atmospheric evolution.

Nevertheless, the observed Jovian water inventory provides a key constraint on the composition of the material accreted, the timing and location of formation, and the internal chemical and structural evolution of Jupiter over the history of the Solar System. A bulk oxygen inventory similar to that of other heavy elements (as suggested by *Juno* MWR results) calls into question formation scenarios that predict either very large or very small water abundances, whereas models that predict roughly similar heavy-element enhancements invite a closer look (e.g., see Owen et al., 1999; Lodders, 2004; Guillot & Hueso, 2006; Wong et al., 2008; Mousis et al., 2019, for references and further discussion). The new results also raise ongoing questions about core-accretion and gravitational collapse during giant planet formation: should we consider Jupiter to be uniformly *enriched* in heavy elements? Or instead *depleted* in H and He? Our understanding of giant planet formation within an evolving protoplanetary disk – informed by ongoing ground-based and *Juno* observations of key species in Jupiter's troposphere – will continue shape how these questions are addressed both inside and outside of our own planetary system.

Acknowledgments
I thank the two anonymous reviewers for their reviews and many constructive suggestions that were incorporated into the commentary. No new data were generated in the preparation of this manuscript. Data used for the abundance profiles in Figure 2 are included in Grassi et al. (2020) and the full JIRAM datasets can be found in Grassi (2019).

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