SOFIA Observations of Variability in Jupiter’s Para-H2 Distribution and Subsurface Emission Characteristics of the Galilean Satellites

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Received 2021 July 9; revised 2021 September 22; accepted 2021 October 4; published 2021 November 10

Abstract

We observed Jupiter’s thermal emission with SOFIA/FORCAST in 2018 August and 2019 July. Both broad-band images (8–37 μm) and spectra (17–37 μm) were obtained. We used the shape of the Jovian spectra to determine the latitudinal distribution of temperatures and para-H2 in the upper troposphere, and compared this to similar data obtained in Fletcher et al. (2017). The two data sets were taken approximately half a Jovian year apart, the first (2014) during northern summer (Ls = 158°) and the second (2019) during southern summer (Ls = 304°). During both epochs the high northern latitudes are cooler than the south. Para-H2 is observed in sub-equilibrium at the equator and in super-equilibrium near the poles during all epochs. The largest difference between the two epochs is the detection of high-para-H2 content at high southern latitudes in 2019, in contrast to the earlier (2014) observations. This implies that the high-latitude para-H2 appears to vary over multi-year timescales. In addition to aiding in the calibration of and providing context to the Jovian spectra, the images were used to determine spectra of the four Galilean satellites. Over the 8–35 μm wavelength range the brightness temperatures of all four satellites drop with increasing wavelength. Although this is expected as longer wavelengths probe the satellites’ deeper, cooler layers, our data quantify the brightness temperature gradient with wavelength.

Unified Astronomy Thesaurus concepts: Jupiter (873)

1. Introduction

Jupiter’s global circulation and wind shear can be inferred from upper tropospheric temperatures. These reveal cool anticyclonic zones and warm cyclonic belts, resulting in zonal winds that decay with altitude above the clouds. Although the cool zones may imply upwelling and adiabatic expansion, and the warmer belts subsidence and adiabatic compression, secondary tracers are needed to verify and quantify such vertical motions and mixing. Such information might be derived from the presence of disequilibrium species, such as phosphine (PH₃), germane (GeH₄), arsenic (AsH₃), and the ratio of ortho-H₂ (parallel spin state of molecular hydrogen) to para-H₂ (antiparallel spin state). The presence of disequilibrium species means that the timescale for dynamical mixing must be shorter than that for chemical alteration/destruction, such as the process of oxidation for PH₃ (Fegley & Lodders 1994). Here we examine the ratio of para-H₂ to ortho-H₂, which is governed by chemical equilibrium. It should be 1:3 (a para-H₂ fraction of the total H₂, f_p = 0.25) at the warm temperatures of Jupiters deep atmosphere (temperatures T > 315 K, i.e., at pressures P > 8 bar). As temperatures drop with lower pressures in the troposphere, the equilibrium para-H₂ fraction increases from 0.25 at ~8 bar to ~0.35 near the tropopause, where lower temperatures favor more molecules to be in the lower energy state of the S(0) transition, i.e., para-H₂. Just as for other disequilibrium species, if the dynamical transport time is shorter than the equilibration time, f_p can deviate considerably from the equilibrium value, i.e., be closer to 0.25 in parcels of rising air, while subsiding air might take on values closer to 0.35. However, for pure hydrogen, equilibration times are of order years to decades (Herzberg 1950), while at the 200 mbar level in Jupiter’s atmosphere it may be as high as ~10⁷ yr (Fouchet et al. 2003). When paramagnetic conversion in the gas phase is included, equilibration times are of order 30–50 yr at the 200 mbar level, and catalysis on aerosol surfaces may speed this up by a factor of ~2 (see, e.g., Massie & Hunten 1982; Conrath et al. 1998; Fouchet et al. 2003, for a more extensive discussion on equilibration times). Hence, although deduction of vertical mixing remains challenging, one does need observations to ultimately determine such timescales. Regardless of the precise timescales, deviations from the equilibrium values can be used to deduce whether air may be rising or sinking, and hence help constrain the general circulation in planetary atmospheres. Data on the ortho/para-H₂ ratio are important as they provide information on vertical mixing specific to the region of cloud formation on Jupiter, i.e., at pressures ≤6 bar. Other disequilibrium species have quenching at levels that, depending on their destruction process, vary from ~20 bar down to kbar levels (e.g., Fegley & Lodders 1994), and only provide information on rising parcels of air.

Observations of the spatial variations of Jupiter’s para-H₂ fraction have only been obtained in 1979 with the Infrared Interferometer, Spectrometer, and Radiometer (IRIS) experiments on the Voyager spacecraft (Burke 1974; Hanel et al. 1977; Conrath & Gierasch 1983; Conrath et al. 1998), and in

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Table 1

| UT Date | Filter Name | Wavelength (μm) | Wavenumber (cm⁻¹) | Bandwidth (μm) | Diameter (°) | CML° Sys.III (°) | Latitude Planetographic (°) | Flux Density° Total (kJy) | TP° (K) |
|---------|-------------|----------------|-------------------|---------------|-------------|----------------|--------------------------|---------------------------|---------|
| 2018-08-22 04:28:10 | F088 | 8.800 | 1136.364 | 0.41 | 35.69 | 226 | –3.36 | 12.2 ± 0.4 (0.23) | 141.4 ± 0.4 |
| 2018-08-29 03:27:40 | F253 | 25.248 | 396.071 | 1.807 | 35.04 | 162 | –3.36 | 245 ± 7 (4.1) | 118.7 ± 0.6 |
| 2018-08-29 03:27:40 | F348 | 34.807 | 287.299 | 3.759 | 35.04 | 162 | –3.36 | 464 ± 15 (10) | 119.3 ± 0.8 |

Notes.

° Central Meridian Longitude, measured in System III, West longitude.

° The error includes a 2.5% uncertainty in the determination of the flux density from the images, as based on 8–12 images in F111 taken on 2018 August 22 and 29, augmented by the absolute calibration uncertainty as provided by the SOFIA analysts; the latter quantity (typically between 1 and <2.5%) is provided in brackets.

° Disk-averaged brightness temperature.

2014 with the Faint Object infraRed CAmera (FORCAST) on the SOFIA Telescope (Fletcher et al. 2017). These data sets were all obtained during northern summer, at subsolar latitudes \( \theta_s \) and planetocentric solar longitudes \( L_s \) of \( \theta_s = +0°6, L_s = 170° \) (Voyager-1), \( \theta_s = +0°02, L_s = 180° \) (Voyager-2), and \( \theta_s = +1°4, L_s = 158° \) (SOFIA).° In both the Voyager and SOFIA data, \( f_p \) was well below the equilibrium values over the equatorial regions, which is indicative of large-scale upwelling at low latitudes. In contrast, at high latitudes, \( f_p \) exhibited super-equilibrium values, indicative of subsiding air (Conrath et al. 1998; Fletcher et al. 2017). Interestingly, \( f_p \) was particularly high at high northern latitudes, both in the Voyager-1 and SOFIA data, a phenomenon that was not seen by Voyager-2, 4 months after the Voyager-1 encounter. Based upon a comparison of Voyager and SOFIA data, Fletcher et al. (2017) proposed that the para-H₂ equator-to-pole gradient is caused primarily by catalysis on aerosols in Jupiter’s hazes, while localized circulations, though important too, play a smaller role. Zhang et al. (2013a) showed that there was a hemispheric asymmetry in upper tropospheric/stratospheric hazes, being largest at the north pole, and Fletcher et al. (2017) demonstrated that the north pole was colder than the south pole during the Voyager-1 and SOFIA observations. This could explain why \( f_p \) was found to be highest in the north. To further investigate this polar asymmetry in \( f_p \), we observed Jupiter again with FORCAST on SOFIA in 2018 and 2019 when it was summer at southern latitudes. The observations of this campaign are reported in this paper; a preliminary analysis was presented in de Pater et al. (2020b).

2. SOFIA FORCAST Data 2018–2019

We observed Jupiter at infrared wavelengths (8–37 μm) on 2018 August 22 and 29 (\( \theta_s = -3°5, L_s = 279° \)) and on 2019 July 11 (\( \theta_s = -2°9, L_s = 304° \)) with FORCAST (Adams et al. 2010; Herter et al. 2012) on the SOFIA airborne observatory (Gehrz et al. 2009; Young et al. 2012). Both sets of observations were acquired after southern summer solstice (\( L_s = 270° \), 2018 May), meaning that despite Jupiter’s small 3° axial tilt, they afford our best views of the southern high latitudes. Both images (8–37 μm) and spectral data cubes (17–37 μm) were obtained. We compare these new data with previous SOFIA/FORCAST data from 2014 May (\( L_s = 158° \), Fletcher et al. 2017), which occurred shortly after northern summer solstice (\( L_s = 90° \), 2012 March) and therefore provided better views of the northern high latitudes. The new “southern summer” epochs will be contrasted with the “northern summer” epoch to search for any variations in atmospheric properties.

2.1. FORCAST Imaging

Calibration of the spectroscopic data is best performed using images in overlapping filters, as done by Fletcher et al. (2017). We therefore acquired images in 7 different filters, as tabulated in Table 1. Ideally, images and spectra are taken during the same flight. Although a full set of images was obtained on 2018 August 22, no spectra were taken that night due to telescope problems. In addition to the F111 acquisition images (Table 1), images were taken in only two additional filters on 2018 August 29, and none were obtained on 2019 July 11. The images were reduced and calibrated by the SOFIA Science Center using REDUX v1.3.1.° SOFIA/FORCAST is approximately diffraction limited at 24 μm and longer wavelengths, with a FWHM or the width of the point-spread function (PSF) in arcsec equal to a tenth of the wavelength in microns, while at the shorter wavelengths observed in this project the FWHM is 2°.4.° The pixel spacing is 0°/768 which oversamples the PSF for accurate imaging.

Contrast-enhanced images of Jupiter are shown in Figure 1, and images showing the various satellites are shown in Figure 2. Images are background subtracted and a limb-darkening correction was applied. The background was modeled using the SExtractor program suite (Bertin & Arnouts 1996). SExtractor models the background by dividing the image into a grid specified by the user, then uses sigma-

° All latitudes in this paper are planetographic; all longitudes use System III West.

°° https://www.sofia.usra.edu/sites/default/files/USpot_DCS_DPS/Pipeline_User_Manuals/FORCAST/FORCAST_Redux_Users_Manual_RevD.pdf

° SOFIA Observers Handbook: https://www.sofia.usra.edu/science/proposing-and-observing/observers-handbook-cycle-9/4-forcast/41-specifications.
filtering to mask pixels containing a signal from sources and artefacts in the image. The remaining unmasked data is used to calculate a smooth background with a user-specified granularity. Successive iterations of SExtractor were performed to mask, model, and subtract the non-uniform background signal and image artefacts, as well as identify the location and extent of Jupiter and its satellites. An example for the 34.8 \( \mu m \) image is shown in Figure 3. Limb-darkening was corrected via a custom algorithm designed to enhance the contrast of Jupiter’s features. No correction was performed for the 8.8 and 25.3 \( \mu m \) images, as we determined their natural contrast sufficient to see Jupiter’s structure. The FORCAST contribution function probes different altitudes as a function of wavelength, and a guide to the wavelength dependence of the sensitivity is given in Figure 6 of Fletcher et al. (2017). Images in Figure 1 mostly sample the collision-induced H\(_2\)–H\(_2\) and H\(_2\)–He continuum (longward of 17 \( \mu m \)), sensing temperature and para-H\(_2\) in a range between 300 and 600 mbar in nadir viewing. Subdued contrast at the longest wavelengths is a consequence of the diffraction-limited PSF. These images are complemented by images at 8.8 and 11.1 \( \mu m \), which both sense a combination of temperatures, ammonia gas, and aerosol absorption in the 400–600 mbar region.

The belt-zone structure on the planet is clearly recognized at low latitudes in all images, with warm belts and colder zones, caused by latitudinal temperature variations near the \( \sim \)500 mbar level (e.g., Fletcher et al. 2016a). Similarly, the longitudinal variations in brightness can also be explained as variations in temperature at these levels. On 2018 August 29 and 2019 July 11 the Great Red Spot (GRS) is visible as a cold anomaly at 11 \( \mu m \) as indicated. The GRS is cold due to adiabatic cooling of the rising gas, while we see hints of warmer temperatures at its southern edge, as shown at a higher spatial resolution by e.g., Fletcher et al. (2016a). A relatively warm spot is visible at 11.1–32 \( \mu m \) in the far north on 2018 August 22, near 220–230°W longitude in System III; this is the satellite Ganymede, transiting Jupiter during the observing run. Bright south polar auroral emission is observed in the 11.1 \( \mu m \) image on July 11, from the contribution of ethylene near 10.5 \( \mu m \) (e.g., Sinclair et al. 2019).

We determined the disk-integrated flux densities from each image by first carefully modeling the background over the entire image, as described previously, so after subtraction the background was essentially zero. We used SExtractor to determine which pixels contained emission from Jupiter or the Galilean satellites. As much of the background flux is caused by scattered light from Jupiter, we determined the Jovian flux.

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**Figure 1.** SOFIA images of Jupiter at all wavelengths and days during the flights, as indicated. Although several images were taken at 11.1 \( \mu m \), we only show the stacked images here. The images are contrast enhanced sufficiently to demonstrate variations in brightness temperature with latitude and longitude. Jupiter north is up in all images. The GRS and Ganymede are indicated.
densities from images before background subtraction (e.g., as in Figure 3(a)), and subtracted a background determined a large distance away from the planet. The flux density determined this way was of order 1%–2.5% (depending on wavelength) larger than the numbers determined directly from the background-subtracted images (Figure 3(c)). The results for Jupiter are listed in Table 1, where we show both the total flux densities and the derived disk-averaged brightness temperatures. We derived the latter ones from the flux densities using Planck’s radiation law for an oblate planet, using an effective radius of 69,134 km (i.e., \(R_{\text{eff}} = \sqrt{R_{\text{eq}}^2 - R_{\text{pol}}^2}\)). As we had a dozen images in the F111 filter on 2018 August 22 and another eight images on August 29 (only 2 images in 2019), we were able to estimate an uncertainty of \(\sim 2.5\%\) from the dispersion in the measured flux densities for Jupiter across these images. We assumed the same error in all other filters, and added the absolute calibration error in quadrature to obtain the uncertainties as listed in Table 1. The absolute calibration error was provided by the SOFIA Science Center, using the dispersion in the ratio of observed-to-reference fluxes of standard stars, where the reference fluxes are stellar atmosphere models scaled to match observed fluxes (Dehaes et al. 2011). This uncertainty was typically between 1% and \(< 2.5\%\), depending on the filter used. Several of the Galilean satellites are visible in the images, as shown. We were able to determine the flux densities for all four
satellites in a few filters, as tabulated in Table 2 together with the derived disk-averaged brightness temperatures. The uncertainty in the flux densities were estimated from a combination of the dispersion in the F111 values and the estimated accuracy of the background subtraction. We typically estimated the uncertainty at 10%. As shown in Figure 2, at the long (≥30 μm) wavelengths the diagonal striations sometimes interfere with the satellites, which makes extraction of accurate flux densities quite challenging. In these cases, as well as for the relatively faint Europa, we adopted an uncertainty of 25%. The brightness temperature values are shown in Figure 4 together with previous data to show the SOFIA values in context with the satellites’ full thermal emission spectra. The visible-light temperature (open blue squares) are maximum temperatures calculated based upon the Bond albedo and phase integral of the satellites (Morrison & Morrison 1977; Johnson 1978). We note that the measured brightness temperatures, in particular at the shortest wavelengths, may differ some from one another due to variations in heliocentric distance, and there may also be hemispheric (such as leading versus trailing) differences. However, given these potential differences, our calibration is essentially validated by the agreement between the shortest-wavelength SOFIA measured brightness temperatures and previous measurements.

### 2.2. FORCAST Spectroscopy

Jupiter was observed with the two long-wavelength grisms, G227 (17–27 μm, 370–580 cm⁻¹) and G329 (28–37 μm, 270–355 cm⁻¹) (Keller et al. 2010) in “SLITSCAN” mode, i.e., the slit was stepped from east to west on the sky, across Jupiter. The first spectrum was taken from the center and the 2°4 slit of the G227 grism was stepped every 3°1 for 14 spectra, and the 4°7 slit of the G329 grism was stepped every 5°1 for 9 spectra. Details on the observations are provided in Table 3. Although shorter-wavelength (G111) spectra were supposed to be acquired (to offer better constraint on aerosols, tropospheric temperatures, and gaseous composition), in-flight challenges meant that they were never obtained. The spectra were assembled into an image data cube (i.e., images of Jupiter, with the spectral axis as the third coordinate) by the SOFIA Science Center using the slitscan module. For ease with the data analysis, the image spectral data cubes were all rotated so Jupiter north is up. Figure 5 shows the first frame of each data cube. As shown, although most of the planet has been captured in the image data cube, a small part of the planet is missing. We determined that ~7% of the flux density was missing from the G227 cube in 2018, and ~1%–2% in 2019.

The data cubes were calibrated using the fully calibrated images from Section 2.1. As the bandpass of several of the images overlapped with the data cubes, we could calibrate the spectra by equating the total flux density in the images to that of the spectral data cubes integrated over the filter response functions of the images (and after correction for missing pieces of the planet, as mentioned above). The most reliable filter for this process is the narrow-band 25.5 μm filter, which completely covers a small portion of the G227 spectrum. This was therefore used as the “anchor point,” but uncertainties remain. Figure 6 shows a comparison of the spectra of the disk-integrated data in radiance (scaled to 2014; top panels), and the disk-averaged brightness temperatures (bottom panels). Unfortunately, no long-wavelength images were taken simultaneously with the G329 spectra that could be used as a clear “anchor” for the spectra. Moreover, the year-to-year spread and uncertainties in the flux densities of the images is quite large. We therefore choose to shift the G329 spectra such as to provide a good continuous spectrum in radiance.

The combined G227 and G329 (17–37 μm, 270–580 cm⁻¹) spectra are used in Section 3 for a full spectroscopic inversion to derive the zonal-mean thermal structure. After they were navigated and reprojected, the spectra are binned on a 4° latitude grid (Nyquist-sampled with a 2° step) between ±60° latitude. Only spectra within ±20° longitude of the central meridian were included. Jupiter’s far-infrared spectrum is a smooth continuum formed by the broad S(0) and S(1) absorption features, as seen in Conrath & Gierasch (1984). The downturn at the long-wave end of the spectrum (dotted line in Figure 6c) cannot be physical, and we decided to cut the spectrum at 300 cm⁻¹ (333 μm) for subsequent analysis. Figure 7 shows that each FORCAST data set has a slightly different high-wavenumber cutoff due to the calibration process, so we truncate at 550 cm⁻¹ (18.2 μm) to ensure a fair comparison in Section 3. Contour plots of the spectra as a function of latitude and wavenumber are displayed in Figure 7, comparing the three FORCAST epochs (2014, 2018, and 2019) to IRIS observations (Hanel et al. 1979) from Voyager-1 on

### Table 2

SOFIA/FORCAST Images of the Galilean Satellites

| UT Date | Filter Name | Io Flux (Jy) | Io T_B (K) | Europa Flux (Jy) | Europa T_B (K) | Ganymede Flux (Jy) | Ganymede T_B (K) | Callisto Flux (Jy) | Callisto T_B (K) |
|---------|-------------|-------------|-----------|-----------------|---------------|-------------------|-----------------|-----------------|-----------------|
| 2018-08-22 04:28:10 | F088 | 8.3 ± 0.8 | 141.0 ± 1.2 | 34.1 ± 3.4 | 152.3 ± 1.4 | 131 ± 13 | 149.2 ± 1.7 | 1102 ± 110 | 150.5 ± 3.1 |
| 2018-08-22 04:28:10 | F111 | 23.3 ± 2.3 | 131.5 ± 1.3 | 1621 ± 162 | 152.5 ± 4.1 | 1501 ± 150 | 144.2 ± 4.4 | 1289 ± 129 | 136.5 ± 4.3 |
| 2018-08-22 04:28:10 | F197 | 192 ± 19 | 120.9 ± 2.0 | 117.3 ± 5.3 | 1102 ± 110 | 150.5 ± 3.1 | 1104 ± 110 | 134.1 ± 3.1 | 1289 ± 129 | 136.5 ± 4.3 |
| 2018-08-22 04:28:10 | F253 | 318 ± 32 | 118.8 ± 2.5 | 109.5 ± 5.6 | 1621 ± 162 | 152.5 ± 4.1 | 1501 ± 150 | 144.2 ± 4.4 | 1289 ± 129 | 136.5 ± 4.3 |
| 2018-08-22 04:28:10 | F315 | 248 ± 62 | 104.3 ± 5.9 | 114.9 ± 7.2 | 1773 ± 177 | 152.2 ± 5.5 | 1773 ± 177 | 152.2 ± 5.5 | 1773 ± 177 | 152.2 ± 5.5 |

**Note.**

a Total flux density. The error is based upon the dispersion in flux density from the F111 images, and the estimated accuracy of subtracting the background (see Figure 2), which together far exceeds the photometric error (1 – <2.5%). We typically estimated 10% for the most accurate flux densities, and 25% for less accurate flux densities (e.g., Europa, and for some of the long-wavelength filters.
1979 March 3 (inbound Jupiter maps; see Fletcher et al. 2017 for full details).

Brightness temperatures in Figure 7 reveal that the same basic structure exists in all four epochs: high brightness temperatures (125–130 K) below ~330 cm$^{-1}$ ($>30$ μm) and in between the broad S(0) (354 cm$^{-1}$, 28 μm) and S(1) (587 cm$^{-1}$, 17 μm) absorption features, as well as a strong limb-darkening toward higher latitudes (as higher emission angles sound higher, cooler altitudes closer to the tropopause). The high brightness temperature region between the S(0) and S(1) bands show a weakly
banded structure with a cooler equator and warm north and south equatorial belts (near ±10°–20° in each hemisphere). Given the spatial resolution of the FORCAST spectroscopic data, any finescale thermal banding at mid-latitudes, such as that observed by Cassini/CIRS at shorter mid-IR wavelengths (Flasar et al. 2004; Fletcher et al. 2016a), is below the resolution limit of SOFIA.

Figure 7 suggests that the 2018 August epoch stands out as unusual, with broad latitudinal smearing of the bright low-latitude emission compared with 2014 May and 2019 July. The shape of the spectrum in Figure 6 is also noticeably different, with a much higher brightness temperature near 20 μm (500 cm⁻¹) and lower value near 28 μm (355 cm⁻¹) than in 2014 May and 2019 July, and significant spikiness in the G329 grism spectrum (28–37 μm, 270–355 cm⁻¹). The spatial/slit calibration data were not available for the 2018 August epoch, and difficulties in removing telluric features has rendered this spectrum “noisier” than the 2019 July version. Experiments with inverting the 2018 August data suggested that it could not be fitted with a reasonable Jovian atmosphere (para-H₂ had to be adjusted to unreasonably high values; see Figure 7 in Fletcher et al. (2017) for sensitivity studies of the spectral shape on the para-H₂ abundance), and we conclude that a wavelength-dependent calibration issue is distorting the shape of this spectrum. Given that temperature- and para-H₂ derivations rely on precise measurement of the spectral shape, the 2018 data are unfortunately unusable. Thankfully, the 2019 July observation fared better, and the structure is comparable to 2014 May. Note that latitudes poleward of ~40°N show low brightness irrespective of the two different seasons (Lₚ = 158° and Lₚ = 304°), whereas the southern latitudes poleward of ~40°S appear warmer in 2019 July (i.e., brightness temperatures in Figure 7 do not fall below ~115 K at southern latitudes in 2019, whereas they appear cooler in 2014). Some of this is due to the shifting viewing geometry, but to assess whether there are real changes in Jupiter’s atmosphere, we proceed with an inversion of the data in Section 3.

### 3. Spectral Inversion

FORCAST spectra can be inverted to determine the two-dimensional (pressure, latitude) distributions of temperatures (T(p)) and para-H₂ fraction (fₚ(p)), as described by Fletcher et al. (2017). We use an optimal-estimation retrieval algorithm (NEMESIS, Irwin et al. 2008), updated to include H₂–H₂ dimeric absorption (Fletcher et al. 2018), to fit the spectra while applying a cost function to prevent substantial deviations from our priors (see below). Our initial aim was to simply repeat the analysis that had been developed for the 2014 May data, but the 2019 July observations proved to be unexpectedly challenging. The radiometric calibration of the 2014 May data had been scaled downward by 0.9, equally applied to both grisms. However, initial attempts at fitting the 2019 July data revealed that the two grisms would need to be handled separately. This is perhaps not too surprising, as we had no good narrow-band images in the G329 band (see Figure 6), and no images in either band during the 2019 July run. Via comparison to Voyager-1/IRIS observations, using the technique in Figure 5 of Fletcher et al. (2017), we estimated that the 28–37 μm observations needed to be scaled downward by 0.95, and the 17–27 μm observations needed to be scaled upward by 1.03. Given the uncertainties on these radiometric scalings, the following analysis was repeated with independent scalings in the 0.95–1.05 range to assess the effect on our conclusions.

Second, our initial application of the spectral inversion showed a high sensitivity to our prior, manifesting as an exceptionally cold tropopause and a non-physical latitudinal gradient of retrieved properties, quite unlike that seen in any previous determinations of Jupiter’s tropospheric temperatures. We had been using a prior based on Cassini/CIRS observations at 7–17 μm (Fletcher et al. 2009), which lacked constraints at the longer wavelengths of FORCAST. We experimented by jointly fitting FORCAST observations at multiple emission angles (0°–60°) with a single atmosphere (T(p), fₚ(p)), using the limb-darkening to constrain the vertical structure. Although this strategy is not strictly correct, as Jupiter’s temperatures are known to vary from mid-latitudes to the cold polar vortices, it provided a first-order estimate of a “globally averaged” atmosphere for use as a prior. At this stage we also tested a variety of different aerosol models (non-scattering), varying cloud height and optical properties. We used gray clouds, NH₃ ice clouds based on Martonchik et al. (1984), and a simple cloud with a refractive index of 1.4+0.01i. Only the NH₃ ice cloud with small (<20 μm radius) particles could be ruled out, as this provided an absorption near 370 cm⁻¹ that is not observed in the Voyager or SOFIA data. Other clouds provided negligible improvement to the spectral fits, and although some cloud opacity is required to optimize the fitting, FORCAST data can provide no useful constraint on its latitudinal distribution.

The “globally averaged” result had a vertically extended tropopause region, cooler at 20–50 mbar than our CIRS-derived prior (see the central column of Figure 8). This was reminiscent of the difference between the Voyager-1 radio occultation egress and ingress profiles (Figure 3 of Lindal et al. 1981), acquired on 1979 March 5. We therefore constructed a new prior based on the cooler Voyager-1 egress profile (10–1000 mbar, Lindal et al. 1981), Cassini/CIRS stratospheric inversions (p < 10 mbar, Fletcher et al. 2016a), and Galileo probe measurements (p > 1 bar, Seiff et al. 1998). This successfully removed the equator-to-pole artifact described above, and is adopted for the rest of this study.

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**Figure 5.** First frames of each grism data cube to show the coverage of the planet. The intensity scale is chosen such as to bring out some of the details in the images.
Spectral fits from varying \( T(p) \) and \( f_d(p) \) simultaneously are shown for three representative latitudes in Figure 8, along with the retrieved profiles. We show the 2019 data without any scaling, compared with nine models where radiances in the G227 grism (350–550 cm\(^{-1}\)) were scaled by 0.95 (red), 1.0 (green), and 1.05 (blue), and radiances in the G329 grism (300–350 cm\(^{-1}\)) were scaled by 0.95 (dotted), 1.0 (solid), and 1.05 (dashed). The shape and slope of the nine model spectra are all different, reflecting how \( T(p) \) and \( f_d(p) \) have to adjust depending on the radiometric scale factor, and raising serious

![Figure 6](image-url)
questions about the ability of FORCAST to determine absolute temperature and para-H$_2$ values. The differences between the retrieved profiles in Figure 8 provide a good indication of our uncertainties on these quantities. Nevertheless, the radiometric offsets are systematic, such that we can still explore relative changes in these quantities in Figure 9. For consistency, we applied the updated inversion—new prior, new dimeric absorption—also to the 2014 May data from Fletcher et al. (2017). The profiles in Figure 9 are discussed in the following section. The vertical sensitivity of the FORCAST data is as shown in Figure 6 of Fletcher et al. (2017), with maximum sensitivity in the 200–500 mbar range, and weaker sensitivity spanning the 100–700 mbar region.

4. Discussion

4.1. Spectra of the Galilean Satellites

As shown in Figure 4, the brightness temperatures of the satellites are highest at the shortest wavelengths and decrease with increasing wavelength, where, during the day, deeper cooler layers in the subsurface are probed. For rocky objects one typically probes ∼10–20 wavelengths deep into the surface, while this can be hundreds of wavelengths deep for icy bodies. The SOFIA observations appear to probe layers in the subsurface where the temperature decrease with depth is clearly visible. How fast the (physical) temperature decreases with depth depends on the thermal inertia and thermal skin depth of the material, which in turn are determined by the satellite’s rotation rate, and the thermal conductivity, heat capacity, and density, which in turn are determined by, e.g., the composition, temperature, and compactness of the layers (i.e., the density/porosity profile with depth). The surface albedo at visible wavelengths determines how much sunlight is conducted down into the subsurface layers. Once the temperature gradient with depth is determined, the object’s brightness temperature at a particular wavelength can be modeled by integrating the equation of radiative transfer through the subsurface layers; the absorption coefficient of the outgoing thermal emission depends upon the dielectric constant of the material (real and imaginary part), and is inversely proportional to density and wavelength. The brightness temperature further depends on an emissivity parameter, essentially the wavelength-dependent ratio of the observed with the modeled intensity. Details on how to model the thermal emission from solid surfaces can be found in, e.g., Mitchell & de Pater (1994) and de Kleer et al. (2021).

Figure 4 shows that overall the brightness temperature of all satellites drops down to ∼100 K or even lower at mm–cm wavelengths. Callisto’s spectrum is quite typical in that regard. Europa and Ganymede may go down to ∼50 K levels in the 2–6 cm wavelength range, although higher values have been reported at these wavelengths as well. The low microwave brightness temperature measurements agree with the low emissivity (i.e., high albedo) recorded by radar observations (Ostro 1982; Ostro et al. 1992). Assuming that to first order the brightness temperature can be approximated by the product of the physical temperature and an effective emissivity (∼1 − α, with α the geometric radar albedo) at unit optical depth, the decrease in brightness temperature for these two objects is a result of both the decrease in physical temperature with depth and in effective emissivity with wavelength (de Pater et al. 1984). The slight increase in brightness temperature between ∼1 mm and ∼1 cm for Io is intriguing, and one may wonder if this is real, and if so, if it could perhaps be caused by the tidal heating the satellite is subjected to, or by a change in material properties. Ideally, future SOFIA and new measurements at (sub)mm and cm wavelengths will be targeted such as to observe the satellites near their elongations to avoid contamination with Jupiter’s emission. Although an inversion of the present spectra to extract the material properties of the satellites is beyond the scope of this paper, the SOFIA measurements can be useful for future studies of the satellite spectra (such as in, e.g., de Kleer et al. 2021).

4.2. FORCAST Retrievals of Jupiter’s Temperature and Para-H$_2$

Figure 9 compares FORCAST retrievals of temperature and para-H$_2$ from “northern summer” (2014 May) and “southern summer” (2019 July). Absolute comparisons are hampered by the dependence of the inversion on the chosen radiometric scaling. For example, the tropopause warming from ∼112 K in 2014 to ∼118 K in 2019 is unlikely to be real, and shows the challenge of observing Jupiter without a radiometrically stable instrument. However, this offset is systematic, so that relative latitudinal structures can be investigated, and some persistent features can be assessed. First, the latitudinal temperatures are mostly uniform from the equator to the mid-latitudes, but then begin to cool poleward of 45° as we approach the polar vortices beyond 60° in each hemisphere. The northern domain appears
to be cooler at the tropopause and has a higher $f_p$ than the southern domain, irrespective of season, hinting at an asymmetry in the dynamics and radiative balance between the two poles. The cooling is likely to be a radiative effect associated with Jupiter’s hemispherically asymmetric polar aerosols (Zhang et al. 2013b; Guerlet et al. 2020), whereas the enhanced $f_p$ may be due to subsiding air below the cold tropopause (e.g., Conrath et al. 1998). second, the para-$\text{H}_2$ distribution displays an equator-to-pole gradient, with lower values found near the equator, and higher values poleward of $\sim 45^\circ$. Subtracting the equilibrium para-$\text{H}_2$ fraction from the measured $f_p$ in Figure 9 reveals that low latitudes generally display “sub-equilibrium” conditions indicative of uplift of low-$f_p$ air from deeper, warmer levels, primarily concentrated at the equator. This gives way to “super-equilibrium” conditions at higher latitudes, where subsidence of high-$f_p$ air from the cold tropopause may be at work.

The previous paragraph described the similarities between the two epochs, but some differences are also apparent. First, the contrast between the cool equatorial zone (equatorward of $\pm 7^\circ$) and the warm neighboring belts ($\pm 10^\circ$–$20^\circ$) is larger and more distinct in 2019 than in 2014 in Figure 9(a). The region of sub-equilibrium $f_p$ in Figure 9(c) is also more substantial at the equator in 2019 than in 2014, corresponding to a more sharply
peaked \( f_p \) distribution in Figure 9(b). As the tropical zones and belts are known to undergo periodic variations in temperature, aerosol opacity, and visible coloration (Orton et al. 1994; Rogers 1995; Simon-Miller et al. 2006; Fletcher 2017; Antuñano et al. 2018), this change is not surprising. Moreover, these observations were obtained during a weak “equatorial disturbance” event in 2019 (Antuñano et al. 2019), characterized by patches of enhanced 5 \( \mu \)m emission associated with cloud clearing. The observed sharply peaked distribution in \( f_p \) may be indicative of an increase in the rate of vertical
upwelling during this period. Second, the North Temperate Domain (20–30°N) displayed a prominent cool and high-$f_p$ region in 2014 and during the Voyager epoch (Fletcher et al. 2017), that was absent in 2019. Third, and most substantively, the 2014 May data had suggested an asymmetry in the para-H$_2$ disequilibrium, with stronger super-equilibrium $f_p$ conditions at high northern latitudes compared with the south, potentially associated with the asymmetric aerosol distribution. A similar asymmetry was noted in independent Voyager/IRIS retrievals by Conrath et al. (1998), which also suggested super-equilibrium $f_p$ at high northern latitudes. Conversely, the 2019 July FORCAST observations reveal a more symmetric para-H$_2$ distribution, with high-$f_p$ air in both polar domains, although the perturbation still appears larger in the north than in the south.

The comparison of the two FORCAST epochs provides tantalizing hints that we can monitor changes in both the temperatures and para-H$_2$ using SOFIA. Low-latitude $f_p$ may be responding to the quasi-periodic cycles of activity identified at other wavelengths (Rogers 1995; Fletcher 2017), although we note that the 5 yr gap between the two epochs should place us in the same phase of Jupiter’s equatorial stratospheric oscillation (Leovy et al. 1991; Antuñano et al. 2021). High-latitude $f_p$ may be revealing changes in the strength of the circulation within the polar vortices—as polar aerosol content changes with time, so too would radiative balance and the resulting compensating residual-mean circulation. The distribution of para-H$_2$ on Saturn (Fletcher et al. 2016b) varies with time in association with seasonally changing aerosols (acting as sites of catalysis for interconversion of ortho- and para-H$_2$), so future studies are required to determine whether Jovian polar aerosol changes are correlated with the para-H$_2$ variability reported here.

However, with only three snapshots of the para-H$_2$ distribution from Voyager and SOFIA, we cannot be certain that these changes are robust and repeatable over timespans of weeks and months, or whether we are being misled by the radiometric and observational challenges presented by these SOFIA/FORCAST data. Long-term far-infrared observations from a radiometrically stable platform, either a space telescope or from a future orbital mission, are required to validate the variability in the para-H$_2$ distribution suggested by our study.

5. Conclusion

Airborne spectral maps (17–37 μm, 370–580 cm$^{-1}$) and images (8–37 μm, 270–355 cm$^{-1}$) of Jupiter’s thermal emission were acquired with SOFIA/FORCAST in 2018 and 2019, for direct comparison to similar maps by Voyager (1979) and FORCAST in 2014. The images provided context and helped calibrate the spectra. Unfortunately, unlike during previous Jupiter observations, these calibration images were not obtained during the same flight as the spectra, and differences of up to ~10% in flux measurements taken on different days were observed. The best spectral calibrations were obtained using images taken with the narrowest filters that overlapped in spectral range. However, significant uncertainties remained in the spectral radiometric calibration.

On 2018 August 22 and 29, several Galilean satellites were visible in the images. Despite their close proximity to Jupiter, we were able to extract reliable measurements in several filters for all four satellites. The data at the shortest wavelengths agree with previous data, and extend the wavelength coverage to longer wavelengths. The data can be used to constrain the composition and compactness of the subsurface layers of the satellites. It would be useful to get more SOFIA data of the satellites, but targeted when they are near elongation to avoid contamination with Jupiter’s light. Unfortunately, both Jupiter and its satellites will saturate the long-wavelength channels of the MIRI instrument on the JWST, so we have to rely on SOFIA for such measurements. Ideally, these data will be supplemented with new accurate data at (sub)mm and cm wavelengths with the Atacama Large (sub)Millimeter Array (ALMA), the Very Large Array (VLA) and its successor the ngVLA (Selina et al. 2018), as well as spacecraft (e.g., Juno) to solve ambiguities in the shape of the spectra longward of ~100 μm.

The shape of the Jovian spectra, dominated by the collision-induced continuum of H$_2$ and He, were used to determine the latitudinal distribution of temperatures and para-H$_2$ in the upper troposphere. As the spectral shape is significantly affected by radiometric calibration uncertainties, only the 2014 and 2019 data could be reliably compared, capturing Jupiter approximately half a Jovian year apart (from northern summer solstice in 2012 to southern summer solstice in 2018). Tropospheric temperatures are observed to vary over time, particularly the relative contrasts between the cool equatorial zone and its neighboring belts, although cool polar vortices at latitudes ≥50° remain in place, with the north cooler than the south irrespective of Jupiter’s weak seasonal tilt. Sub-equilibrium para-H$_2$ is observed at the equator during all epochs, confirming Voyager/IRIS studies (Conrath et al. 1998), although this exhibits more contrast in 2019 than 2014. The most substantial change is the detection of high-para-H$_2$ air at high (≥50°) southern latitudes (it was absent or had significantly less contrast in 1979 and 2014), which suggests that polar para-H$_2$ varies over multi-year timescales. Further studies are needed to assess whether this change is correlated with variations in other atmospheric properties, such as aerosol content and gaseous composition.

Monitoring of Jovian para-H$_2$ requires access to spectral regions beyond 24 μm that are obscured from ground-based facilities. Although SOFIA/FORCAST can achieve this aim, a radiometrically stable space-based facility (a telescope or future mission) will likely be required to assess how para-H$_2$ varies in response to atmospheric phenomena on Jupiter.

We thank two anonymous referees for their help in improving this paper. This work was based on observations made with the NASA/DLR Stratospheric Observatory for Infrared Astronomy (SOFIA), and was financially supported through SOF-06-0009 to the University of California, Berkeley. SOFIA is jointly operated by the Universities Space Research Association, Inc. (USRA), under NASA contract NNA17BF53C, and the Deutsches SOFIA Institut (DSI) under DLR contract 50 OK 0901 to the University of Stuttgart. We are grateful for all those involved in the telescope engineering, operations sup- port and the flight crews. Fletcher is supported by a European Research Council Consolidator Grant (under the European Union’s Horizon 2020 research and innovation program, grant agreement No. 723890) at the University of Leicester. This research used the ALICE High Performance Computing Facility at the University of Leicester. R.D.G. was supported, in part, by the United States Air Force. Orton is supported by NASA using funds distributed to the Jet Propulsion Laboratory, California Institute of Technology, under contract 80NM0018D0004. Wong is grateful for the chance to fly aboard SOFIA OC6-J Flight 6.
