Supporting Online Material for

Temperature and Composition of Saturn’s Polar Hot Spots and Hexagon


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Temperature and Composition of Saturn’s Polar Hotspots and Hexagon

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Materials and Methods

This article takes advantage of Cassini's high orbital inclinations between late 2006 and early 2007 to obtain low viewing-angle observations of the polar regions. Cassini/CIRS measures Saturn's thermal emission from 10 - 1400 cm\(^{-1}\) (7-1000 µm) at apodized spectral resolutions of 0.5-15.0 cm\(^{-1}\). We used mid-IR data (600-1400 cm\(^{-1}\)) at two spectral resolution settings - 15.0 cm\(^{-1}\) for global mapping of tropospheric and stratospheric temperatures, and 2.5 cm\(^{-1}\) to resolve the absorption features of PH\(_3\).

**Low Spectral Resolution Mapping:** Global radiance maps were obtained by scanning the mid-infrared focal plane arrays over each hemisphere at the lowest spectral resolution setting of 15 cm\(^{-1}\). The north polar map was obtained on March 2nd 2007, when the sub-spacecraft latitude was around 50°N, providing viewing angles of 37° from the zenith at the north pole. No similar low viewing-angle maps of the southern pole have been obtained, so we used an observation from July 30th 2005, from a sub-spacecraft latitude of 19°S and distance of 28 Rs, the only one to penetrate all the way to the south pole with a viewing angle of around 70° from the zenith angle at the south pole (S1). The mid-IR focal planes had a field of view (FOV) of 0.6-1.0° over both hemispheres. Each of these observations was binned onto a grid to create the images in Fig. 1, with latitude bins 1° wide and longitude bins 2° wide, stepped to achieve Nyquist sampling. Zonal averaging of spectra was used for Fig. 2, stepping the 1°-latitude bins every 0.5°. The viewing angle for each focal plane was treated separately, by averaging several hundred spectra with viewing angles within 10° of the modal value.

**High Spectral Resolution Zonal Averaging:** To validate the derived temperatures and provide additional constraints on phosphine, we zonally averaged mid-IR spectra at 2.5 cm\(^{-1}\) resolution at low zenith angles. Observations acquired on April 6th 2007 covered the northern hemisphere with viewing angles between 35-55° and a FOV of 0.5-1.0°. The south polar region was viewed in small latitude-segments on October 11th 2006, January 31st 2007 and during several rider observations in February and March 2007 from sub-spacecraft latitudes of around 55°S. Examples of the zonal averages at each pole are shown in Fig. S1 to demonstrate the essential differences.
Atmospheric Retrievals: Synthetic spectra for comparison with observations were generated using an atmospheric retrieval algorithm (S2), reference atmospheric model and line database described in full by (S1). Vertical temperature profiles at each latitude were derived by fitting the collision-induced S(1) line of H$_2$ between 600-680 cm$^{-1}$ (sensitive to 60-250 mbar) and the emission features of CH$_4$ between 1200-1400 cm$^{-1}$ (1.0-6.6 mbar). Additional temperature information was obtained from the PH$_3$ and NH$_3$ vibrational bands between 875-1200 cm$^{-1}$ (440-830 mbar), but these were highly correlated with the abundances of both gases beneath 550 mbar or so. Temperatures outside of this range were based on smooth relaxation to the a priori profile.

Better constraints on temperatures beneath the 550-mbar level could be obtained via inclusion of the far-IR CIRS focal plane (S3), but this had insufficient spatial resolution for this application. As an alternative, tests showed that the quality of the spectral fits to the 600-1400 cm$^{-1}$ region could be significantly improved (by $\chi^2$ values of 1-2$\sigma$) by simultaneously retrieving both temperature and PH$_3$. Spectra do not have the signal-to-noise for independent estimates of the ammonia abundance.

One of the key findings of this article is that the polar hotspots persist throughout the 100-800 mbar range. Fixing PH$_3$ as a constant provides greater temperature contrasts than when we allow PH$_3$ to vary, but in the latter case we obtain better spectral fits and the hotspots are still evident throughout the range of sensitivity. Using this assumption, the north pole remains 1.5 K warmer than 85°N and the south pole is 2.5 K warmer than 85°S even at 800 mbar. Finally, following (S1), we assume that the opacity due to tropospheric and stratospheric aerosols is negligible throughout the mid-IR.
Supplementary Text

Previous Polar Observations:

Early work investigating Saturn's insolated pole demonstrated that bright emissions in the methane, ethane and acetylene bands in the mid-IR were due to changes in stratospheric temperatures in accordance with Saturn's seasonal cycle. The southern hemisphere was bright prior to and during the Voyager encounters in 1980/81 (S4-S7). Seasonal stratospheric models (S8) then predicted the northern hemisphere would become brighter from 1985 onwards, confirmed by ground-based observations (S9-S10). But it wasn't until high spatial resolution observations were obtained from the Keck telescopes (S11) that a concentrated hotspot was discovered to be centred on the summer pole.

Thermal Windshear Equation:

In the geostrophic approximation, a balance exists between meridional pressure gradients and the Coriolis forces related to the zonal winds (e.g., (S12)). In log-pressure coordinates, the thermal wind equation is;

\[ f \frac{\partial u}{\partial \ln(p)} = -\frac{R}{a} \frac{\partial T}{\partial \theta} \]

where \( f \) is the Coriolis parameter \( f=2\Omega \sin \theta \) (where \( \Omega \) is the planetary angular velocity, \( \theta \) is the latitude), \( a \) is the mean planetary radius, \( u \) is the zonal (eastwards) velocity and \( R \) is the molar gas constant divided by the mean molar weight of Saturn's atmosphere. Saturn's zonal velocity profile at the cloud-tops, \( u \), was constructed for high latitudes using Cassini-era data for the southern hemisphere (S13, S14), and Voyager-era data for the northern hemisphere (S15, S16). The zonal velocity \( u \) was determined by tracking visible cloud features, thought to exist in the 500-1000 mbar region beneath the high-altitude tropospheric haze (S14, S16), though the precise altitude of these cloud-top tracers is subject to considerable uncertainties. We calculate the vertical windshear in Fig. S2, then integrate the thermal wind equation both upwards and downwards, using the zonal winds placed at 500 mbar, to estimate the decay of the zonal jets with altitude into the stratosphere. No cloud-tracking has been possible polewards of 82°N at this time.

Regions of negative windshear correspond to prograde jets in both hemispheres, so that they decay with altitude throughout the region where radiative effects are likely to be significant. However, the nature of the phenomena causing the slowing of the zonal winds remains unknown.
Thermodynamic Energy Equation:

The thermodynamic energy equation for atmospheric circulation provides a diagnostic balance between vertical advection (leading to adiabatic heating or cooling of the atmosphere) and the relaxation of the atmosphere to an equilibrium state by radiative heating and cooling. However, the relationship between vertical motion and zonal flow contains no information concerning the mechanism driving this atmospheric circulation, which is probably related to the details of the processes governing the decay of the zonal jets with height into the stratosphere. Nevertheless, the relationship can be used to estimate the vertical windspeeds at each pole. The thermodynamic energy, or heat equation, can be expressed as;

\[
\frac{DT}{Dt} + \frac{RT}{cp} w = \frac{Q}{\rho cp} \approx \frac{T_e - T}{\tau_R}
\]

where \( DT/Dt \) is the advective derivative of temperature, \( cp \) is the specific heat capacity of Saturn's atmosphere with density \( \rho \), \( Q \) is the net diabatic heating of the atmosphere, \( T_e - T \) is the perturbation of the atmosphere away from the radiative equilibrium profile, \( T_e \), and \( \tau_R \) is the radiative relaxation time. Under the assumption that the small-scale tropospheric temperature variations are the result of dynamical perturbations of \( T_e \), rather than radiative forcings; and that \( w(\partial T/\partial z) \) is the only term contributing significantly to the advective derivative, we can derive an estimate for \( w \), the vertical wind speed.

A full calculation of \( T_e \) and \( \tau_R \) requires radiative transfer calculations which are beyond the scope of this article (see e.g., (S17)), but we can make headway by considering temperature perturbations from the mean temperature field (i.e. subtracting the seasonal asymmetry in Fig. 2). We used estimates of \( \tau_R \) from (S17). \( cp \) was calculated assuming a simple H2-He-CH4 atmosphere and a thermal equilibrium para-hydrogen fraction. The estimates for the vertical velocities are presented in Fig. S3, with values which are comparable to the more detailed models of Conrath et al. (1990). We find that the polar hotspots are related to localised subsidence at rates of around \( 1\times10^{-5} \text{ ms}^{-1} \) (around 1 m per day), and that the cold tropospheric polar collars can then be reproduced by vertical upwelling with a similar windspeed. Weaker subsidence at 1 mbar (0.5\( \times 10^{-5} \text{ ms}^{-1} \)) could be responsible for the stratospheric hotspots within 2-3° of each pole.

Periodogram Analysis:

To investigate the periodic structure within the low spectral-resolution maps, we follow (S18) and calculate Lomb-Scargle periodograms for radiances within latitude bands (Fig. S4) to identify the zonal wavenumbers that contain the most spectral power (S19). Firstly, zonal mean radiances were computed in the 600-625 cm\(^{-1}\) range (sensitive to 150 mbar) in latitude bins 4 degrees wide and
stepped every degree. The zonal means were subtracted from the radiances at each longitude, and the residuals were searched for periodicity. The periodogram study allows the analysis of series of unequally spaced data without the need for interpolation onto a uniform grid, reducing aliasing of high onto lower spatial frequencies (S18). To estimate the statistical significance of the spectral power, the probability of the peak being produced by white noise (the false-alarm probability, \( f \)) was also plotted on the scale bar of Fig. S4. Although the false-alarm probability is not a true estimate of the confidence-level for each wave mode, it serves as a useful guide, as smaller false-alarm probabilities are related to more significant wave features.

The north polar hexagon appears clearly as a wavenumber-6 feature (\( f<0.001 \)) at 76-81°N in the periodogram in Fig. S4, covering both the polar belt and zone surrounding the jet at 77°N (i.e. six wavelengths contained within 360° longitude). No southern counterpart to the northern hexagon was observed in the southern hemisphere, confirming (S20).

The periodogram analysis reveals evidence of zonal wave activity in both hemispheres, such as the wavenumber-5 and -7 features associated with the zone at 60°N, the wavenumber-4 and -11 features associated with the zones at 48°S and 45°N and the wavenumber-11 feature in the zone at 60°S. Features with wavenumbers of 1 or 2 were not considered here, as they may result from changes in instrument conditions and absolute calibration over the period of the scan. Periodograms were also computed in the stratosphere using zonal radiances in the 1250-1350 cm\(^{-1}\) range, but no wavelike structures were apparent above the signal-to-noise. In particular, no evidence was found for the north polar hexagon persisting up to pressures of 1 mbar. The full range of Saturn's thermal wave activity and its temporal evolution will be the topic of future studies.
**Fig. S1.** A comparison of CIRS spectra at 2.5 cm$^{-1}$ averaged within 3 degrees of the summer and winter poles. Emission features of methane are substantially more subdued in the north (blue line, brightness temperature of around 120 K) than in the south (black line, 150-160 K), as are the features of ethane and acetylene, due to the cold northern stratospheric temperatures. The collision-induced H$_2$-He continuum is sensitive to tropospheric temperatures (70-250 mbar), and is warmer at the south pole (100K) than in the north (87 K). Brightness temperatures are similar for the ammonia and phosphine regions, suggesting that they arise from regions of similar temperatures at both poles.
Fig. S2. The calculation of zonal winds (C) based on meridional temperature gradients and cloud-tracked zonal winds from visible images during the Cassini and Voyager eras (A). No data is available on the cloud-top windspeeds polewards of 82°N. Plot B demonstrates the relation between the thermal windshear and the prograde zonal jets (dotted lines). We placed the cloud-traced winds at 500 mbar and integrate the thermal wind equation both upwards and downwards to derive the zonal windfield in C. In B and C, contours are shown for 0 ms⁻¹, based upon the System III rotation period calculated by Voyager.
Fig. S3. Vertical windspeeds inferred from the temperature plots of Fig. 2. The vertical dotted lines indicate the peaks of eastwards jets measured by cloud feature tracking. Vertical winds are estimated by balancing the heating due to vertical advection with relaxation to radiative equilibrium. The high temperatures within the cores of the polar vortices can be explained in terms of subsidence at both poles both in the troposphere and stratosphere. Black contours are shown for 0 ms$^{-1}$. 
To investigate the zonal periodicity in the 15.0 cm\(^{-1}\) datasets at each pole, we calculated Lomb-Scargle periodograms (ideally suited to irregularly gridded datapoints, \((S18)\)) in the northern (A) and southern (B) hemispheres. The zonal-mean radiance in the 600-625 cm\(^{-1}\) spectral range (sensitive to approximately 150 mbar) was subtracted from the radiance at each longitude, and the residual was used to search for zonal waves. The scale shows the spectral power, normalised by the data variance, associated with each zonal wavenumber. Horizontal lines on the scale bar indicate the power levels associated with the false-alarm probabilities of \(f = 0.001, 0.01\) and 0.1. The polar hexagon at 79\(^\circ\)N shows up clearly as a wavenumber-6 feature. No comparable features are visible in the southern hemisphere.
Supporting References


