

Emitted power of Jupiter based on Cassini CIRS and VIMS observations

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[1] The emitted power of Jupiter and its meridional distribution are determined from observations by the Composite Infrared Spectrometer and Visual and Infrared Mapping Spectrometer onboard Cassini during its flyby en route to Saturn in late 2000 and early 2001. Jupiter's global-average emitted power and effective temperature are measured to be $14.10 \pm 0.03 \text{ Wm}^{-2}$ and $125.57 \pm 0.07 \text{ K}$, respectively. Jupiter's $5 \mu\text{m}$ thermal emission contributes $0.7 \pm 0.1\%$ to the total emitted power at the global scale, but it can reach $1.9 \pm 0.6\%$ at 15°N . The meridional distribution of emitted power shows a significant asymmetry between the two hemispheres with the emitted power in the northern hemisphere $3.0 \pm 0.3\%$ larger than that in the southern hemisphere. Such an asymmetry shown in the Cassini epoch (2000–2001) is not present in the Voyager epoch (1979). In addition, the global-average emitted power increased $3.8 \pm 1.0\%$ between the two epochs. The temporal variation of Jupiter's total emitted power is mainly due to the warming of atmospheric layers around the pressure level of 200 mbar.

The temporal variation of emitted power was also discovered on Saturn. Therefore, we suggest that the varying emitted power is a common phenomenon on the giant planets.

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1. Introduction

[2] The absorbed solar radiance and the emitted thermal emission determine the energy budget of an astronomical body. For three of the four giant planets in our solar system (i.e., Jupiter, Saturn, and Neptune), large energy imbalances between the absorbed solar radiance and the emitted thermal emission were discovered, and hence the internal heat was inferred. Such large energy imbalances and internal heat

have important implications for atmospheric circulation and planetary formation/evolution, as reviewed in two related studies [Conrath *et al.*, 1989; Hanel *et al.*, 2003] and in our previous study of Saturn's emitted power [Li *et al.*, 2010].

[3] Previous observations of Jupiter [Ingersoll *et al.*, 1975; Hanel *et al.*, 1981; Pirraglia, 1984] have provided some important characteristics of the energy budget, the internal heat, and their meridional distributions. However, the temporal variability of the energy budget for Jupiter has not been explored mainly due to the limited observation set. Yet, it provides valuable clues for examining the time scale of internal heat referred from the theories of planetary formation/evolution [Smoluchowski, 1967; Salpeter, 1973; Flasar, 1973; Stevenson and Salpeter, 1977; Grossman *et al.*, 1980; Guillot *et al.*, 2004]. In addition, the meridional distribution of energy budget and its temporal variation provide insights into atmospheric dynamics and general circulation [Pirraglia, 1984; Friedson and Ingersoll, 1987]. The measurements of Jupiter's energy budget set important constraints on the heating/cooling rates as a function of altitude in the Jovian atmosphere, following a similar study for the saturnian atmosphere [Pérez-Hoyos and Sanchez-Lavega, 2006]. The exploration of the heating/cooling rates and their temporal variation will help us study the atmospheric circulation and dynamics on Jupiter. As well, the temporal variation of the energy budget also provides one more perspective on Jupiter's climatology. The

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decadal-scale variation of cloud activity and the related convection has been characterized on Jupiter [Baines *et al.*, 2007]. Moist convection is inferred to be a prime transporter of internal heat on Jupiter [Gierasch *et al.*, 2000; Ingersoll *et al.*, 2000]. Therefore, measurements of the temporal variation of the internal heat help determine if the decadal variation of convection, and hence cloud variability, acts as a valve that varies the flux from the interior of Jupiter and further adjusts possible climate change [Marcus, 2004].

[4] The Cassini observations provide an opportunity to revisit the energy budget on Jupiter. Furthermore, the combination of the Cassini observations and the previous observations provides an opportunity to explore its temporal variability. This study is the first of a series of studies examining the temporal variability of the energy budget on Jupiter. In this study, we present the exploration of Jupiter's emitted power as determined by Cassini observations and compare it with previous measurements from Pioneer/Voyager [Ingersoll *et al.*, 1975; Hanel *et al.*, 1981; Pirraglia, 1984]. Observations from Earth-based and airborne telescopes are not included in this study because of the relatively large uncertainties and the discrepancies among them (refer to Hanel *et al.* [1981, Table 1] and Conrath *et al.* [1989, Table 1]). Note that planetographic latitude is used in this study. In addition, the solar longitude, which is defined as the angular distance along Jupiter's orbit around the Sun measured from a reference point in the orbit (i.e., the zero of solar longitude at northern spring equinox), is used to track the different seasons.

2. Methodology

[5] The methodology of computing a planet's emitted power (i.e., the emitted energy per unit time over a unit area) with the Cassini observations was introduced in our previous study of Saturn's emitted power [Li *et al.*, 2010]. The basic idea is that we will integrate recorded radiance over emission angle and wavelength to obtain Jupiter's emitted power.

[6] In comparison to the on-orbit, long-term (2004-) observations of Saturn, the Jupiter flyby observations by Cassini are somewhat limited in the coverage of emission angle. To fill the observational gaps in the coverage of emission angle, additional techniques (e.g., linear regression) are needed beyond the least squares fit method (see section 4). In addition, the thermal emission near $5\ \mu\text{m}$ is significantly strong on Jupiter [Westphal, 1969] and is thus included in our computation of Jupiter's emitted power [Conrath *et al.*, 1989].

[7] Finally, the method of addressing the dependence of atmospheric radiance upon the emission angle is different between this Cassini study and the previous Voyager studies [Pirraglia, 1984; Ingersoll, 1990]. In the Cassini analysis, the least squares fit and the linear regression are used to fill the observational gaps in the emission angle (see section 4). Such a method does not require the knowledge of the temperature structure and chemical components of Jupiter's atmosphere. The Voyager observations have much less coverage in the emission angle than the coverage in the Cassini observations in the middle infrared (i.e., FP3 and FP4), so the method of the least squares fit does not work for filling the observation gaps in the Voyager observations. Instead, the

dependence of the atmospheric radiance upon the emission angle was addressed by the radiative-transfer calculations with the retrieved atmospheric temperature and opacity [Hanel *et al.*, 1981] in the previous Voyager studies [Pirraglia, 1984] (also see section 4).

3. Cassini Observations and Data Processing

[8] The measurements of Jupiter's emitted power are based on the Cassini observations obtained during the period of the Jupiter flyby, from 1 October 2000 to 22 March 2001. We use the observations from two instruments. The Composite Infrared Spectrometer (CIRS) measures the great majority of the outgoing thermal emission of Jupiter with wavelengths from 7 to $1000\ \mu\text{m}$. The Visual and Infrared Mapping Spectrometer (VIMS) records the $5\ \mu\text{m}$ thermal emission. The two instruments and the corresponding data processing are described below.

3.1. Cassini/CIRS Observations

[9] The CIRS instrument [Flasar *et al.*, 2004a] acquires Jupiter's spectra in three focal planes: FP1, FP3, and FP4, covering 10–600, 600–1050, and 1050–1430 cm^{-1} , respectively. With all three focal planes, CIRS measures Jupiter's thermal emission in wave number over 10–1430 cm^{-1} (i.e., 7–1000 μm) with adjustable spectral resolutions from 0.5 to 15.5 cm^{-1} . In this study, we analyze Jupiter's spectra with two resolutions (i.e., 2.8 and 0.5 cm^{-1}) that provide the best spatial coverage. Data with other spectral resolutions are not included because their spatial coverage is negligible compared with the spectra with resolutions of 2.8 and 0.5 cm^{-1} .

[10] Figure 1 displays a typical spectrum of Jupiter recorded by CIRS. The theoretical framework introduced in previous studies [Conrath *et al.*, 1989; Li *et al.*, 2010] shows that the outgoing thermal emission is determined by measurements of outgoing radiance at different emission angles and different latitudes. Therefore, we process the CIRS spectra into two-dimensional (latitude $\times$ emission angle) wave number-integrated radiance [Li *et al.*, 2010] with a resolution of 1° in both latitude and emission angle. Here, we average all CIRS observations within each 1° latitude bin based on the center latitudes of spectra. The spatial resolution of processed data (1°) is higher than the spatial resolution of the raw CIRS observations ($\sim 3\text{--}40^\circ$), which is determined by the field of view of CIRS and the distance between Jupiter and Cassini. Figure 2 shows the final data products: zonal-mean wave number-integrated radiance in the plane of latitude and emission angle recorded by FP1, FP3, and FP4, respectively. Figure 2 suggests that Jupiter's radiance varies not only in the direction of latitude but also in the direction of emission angle. The variation of Jupiter's radiance along the direction of longitude is generally less than 3%, which is not shown in Figure 2, but is accounted in the estimates of the uncertainty of Jupiter's emitted power (see section 4).

3.2. Cassini/VIMS Observations

[11] The shortest wavelength (i.e., largest wave number) of the CIRS spectra is $\sim 7\ \mu\text{m}$ (i.e., $\sim 1430\ \text{cm}^{-1}$). Therefore, the CIRS observations do not record the $5\ \mu\text{m}$ thermal emission spectral component of Jupiter. This range is covered by another Cassini infrared instrument: VIMS. The VIMS instrument is a color camera that acquires spectral

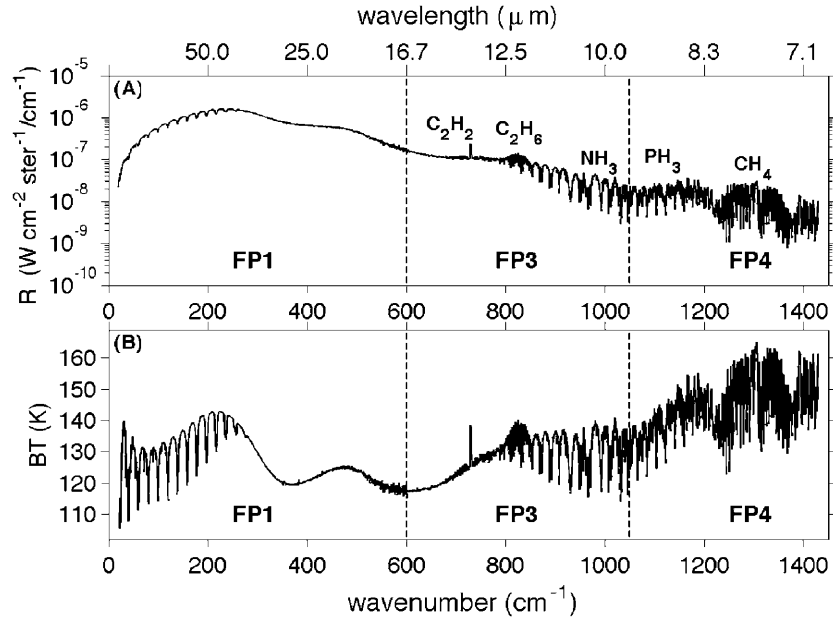


Figure 1. Jupiter's combined spectrum based on the three spectra obtained by FP1, FP3, and FP4. The combined spectrum, which was recorded at a spectral resolution of 0.5 cm^{-1} , is a mean spectrum averaged over latitudes 10°S – 10°N and over emission angle 20° – 30° . (a) CIRS radiance. (b) Corresponding brightness temperature.

cubes encompassing 352 different wavelengths between 0.35 and $5.1 \mu\text{m}$ [Brown *et al.*, 2004]. It is designed to measure scattered and emitted light from surfaces and atmospheres, with emphasis on covering a broad spectral domain with moderate spatial resolution.

[12] In this study, we use 11 full-disk VIMS observations recorded on 7–8 January 2001, about 8 days after the closest approach to Jupiter. The VIMS observations from 4.4 to $5.1 \mu\text{m}$ are utilized to explore the emitted power of the $5 \mu\text{m}$ thermal band, which has a spectral range of 4.4 – $5.6 \mu\text{m}$

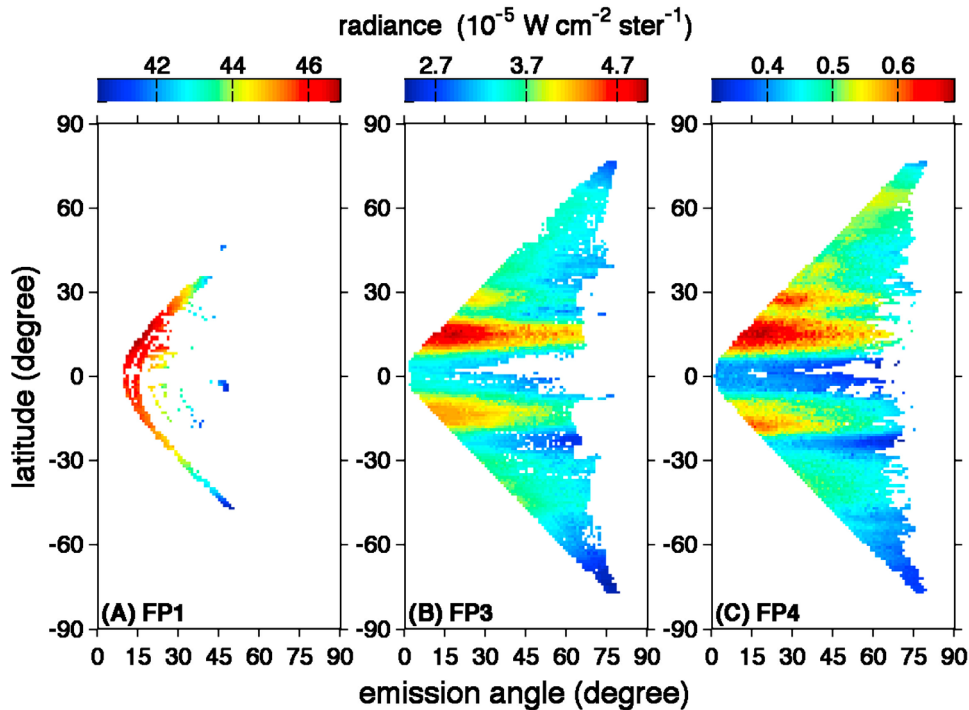


Figure 2. Coverage of wave number-integrated CIRS radiance in the plane of latitude and emission angle. (a) FP1. (b) FP3. (c) FP4. The limited coverage of FP1 is due to its large field of view with respect to FP3 and FP4.

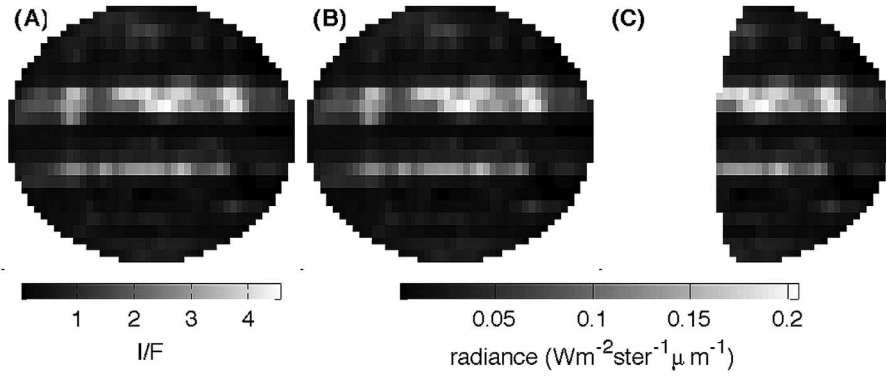


Figure 3. VIMS maps at 5 μm . (a) Map with unit of I/F. (b) Map with unit of radiance. (c) Night-side map with unit of radiance. The emission angle increases from $\sim 0^\circ$ at the center of disk to $\sim 90^\circ$ at the limb of this disk. The spatial resolution of the VIMS maps is $\sim 3^\circ$ in both latitude and longitude.

(see section 4.2). All global VIMS images at different wavelengths are well navigated and calibrated by the VIMS Operations Team based at the University of Arizona, following techniques discussed by *Barnes et al.* [2007]. The raw 5- μm VIMS global images are generally stored in units of I/F, the ratio of recorded radiance to the known total incident solar radiance [Thekaekara, 1973]. Figure 3a displays one example of the 5 μm VIMS global images in such units. With the known total incident solar radiance, we can convert the recorded VIMS radiance from I/F to a general radiance unit (Figure 3b). To obtain the intrinsic thermal emission of Jupiter around 5 μm , we eliminate the solar scattering component by analyzing only the night-side portions of these VIMS images (Figure 3c).

4. Results

4.1. Emitted Power in the Wave Number Range of CIRS

[13] As is evident in Figure 2, the CIRS observations do not occupy the whole plane of latitude and emission angle. In order to calculate the emitted power at each latitude from integration of the radiance over the entire range of emission angle [Li *et al.*, 2010], it is necessary to fill the gaps in the observed emission angle. Following the method used in our study of Saturn's emitted power [Li *et al.*, 2010], wherein the interpolation/extrapolation from the existing observations was accomplished with a technique of least squares fit [Bevington and Robinson, 1992], we fill the observational gaps in FP3 and FP4 (Figures 2b and 2c). Different polynomials of emission angle were tried for the best-fitting (i.e., the fitting with the least fitting residual). Here, the fitting residual is defined as the difference between the fitting value and observational data (i.e., fitting value-observational data). We find that the following first-order (degree) polynomial has the best fitting results for observed radiance by FP3 and FP4:

$$I(\delta) = c_1 \cos \delta + c_2, \quad (1)$$

where δ is the emission angle. The parameters c_1 and c_2 are coefficients that are fitted and determined by the observed radiance. Figure 4 shows some example fits with equation (1) at different latitudes for the focal planes FP3 and FP4, which

suggests that the least squares fit works well for the existing observations.

[14] The fitting function, equation (1), with the known coefficients (c_1 and c_2) is used to fill the observational gaps in emission angle for the radiance recorded by FP3 and FP4 (Figures 2b and 2c). The radiance after filling the observational gaps is shown in Figures 5a and 6a. Figures 5b and 6b are the ratio of fitting residual to the raw radiance for these observational points, which highlights the difference between the observations and the fitting results. Figures 5b and 6b show that the ratio is mostly less than 5% at all latitudes. The fitting residual is further utilized in the following estimates of the uncertainty of filling observational gaps.

[15] However, the same technique does not work for the FP1 observations, because the coverage of observed FP1 radiance is very limited (Figure 2a). For a planetary atmosphere, the thermal radiances at different wave numbers are correlated with each other. Such a correlation can be utilized to estimate the radiance at the unmeasured wave numbers from the radiance at the measured wave numbers [Ingersoll *et al.*, 1975]. Here, we estimate the unmeasured FP1 radiance ($10\text{--}600\text{ cm}^{-1}$) from the FP3 radiance ($600\text{--}1050\text{ cm}^{-1}$), which has much better spatial coverage.

[16] First, we examine the correlation between the FP1 radiances and the FP3 radiances. Our experiments show that there is good correlation between the FP1 radiances and the FP3 radiances with the each latitude bin. Figure 7 displays the scatterplots for these latitude bins with the relatively more simultaneous observations from FP1 and FP3, which are based on Figures 2a and 2b. The good correlation between the FP1 radiances and the FP3 radiances makes it possible to regress the FP1 radiances from the FP3 radiances. Figure 8 shows the ratios of the FP1 radiances to the FP3 radiances (i.e., FP1/FP3). Figure 8 suggests that the ratio FP1/FP3 does not vary significantly with emission angle, probably because the FP1 and FP3 radiances have the same variation with emission angle (Figure 2). Figure 9 further presents the zonal mean value and the standard deviation of FP1/FP3 within each latitude bin in Figure 8. The ratio of the standard deviation (Figure 9b) to the zonal mean value (Figure 9a) is less than 1.5% (Figure 9c), which indicates that there is no significant variation along the direction of emission angle. Figure 8 also shows that there are some banded structures of the radiance ratio FP1/FP3 in

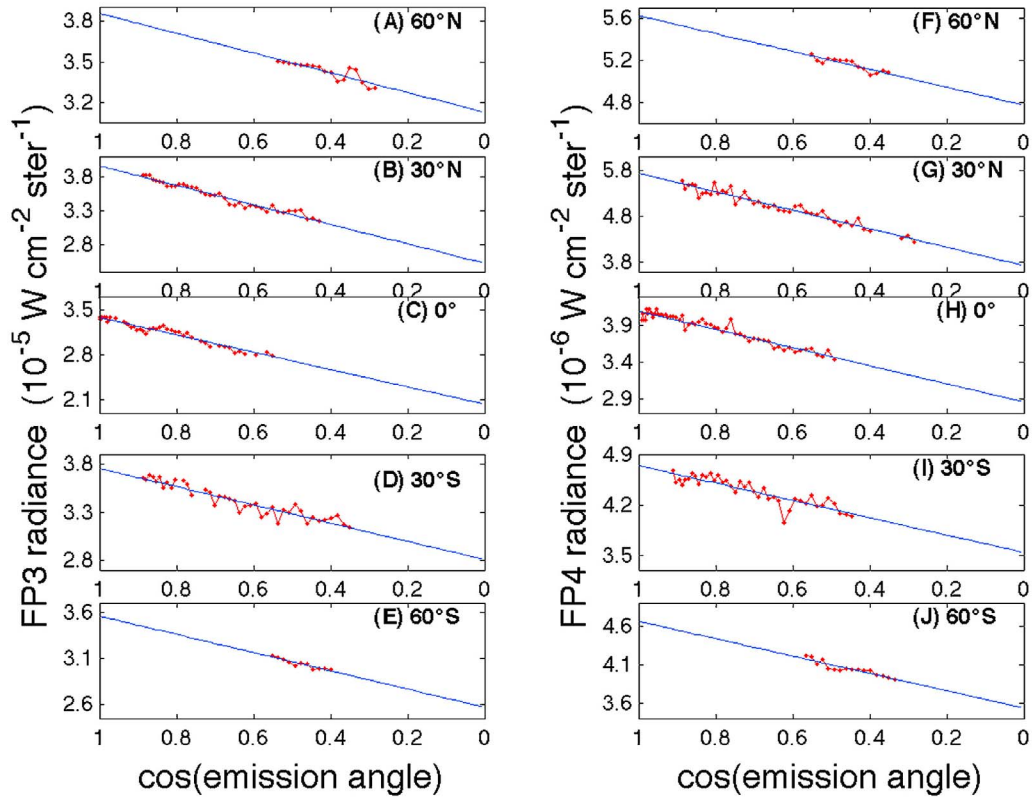


Figure 4. Least squares fitting of the CIRS observations by the focal planes FP3 and FP4 at different latitudes. The red dots are observations, and the blue lines are fitted lines. (a–e) Fits for the FP3 observations at 60°N, 30°N, 0°, 30°S, and 60°S, respectively. (f–j) Same as Figures 4a–4e except for the FP4 observations.

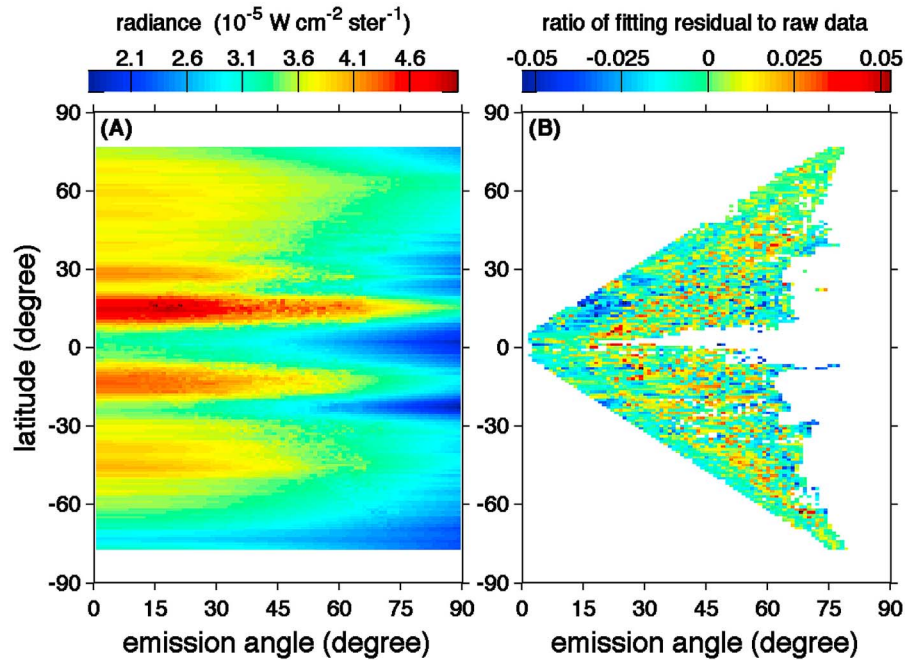


Figure 5. Filling the FP3 observational gaps (Figure 2b) with the interpolation/extrapolation by the least squares fit. (a) Raw FP3 radiance and the fitted data. (b) Ratio of fitted residual to the raw observational data.

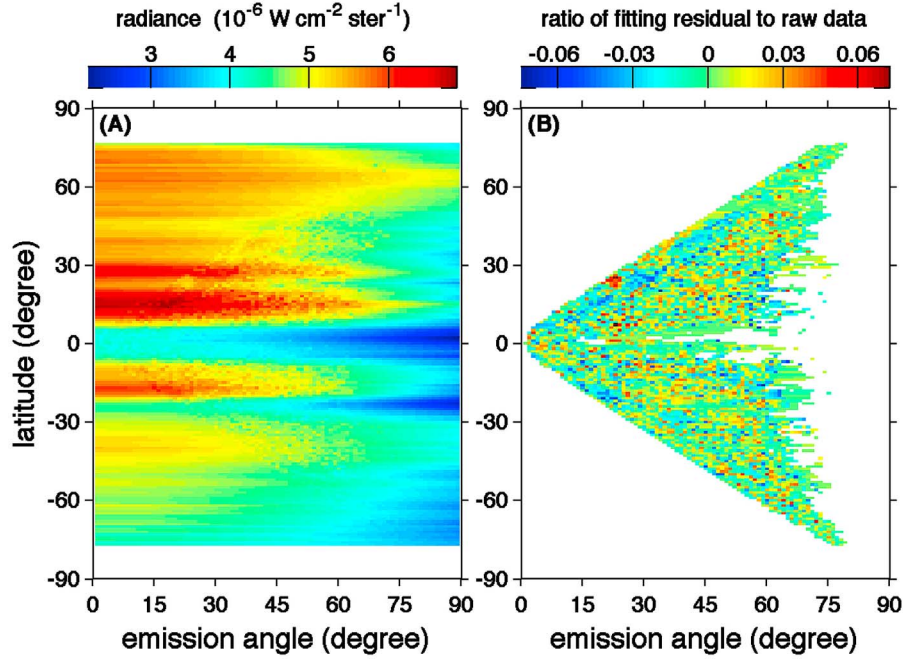


Figure 6. Same as Figure 5 except for the FP4 radiance.

the meridional direction. The banded structures in Figure 8 are correlated to the banded structures in the radiance recorded by FP3 (Figure 5a), which are further related to the banded structures of clouds on Jupiter.

[17] The correlation of the banded structures between the ratio FP1/FP3 (Figure 8) and the FP3 radiance (Figure 5) can be used to explore the FP1 radiance. Figure 10a shows the zonal mean of the FP3 radiance within each latitude bin,

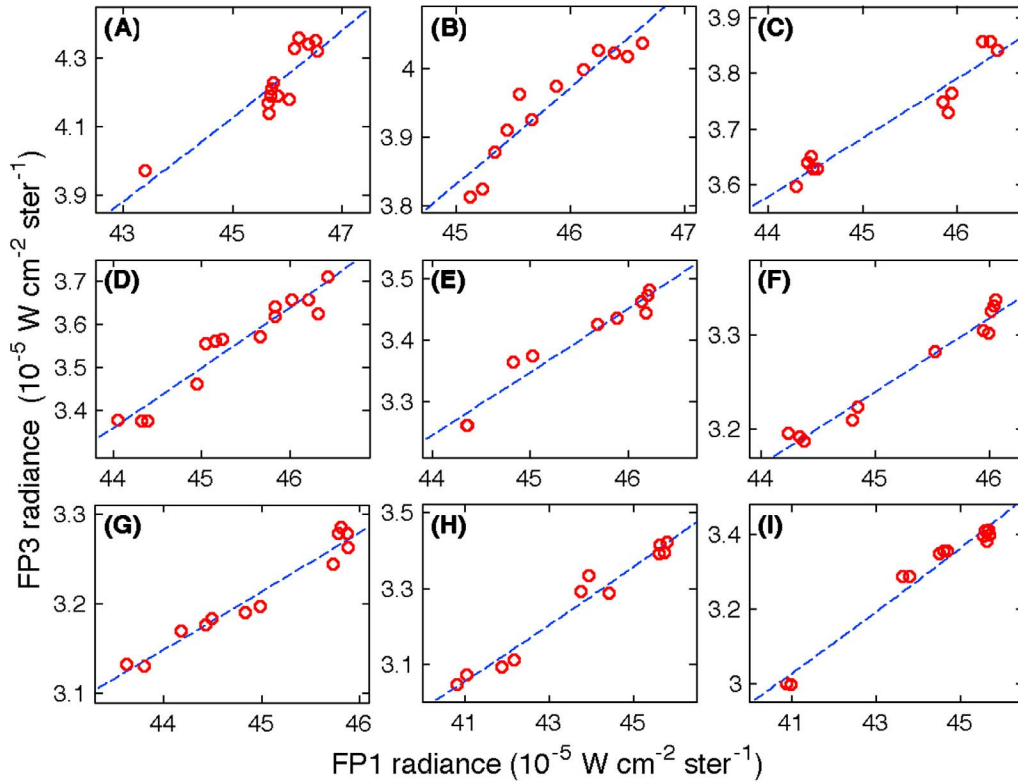


Figure 7. Scatterplots of the FP1 radiances and the FP3 radiances. Only these latitude bins with the number of the simultaneous FP1 and FP3 observations more than 10 are shown. (a–i) Observations at 10°N, 9°N, 8°N, 7°N, 6°N, 3°N, 1°N, 4°S, and 5°S, respectively.

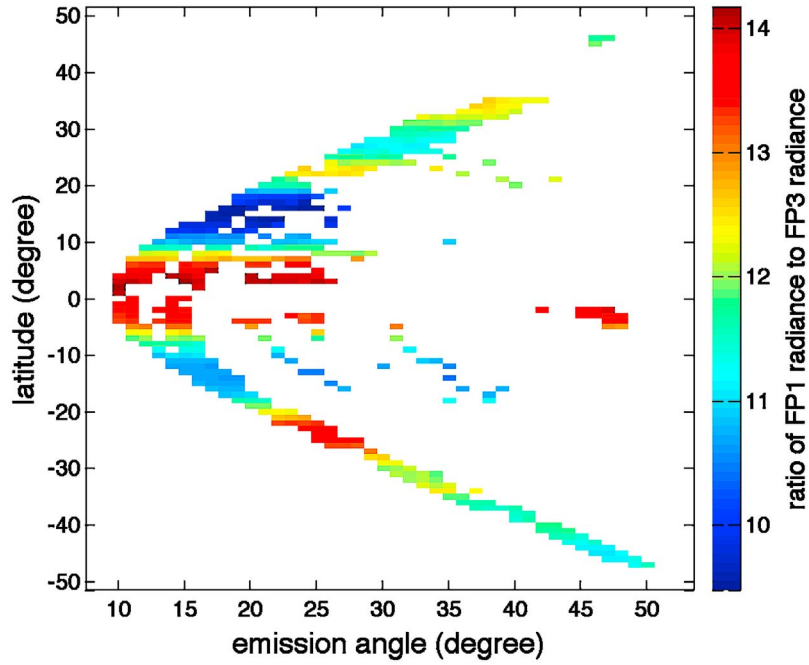


Figure 8. Ratio of wave number-integrated radiance between FP1 and FP3 (FP1/FP3). The plot is for the overlap areas observed by both FP1 and FP3.

which is based on Figure 5a. The structures of the FP3 radiance in the meridional direction have a similar shape as the structures of the ratio FP1/FP3 (Figure 9a), but with an opposite direction, which suggests that the FP3 radiance is

dominant in the ratio FP1/FP3. Therefore, we can utilize the linear regression of the FP3 radiance to estimate the ratio FP1/FP3 in these latitudes where the FP1 observations are not available. Figure 10b shows the comparison between

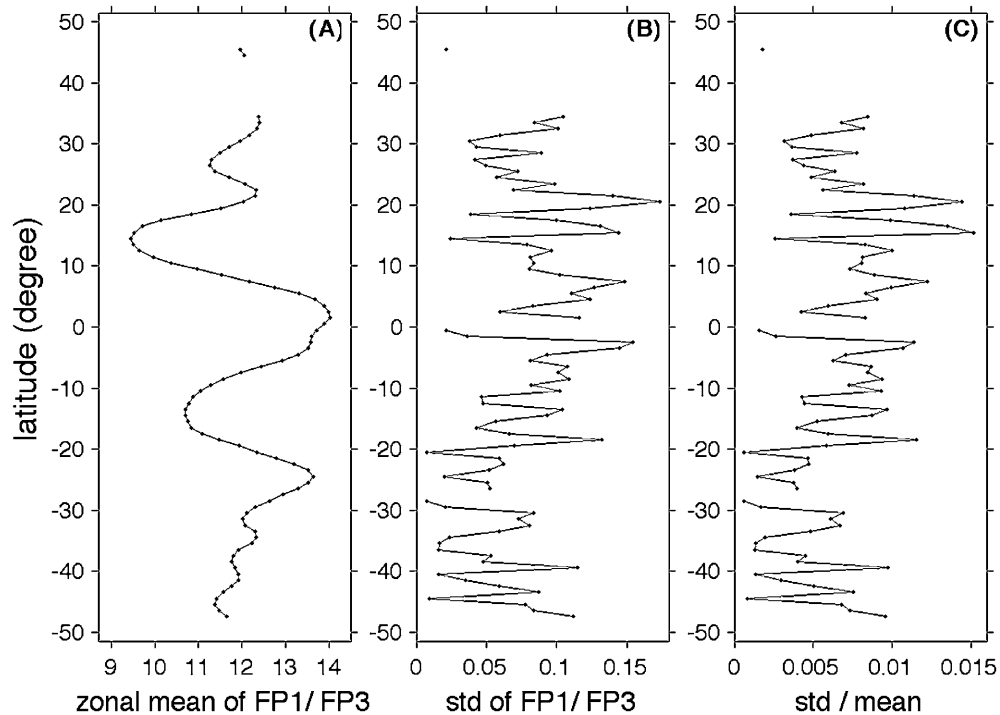


Figure 9. Zonal mean and standard deviation of the radiance ratio FP1/FP3. The zonal mean and standard deviation are along the direction of the emission angle, which is based on the plane of latitude and emission angle shown in Figure 8. (a) Zonal mean of the ratio. (b) Standard deviation (std) of the ratio. (c) Ratio of standard deviation to zonal mean.

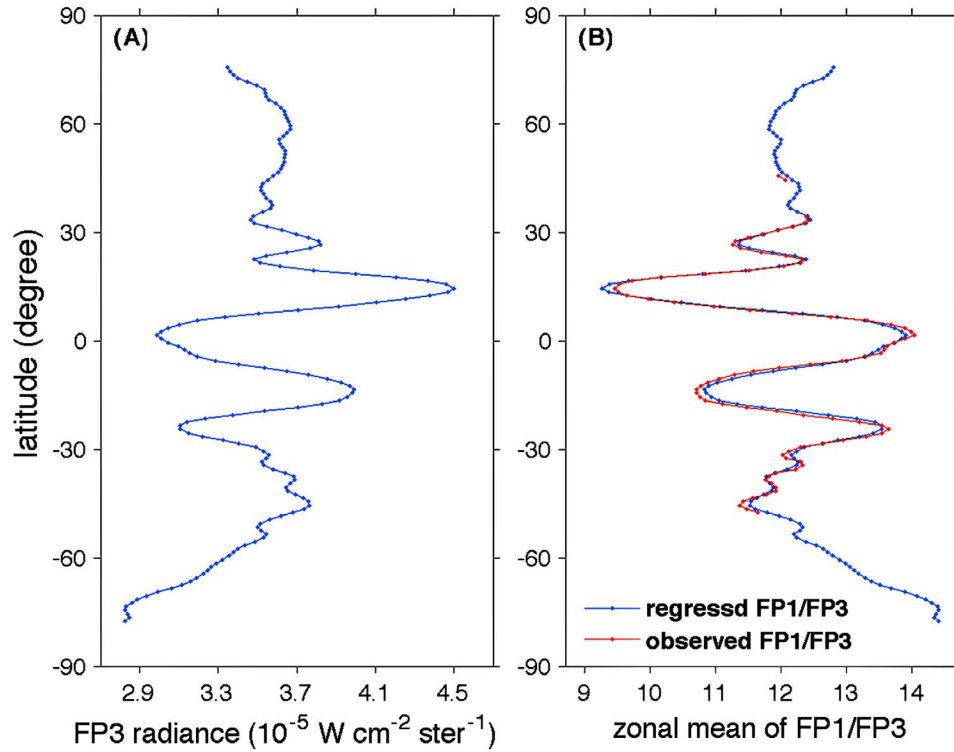


Figure 10. Zonal mean of FP3 radiance and the comparison between the observed ratio FP1/FP3 and the regressed ratio FP1/FP3. (a) Zonal mean of the FP3 radiance. The zonal mean of the FP3 radiance is along the direction of the emission angle, which is based on Figure 5a. (b) Comparison of the ratio FP1/FP3 between the regression and the observation.

the linearly regressed ratio FP1/FP3 and the observed ratio FP1/FP3. The correlation coefficient between the observed FP1/FP3 and the regressed FP1/FP3 is beyond 0.99, which suggests that the linear regression works well.

[18] Based on the fitting results of the FP3 radiance (Figure 5a) and the regressed ratio FP1/FP3 (Figure 10b), we can estimate the FP1 radiance in the plane of latitude and emission angle, which is displayed in Figure 11a. Figure 11b shows the ratio of the regression residual (i.e., difference between the regressed FP1 radiance and the raw FP1 radiance) to the raw FP1 radiance. The ratio in Figure 11b is basically less than 2%, which suggests that the linear regression of the FP3 radiance works well for estimating the FP1 radiance.

[19] After filling the observational gaps in the thermal radiance recorded by the three CIRS focal planes (Figures 5a, 6a, and 11a), we can estimate Jupiter's emitted power. Figure 12 shows the meridional profile of Jupiter's emitted power in the CIRS spectral range ($10\text{--}1430\text{ cm}^{-1}$ to $\sim 7\text{--}1000\text{ }\mu\text{m}$). The uncertainties shown in Figure 12 include three sources: (1) the uncertainty related to the CIRS calibration; (2) the uncertainty related to the filling of observational gaps in the emission angle along the each latitude; and (3) the standard deviation of multiple CIRS observations at different longitudes with the same latitude and emission angle. The first uncertainty source, which is related to the CIRS calibration by removing the radiance of the background, can be estimated by the spectra of deep space [Li *et al.*, 2010]. The second uncertainty source is

related to the filling of observational gaps in FP1 and FP3/4 by the linear regression and the least squares fit, respectively. The method of estimating the uncertainties related to the filling of the observational gaps by FP3/4 by the least squares fit, which is based on the fitting residual (i.e., fitting value-observational data), has been discussed in our previous Saturn paper [Li *et al.*, 2010]. Along each latitude, the standard deviation of the fitting residual at these emission angles with available FP3/FP4 data is used to estimate the uncertainty of the fitting radiances at these emission angles, where the FP3/FP4 raw data are not available (i.e., observational gaps) [Li *et al.*, 2010]. As for the uncertainty related to the regressed FP1 radiance by the linear regression of the FP3 radiance, we use the standard deviation of the regression residual (Figure 11b) to estimate the uncertainty at these latitudes where the FP1 raw data are available. Based on the existing estimates of the FP1 uncertainty, we use a linear interpolation/extrapolation to estimate the FP1 uncertainty in these latitudes where the raw FP1 observations are not available. The second uncertainty, which has a magnitude of 10^{-1} Wm^{-2} , is two orders of magnitude larger than the first uncertainty, which has a magnitude of 10^{-3} Wm^{-2} . The third uncertainty, which is the standard deviation of multiple CIRS measurements at different longitudes with the same latitude and emission angle, has the same magnitude as that of the second uncertainty. Considering that the three uncertainty sources are independent, we combine them by the square root of the sum of the squares of the individual uncertainties [Daley, 1991].

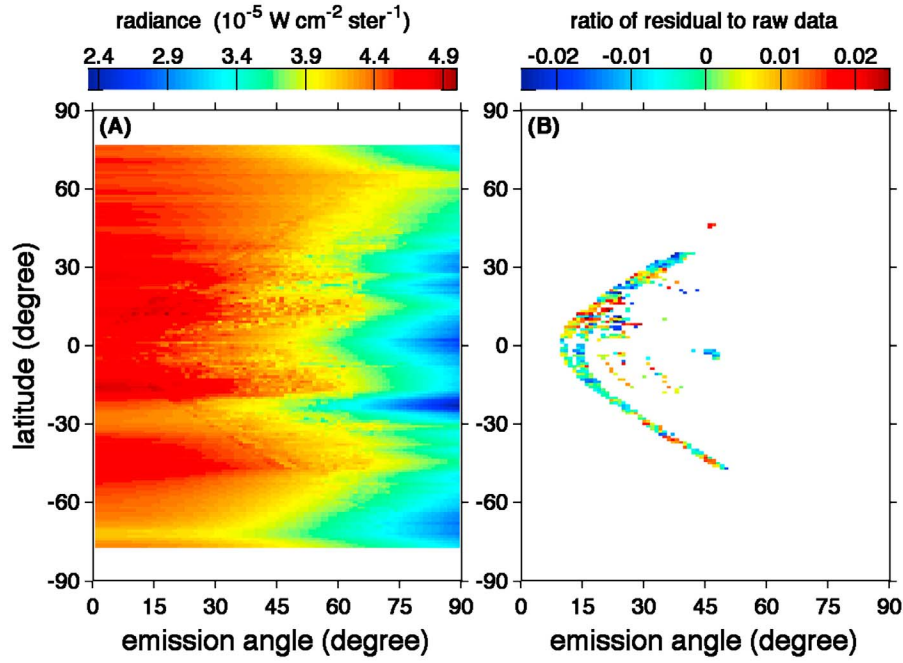


Figure 11. Filling the FP1 observational gaps by the linear regression of the FP3 radiance. (a) Raw FP1 radiance and regressed FP1 data. The regressed FP1 data are based on the FP3 radiance (Figure 5a) and the regressed ratio FP1/FP3 (Figure 10b). (b) Ratio of the regression residual to the raw observational data.

4.2. Emitted Power From the $5\ \mu\text{m}$ Thermal Emission

[20] We use the VIMS observations to measure Jupiter's emitted power around $5\ \mu\text{m}$, which is outside of the spectral

range of the CIRS spectra. The complete $5\ \mu\text{m}$ thermal emission band covers the spectral range $4.4\text{--}5.6\ \mu\text{m}$ [Irwin, 1999], longer than the spectral range of $4.4\text{--}5.1\ \mu\text{m}$ covered

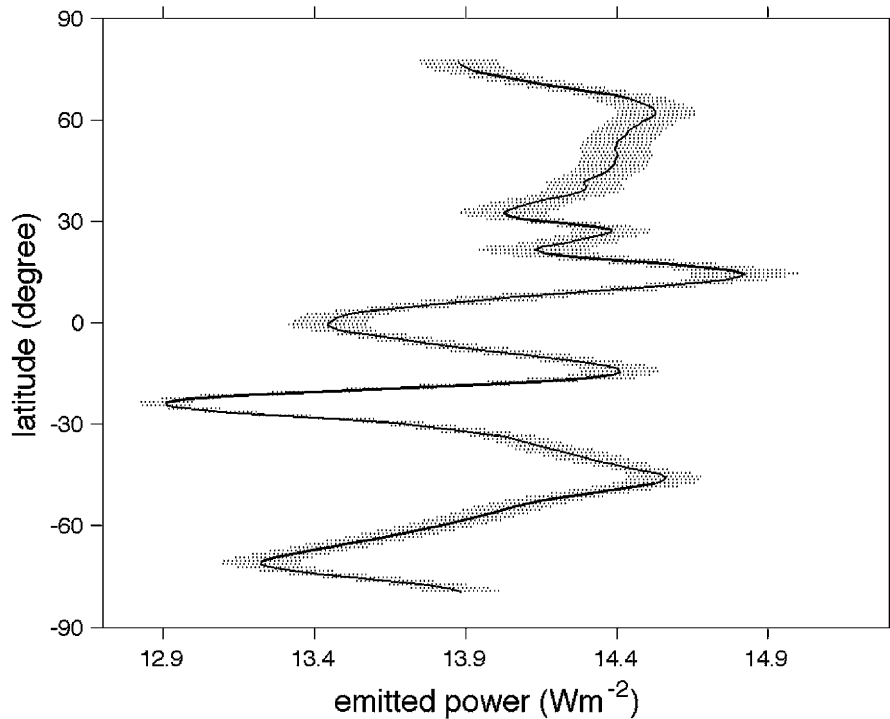


Figure 12. Meridional profile of the emitted power in the wave number range of Cassini/CIRS ($10\text{--}1430\ \text{cm}^{-1}$). The solid line is the profile of emitted power. The stippling represents the uncertainty of emitted power, which includes different uncertainty sources from the calibration, the filling of the observational gaps, and the variation of Jupiter's radiance along the longitude.

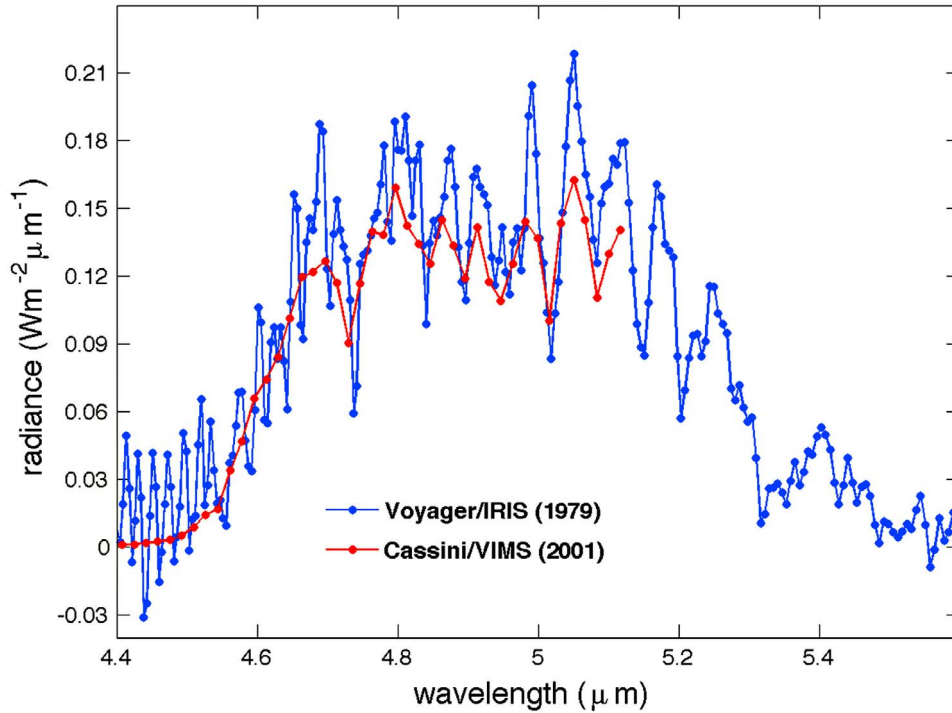


Figure 13. Comparison of the global-average $5 \mu\text{m}$ spectra between Voyager/IRIS and Cassini/VIMS. The spectral resolutions are ~ 0.005 and $\sim 0.017 \mu\text{m}$ for Voyager/IRIS and Cassini/VIMS, respectively.

by VIMS. To derive the power over the full $5 \mu\text{m}$ thermal band, we first integrate VIMS spectra over the spectral range of $4.4\text{--}5.1 \mu\text{m}$. We then explore the ratio of wavelength-integrated radiance between the VIMS spectral range (i.e., $4.4\text{--}5.1 \mu\text{m}$) and the complete spectral range (i.e., $4.4\text{--}5.6 \mu\text{m}$). Finally, the VIMS observations and the radiance ratio between $4.4\text{--}5.1 \mu\text{m}$ and $4.4\text{--}5.6 \mu\text{m}$ are combined together to estimate the total emitted power from the $5 \mu\text{m}$ thermal band.

[21] Our examination (not shown) and the previous study [Roos-Serote and Irwin, 2006] both suggest that the magnitude of Jupiter's $5 \mu\text{m}$ spectra varies with time and space, but the shape of the spectra basically remains unchanged. Therefore, it is reasonable to assume that the ratio of wavelength-integrated radiance between the VIMS spectral range (i.e., $4.4\text{--}5.1 \mu\text{m}$) and the complete spectral range (i.e., $4.4\text{--}5.6 \mu\text{m}$) does not change significantly with time and space on Jupiter. Therefore, we can estimate the total $5 \mu\text{m}$ thermal emission over $4.4\text{--}5.6 \mu\text{m}$ from the known VIMS measurements over $4.4\text{--}5.1 \mu\text{m}$ if we know the ratio between them.

[22] We use the complete $5 \mu\text{m}$ spectra from the infrared interferometer spectrometer (IRIS) on Voyager to get the ratio of wavelength-integrated radiance between the VIMS spectral range ($4.4\text{--}5.1 \mu\text{m}$) and the complete spectral range ($4.4\text{--}5.6 \mu\text{m}$). Figure 13 shows the comparison of the global-average spectrum between Cassini/VIMS and Voyager/IRIS, which suggests that the $5 \mu\text{m}$ spectra from IRIS and VIMS have basically the same structures. It should be mentioned that some fine spectral structures shown in the IRIS spectrum do not show in the VIMS spectrum, because the spectral resolution is much higher in IRIS ($\sim 0.005 \mu\text{m}$) than in VIMS ($\sim 0.017 \mu\text{m}$). We use the complete IRIS spectrum to compute the ratio of wavelength-integrated

radiance between the VIMS spectral range (i.e., $4.4\text{--}5.1 \mu\text{m}$) and the complete spectral range (i.e., $4.4\text{--}5.6 \mu\text{m}$), which has a value of 0.711.

[23] We divide the wavelength-integrated radiance from the VIMS measurements ($4.4\text{--}5.1 \mu\text{m}$) by the ratio to estimate the total emitted power from the thermal emission around $5 \mu\text{m}$, which is shown in Figure 14. The uncertainty (error bar) shown in Figure 14 is based on two factors: (1) the absolute calibration error and (2) the standard deviation of multiple VIMS measurements within each latitude bin (1°) and within the 2 day period (7–8 January 2001 with 11 global observations). For the first factor, we refer to the study by Buratti *et al.* [2010], in which the absolute error of the VIMS data was estimated to be 5–10% of the recorded VIMS radiance. Here, we use the average value (i.e., 7.5%) to represent the absolute calibration error. The second uncertainty factor, which is related to the longitudinal and temporal variation of the $5 \mu\text{m}$ radiance, can reach $\sim 50\%$ of the total $5 \mu\text{m}$ radiance at some latitudes. Figure 14 shows the strongest $5 \mu\text{m}$ thermal emission exists in the latitude band around 15° in the two hemispheres. The global-average emitted power of the $5 \mu\text{m}$ thermal emission is $0.09 \pm 0.01 \text{ Wm}^{-2}$, which is $0.7 \pm 0.1\%$ of Jupiter's total emitted power of $14.10 \pm 0.02 \text{ Wm}^{-2}$ (section 4.3). The strongest $5 \mu\text{m}$ thermal emission around 15°N can reach $1.9 \pm 0.6\%$ of Jupiter's total emitted power at this latitude.

4.3. Total Emitted Power of Jupiter

[24] Thermal radiance outside the spectral range of CIRS ($10\text{--}1430 \text{ cm}^{-1}$) and the $5 \mu\text{m}$ emission band ($1800\text{--}2250 \text{ cm}^{-1}$) has negligible contribution to the total emitted power of Jupiter [Conrath *et al.*, 1989], and so it is not considered in this study. Thus, we estimate Jupiter's emitted

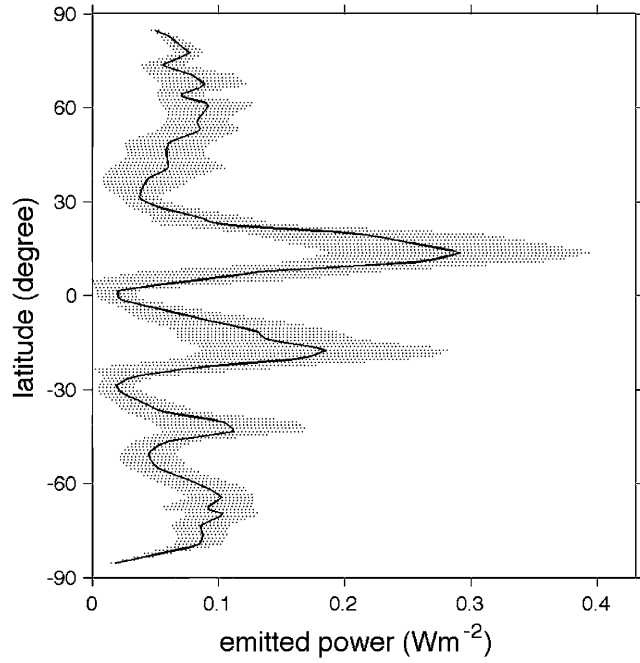


Figure 14. Meridional profile of the emitted power from the $5\ \mu\text{m}$ thermal band ($1800\text{--}2250\ \text{cm}^{-1} \sim 4.4\text{--}5.6\ \mu\text{m}$). The solid line is the profile of emitted power, and the stippling represents the uncertainty of measurements.

power and effective temperature at different latitudes by simply adding the values in Figures 12 and 14. The corresponding uncertainty is estimated by the square root of the sum of the squares of the uncertainties from the CIRS measurements (Figure 12) and the VIMS measurements (Figure 14), because the two uncertainties are independent [Bevington and Robinson, 1992]. The meridional distribution of Jupiter's total emitted power is displayed in Figure 15, which shows an asymmetry of emitted power/effective temperature between the northern and southern hemispheres. There are very limited observations in the polar region beyond 77° in the Jupiter flyby mission by Cassini, so we cannot estimate the emitted power in the polar region. Assuming the emitted power at the unmeasured polar region ($77\text{--}90^\circ\text{S/N}$) has the same value and uncertainty as the value at 76°S/N , we can evaluate the hemispheric average of emitted power and the corresponding effective temperature, which are shown in Table 1. Table 1 shows that the emitted power and effective temperature are higher in the northern hemisphere (NH) than in the southern hemisphere (SH) by $0.41 \pm 0.04\ \text{Wm}^{-2}$ ($3.0 \pm 0.3\%$) and $0.92 \pm 0.09\ \text{K}$ ($0.7 \pm 0.1\%$), respectively.

[25] In addition to the asymmetry between the two hemispheres, there are some relatively small-scale oscillations of emitted power/effective temperature shown in Figure 15, which are related to the temperature structures in Jupiter's troposphere. The tropical temperature shown in Figure 15 was retrieved from the Cassini/CIRS spectra at a wave number range of $600\text{--}690\ \text{cm}^{-1}$ [Flasar et al., 2004b; Simon-Miller et al., 2006]. Figure 16 shows that the profile of effective temperature sits between the 330 mbar profile and the 420 mbar profile of atmospheric temperature. Therefore,

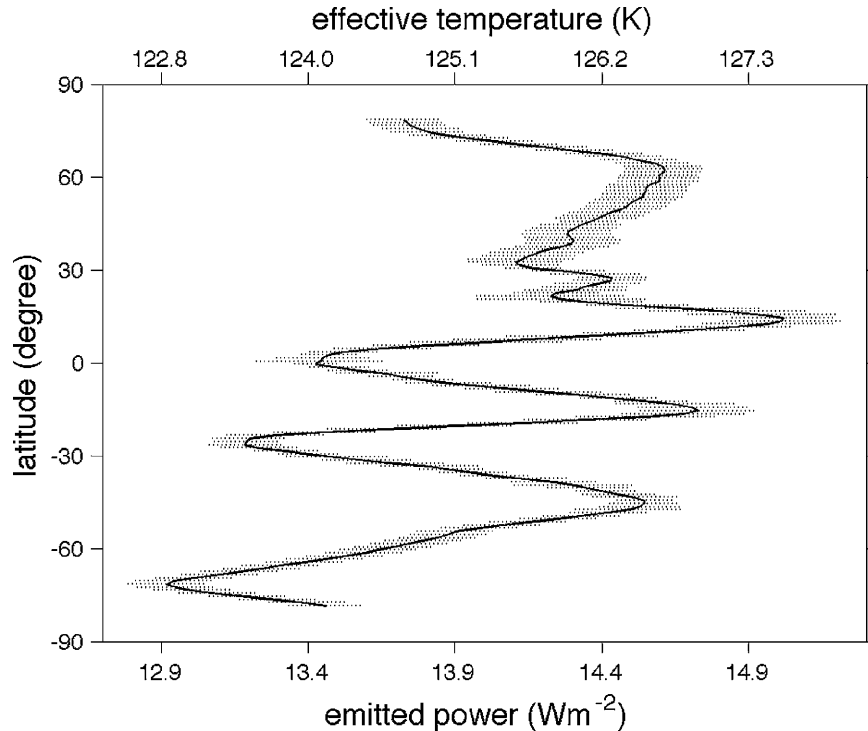


Figure 15. Meridional profile of Jupiter's emitted power and effective temperature. The solid line is the profile of emitted power and effective temperature, and the stippling represents the uncertainty of measurements.

Table 1. Hemispheric Average of the Emitted Power and Effective Temperature of Jupiter During the Cassini Epoch (2000–2001)

	NH Average	SH Average
Emitted power (W/m^2)	14.30	13.89
Uncertainty (W/m^2)	± 0.03	± 0.02
Effective temperature (K)	126.03	125.11
Uncertainty (K)	± 0.07	± 0.05

the weighting function of the outgoing thermal radiance peaks around the two pressure levels. Figure 16 also shows that the structures of effective temperature in the two hemispheres are more similar to the temperature profiles of the shallower atmosphere (170–270 mbar), suggesting that they also contribute to Jupiter’s outgoing thermal radiance. Figure 16 suggests that Jupiter’s emitted power (i.e., effective temperature) is related to the atmospheric temperature. However, the asymmetry between the two hemispheres, which is shown in Jupiter’s emitted power (Figure 15), does not significantly show in the atmospheric temperature (Figure 16). Therefore, we suggest that there are other mechanisms (e.g., spatial distribution of cloud/haze) possibly influencing the meridional distribution of Jupiter’s emitted power.

[26] The meridional distribution of emitted power was also measured in some previous studies [Pirraglia, 1984; Ingersoll, 1990]. Pirraglia [1984] measured the meridional profile of emitted power with the flyby observations by Voyager 1. The meridional profile in the paper by Ingersoll [1990] was combined from the Voyager observations in the

low and middle latitudes [Pirraglia, 1984] and the Pioneer observations in the high latitudes [Ingersoll *et al.*, 1975]. There are no multiple focal panels in the Voyager/IRIS [Hanel *et al.*, 1980], and the observations recorded by the Voyager/IRIS have very limited coverage in the plane of latitude and emission angle [Hanel *et al.*, 1981; Pirraglia, 1984]. Therefore, the method we used in this study for computing Jupiter’s emitted power from the Cassini/CIRS observations (i.e., interpolating the FP3/FP4 observations and regressing the FP1 observations from the FP3/FP4 observations) does not work for the Voyager/IRIS observations. Instead, a method, in which the gaps in the emission angle are considered by the radiative-transfer calculations with the given atmospheric temperature and opacity profiles [Hanel *et al.*, 1981, 1983], was used in the analysis of the Voyager observations [Pirraglia, 1984; Ingersoll, 1990]. The comparison between the limited observations and the radiative-transfer calculations [Pirraglia, 1984] suggests that the above method also works well under the condition of lacking the necessary coverage of latitude and emission angle.

[27] Figure 17 displays the profile of emitted power from the Voyager observations in 1979, compared to the profile from the Cassini observations in 2000–2001. The uncertainty in the Voyager profile comes from the measurements by Pirraglia [1984]. In the study by Pirraglia [1984], the standard deviation of multiple measurements within each latitude bin, corresponding to the zonal mean emitted power along the longitude direction, was taken as the uncertainty. Such an estimate of uncertainty does not account for the uncertainty related to the calibration of the Voyager/IRIS,

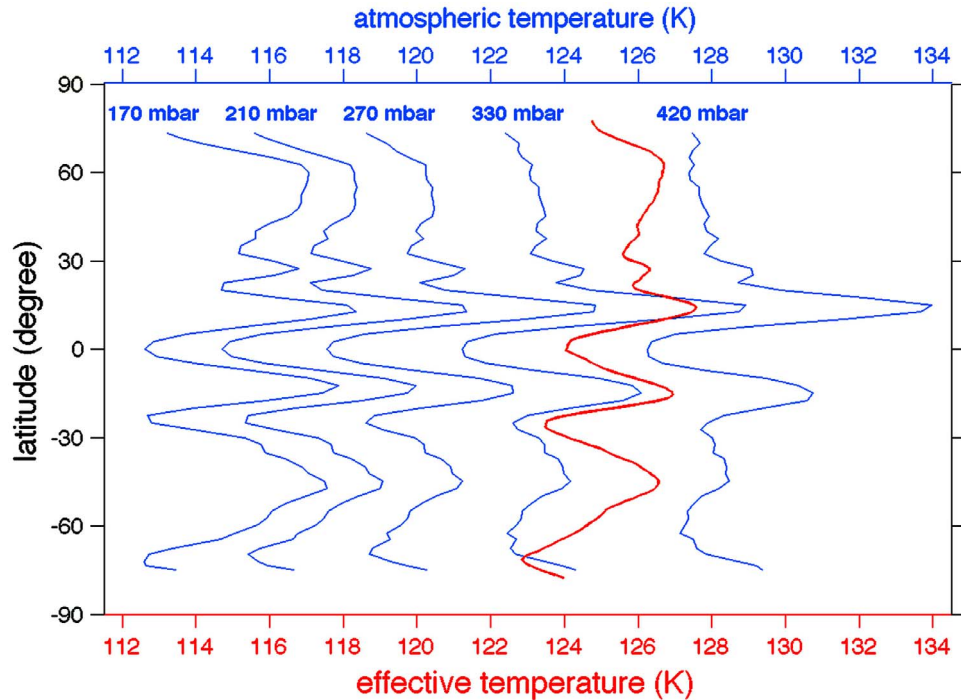


Figure 16. Comparison between the effective temperature and the atmospheric temperature in the Cassini epoch. The red line is Jupiter’s effective temperature during the period of October 2000 to March 2001. The blue lines are the atmospheric temperatures of Jupiter in roughly the same period [Simon-Miller *et al.*, 2006].

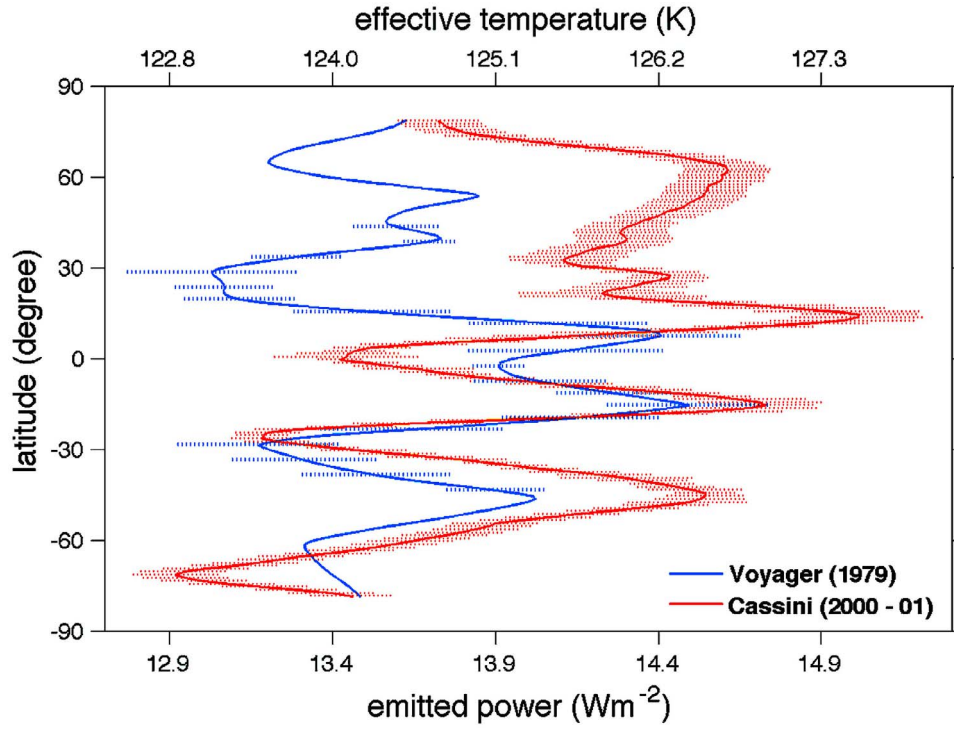


Figure 17. Comparison of meridional profile of the emitted power and effective temperature between the Voyager epoch and the Cassini epoch. The Voyager profile is mainly based on the Voyager observations in 1979 [Pirraglia, 1984]. The Voyager profile in the high latitudes comes from the Pioneer observations [Ingersoll *et al.*, 1975; Ingersoll, 1990]. The uncertainty of the Voyager profile comes from the estimates by Pirraglia [1984]. The Cassini profile comes from Figure 15.

which has a magnitude 10^{-2} Wm^{-2} [Hanel *et al.*, 1981]. However, the uncertainty due to the calibration is approximately one order of magnitude smaller than the standard deviation shown in Figure 17 ($\sim 10^{-1} \text{ Wm}^{-2}$). Therefore, it does not significantly vary the uncertainty estimated by Pirraglia [1984]. The uncertainty of the Cassini profile is based on more uncertainty sources from the CIRS measurements (section 4.1) and the VIMS measurements (section 4.2). The latitude bin in the Cassini measurements (i.e., 1°) is narrower than the latitude bin in the Voyager/IRIS measurements (i.e., $4\text{--}5^\circ$) [Pirraglia, 1984]. The standard deviation of multiple measurements within each latitude bin in the previous study [Pirraglia, 1984] is roughly three times of that in our study. Figure 17 shows that the total uncertainty considering more sources in our study is still smaller than the uncertainty in the Voyager measurements by Pirraglia [1984].

[28] Figure 17 shows significant difference between the two profiles, which is larger than the measurement uncertainty at most latitudes. In particular, the asymmetry of emitted power/effective temperature between the two hemispheres, which is evident in the Cassini observations, does not appear in the Voyager measurements. Table 2 shows the comparison of global-average emitted power and effective temperature between the current measurements by Cassini and the previous measurements by Voyager 1 [Hanel *et al.*, 1981]. In addition, the global-average value from the measurements by Pioneer [Ingersoll *et al.*, 1975], which have relatively larger uncertainty, is also listed in Table 2. The differences of emitted power and effective temperature between Voyager and Cassini are larger than the corresponding uncertainties. From the Voyager epoch to the Cassini epoch, the global-average emitted power and effective temperature increased by $0.51 \pm 0.14 \text{ Wm}^{-2}$ ($3.8 \pm 1.0\%$) and $1.17 \pm 0.31 \text{ K}$ ($0.9 \pm 0.2\%$), respectively. When exploring

Table 2. Global-Average Values of Emitted Power and Effective Temperature by Pioneer, Voyager, and Cassini^a

	Pioneer 10/11	Voyager 1	Cassini
Time	December 1973 and December 1974	March 1979	October 2000 to March 2001
Solar longitude	16.8°	169.5°	110.5°
Subsolar latitude	0.6°N	0.5°N	2.9°N
Emitted power (W/m^2)	13.8	13.59	14.10
Uncertainty (W/m^2)	± 1.4	± 0.14	± 0.02
Effective temperature (K)	125	124.4	125.57
Uncertainty (K)	± 3	± 0.3	± 0.05

^aThe global values of Pioneer come from the study by Ingersoll *et al.* [1975]. The global values of Voyager 1 come from the study by Hanel *et al.* [1981].

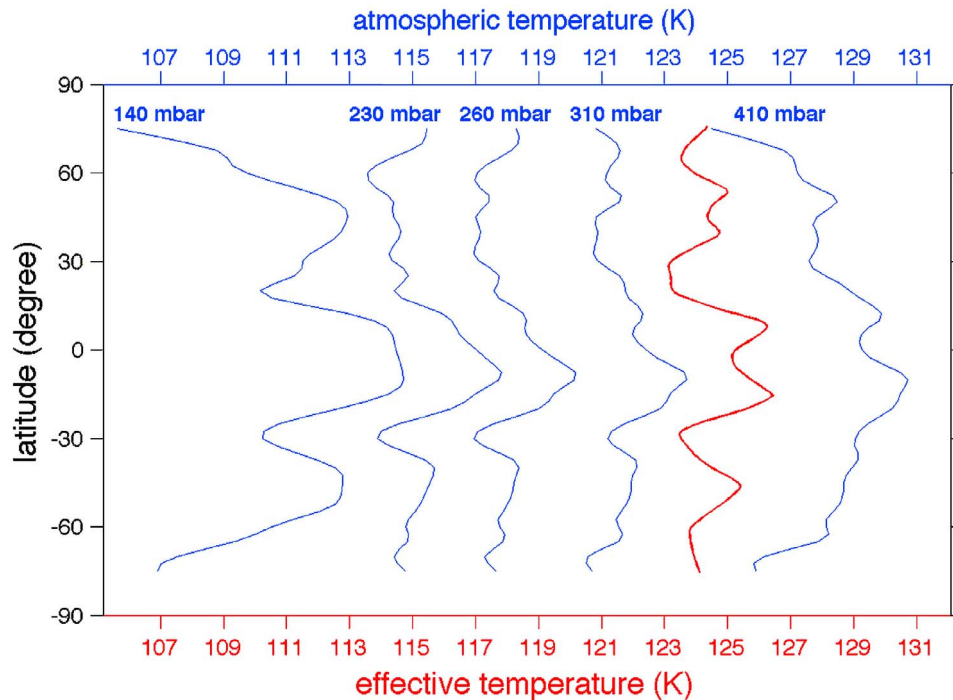


Figure 18. Comparison between the effective temperature and the atmospheric temperature in the Voyager epoch. The profile of Jupiter's effective temperature (i.e., red line) comes from Figure 17. The profiles of Jupiter's atmospheric temperature (i.e., blue lines) come from a previous study by *Simon-Miller et al.* [2006].

the temporal variation of the global values between the two epochs, the known uncertainty sources including data calibration are considered in the measurements by Voyager [*Hanel et al.*, 1981] and by Cassini (this study). It should be mentioned that it is still possible that there are unknown calibration issues affecting the measurements in the two epochs.

[29] Why did Jupiter's emitted power and effective temperature change with time? We first examine if there is any variation in the altitude of the atmospheric layers involving the outgoing thermal radiance on Jupiter. Figure 18 displays the comparison of the effective temperature and the atmospheric temperature in the Voyager epoch. The tropospheric temperature shown in Figure 18 comes from the retrievals of the Voyager/IRIS spectra in the spectral intervals 320–430 and 520–600 cm^{-1} [*Simon-Miller et al.*, 2006]. The comparison shows that the profile of effective temperature sits between the 310 mbar profile and 410 mbar profile of atmospheric temperature, which suggests that the atmospheric layers around the two pressure levels contribute significantly to the outgoing thermal radiance on Jupiter. The difference between the profile of effective temperature and the profiles of atmospheric temperature at 310 and 410 mbar suggests that the atmospheric layers at other pressure levels also contribute to Jupiter's outgoing thermal radiance. The comparison between Figure 16 (Cassini profiles) and Figure 18 (Voyager profiles) further suggests that the peak of the weighting function of the outgoing thermal radiance did not change significantly from the Voyager epoch to the Cassini epoch. Therefore, we rule out the varying weighting function of outgoing thermal radiance as the main physics behind the temporal variation of emitted power/effective temperature shown in Figure 17.

[30] Jupiter's emitted power is directly related to the temperature of atmospheric layers, so the temporal variation of emitted power (Figure 17) means that there is the corresponding variation in the atmosphere temperature. Figure 19 is the comparison of Jupiter's temperature in the upper troposphere between the Voyager epoch and the Cassini epoch. Figure 19 suggests that the warming of the atmospheric layers around 200 mbar contributes to the increased emitted power in the latitude bands outside of the equatorial region (i.e., 10°N–10°S) (Figure 17). In addition, the cooling of the atmospheric layers between 50 and 500 mbar in the equatorial region explains the decreased emitted power in that region from the Voyager epoch to the Cassini epoch. Much of this cooling was noted immediately after the Voyager encounters [*Orton et al.*, 1994] and was even detectable between Voyagers 1 and 2.

[31] The temporal variation of the atmospheric temperature provides one explanation for the varied emitted power from Voyager to Cassini. The continuous observations from 1980 to 1993 [*Orton et al.*, 1994] and from 1979 to 2001 [*Simon-Miller et al.*, 2006] suggest that Jupiter's tropospheric temperature changed gradually from the Voyager epoch to the Cassini epoch (i.e., ~ 2 Jovian years), with little obvious seasonal or short-term variation. In other words, there is probably long-term variation (e.g., interannual variation) in Jupiter's tropospheric temperature. As a result, Jupiter's emitted power and effective temperature, which are mainly determined by Jupiter's tropospheric temperature, probably have a corresponding inter-annual variability existing in the temporal variation shown in Figure 18.

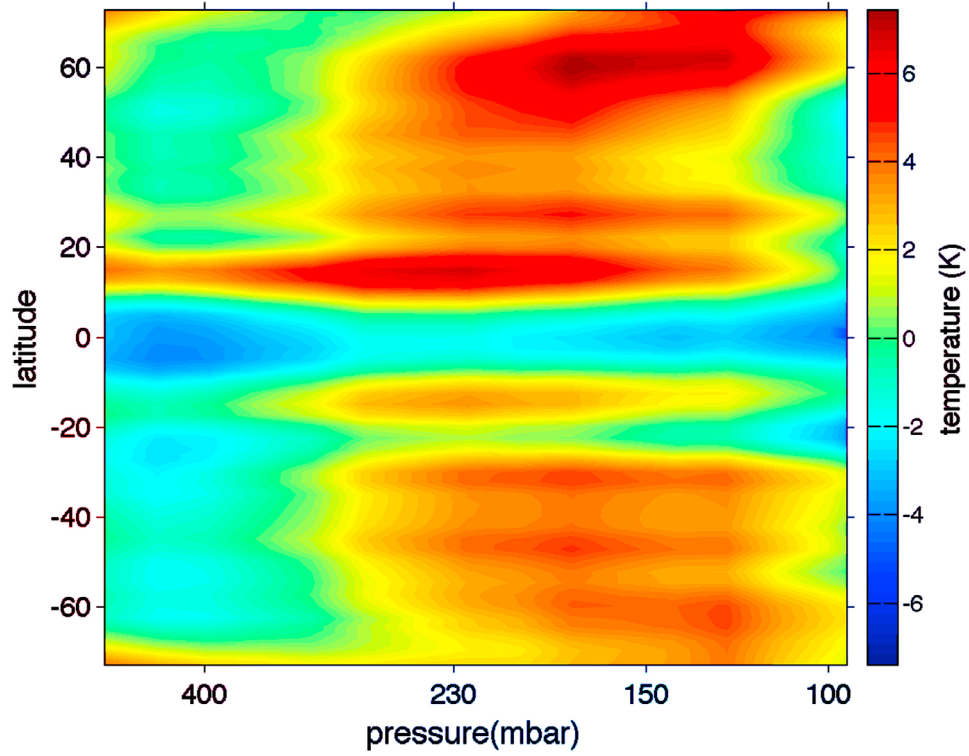


Figure 19. Temporal variation of the atmospheric temperature from the Voyager epoch to the Cassini epoch as a function of atmospheric pressure and latitude. There is no available Cassini/CIRS-retrieved temperature for the atmospheric layers deeper than 430 mbar due to the limitation of the content information in Jupiter's spectra.

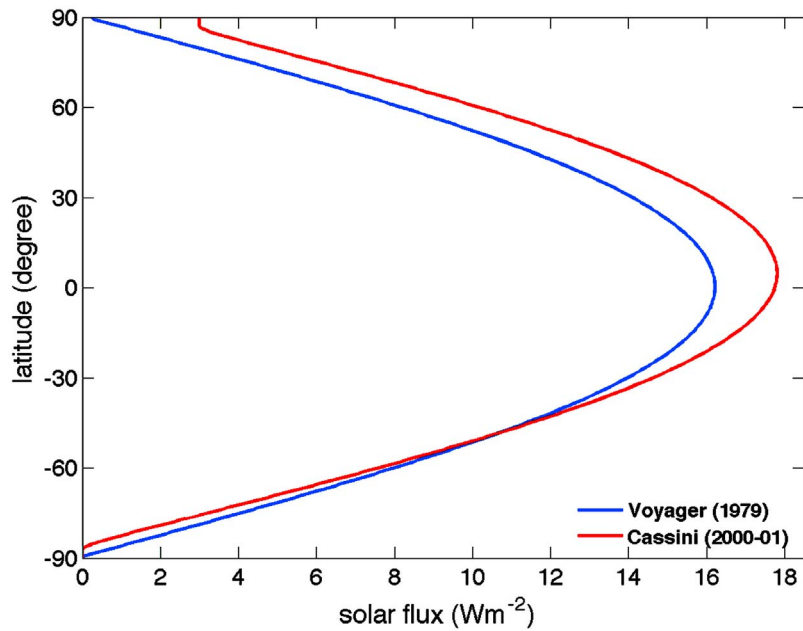


Figure 20. Comparison of solar flux at the top of Jupiter's atmosphere between the Voyager epoch and the Cassini epoch. The meridional profile of solar flux is determined by the four factors (i.e., obliquity, eccentricity, incidence angle, and incidence time). The effects due to rings' shadowing and Jupiter's precession are too small to be considered in the computation.

[32] Next, we explore the physics behind the temporal variation of the atmospheric temperature and hence the temporal variation of emitted power from the Voyager epoch to the Cassini epoch. First, let us take a look at the solar flux on Jupiter. The average solar longitude of the Voyager observations was 174.5° . The average solar longitude of the Cassini mission in 2000–2001 was 110.5° . Figure 20 shows the seasonal variation of solar flux from the Voyager epoch (i.e., solar longitude $\sim 174.5^\circ$; northern late summer) to the Cassini epoch (i.e., solar longitude $\sim 110.5^\circ$; northern early summer). On Earth, the temporal variation in the meridional distribution of solar flux is the main driver of the seasonal variation of atmospheric temperature. However, the temporal variation in the meridional distribution of solar flux (Figure 19) is probably not the main driver for the temporal variation of atmospheric temperature (Figure 18), mainly because of the relatively small temporal variation of solar flux on Jupiter due to its small orbital obliquity (i.e., 3°). The comparison between Figures 19 and 20 also suggests that there is no direct relationship between the varying solar flux and the temporal variation of atmospheric temperature. First, the increased solar flux in the NH cannot explain the cooling of atmospheric temperature between 50 and 100 mbar (Figure 19). Second, the decreased solar flux in the high latitudes of the SH cannot explain the increased atmospheric temperature around 200 mbar in the same latitudes. Finally, the smooth profile of solar flux and its temporal variation cannot explain the temporal variation of atmospheric temperature at the small-length scale (i.e., a few latitude degrees) in Figure 19. Therefore, the above analyses suggest that there are probably other mechanisms to drive the temporal variation of tropospheric temperature, emitted power, and effective temperature on Jupiter.

[33] The second possible driving force is the decadal-scale variability of cloud cover on Jupiter [Baines *et al.*, 2007]. The variation of cloud cover will redistribute the solar flux on Jupiter and hence modify the thermal structure and the related emitted power. The third possible driving force is wave activity. The atmospheric waves, which are thought to be the mechanism of the quasi-biennial oscillation [Lindzen and Holton, 1968; Baldwin *et al.*, 2001] and sudden warming [Baldwin and Dunkerton, 1989] in the stratosphere of Earth, can also drive the large-scale variation of temperature and wind fields. Likewise, such a mechanism works for the quasi-quadrennial oscillation on Jupiter [Leovy *et al.*, 1991; Orton *et al.*, 1991; Friedson, 1999; Li and Read, 2000]. The wave-driven oscillations mainly exist in the stratospheres of planetary atmospheres, but we cannot rule out the roles of waves [Porco *et al.*, 2003; Li *et al.*, 2006] and other dynamical processes (e.g., vortices, eddies, and storms) in modifying the large-scale thermal structure in the troposphere of Jupiter.

5. Conclusion and Discussion

[34] Jupiter's spectra recorded by Cassini CIRS and VIMS during the period of 2000–2001 are systematically analyzed to evaluate the emitted power and effective temperature of Jupiter. Our analysis indicates that, in the Cassini epoch, the global-average emitted power and effective temperature were $14.10 \pm 0.03 \text{ W m}^{-2}$ and $125.57 \pm 0.07 \text{ K}$, respectively. Jupiter's $5 \mu\text{m}$ thermal emission, which is produced

near the 6 bar level and is modulated by relatively deep cloud layers of ammonia hydrosulfide (i.e., $\sim 1\text{--}3 \text{ bar}$), contributes $\sim 0.7 \pm 0.1\%$ to the total emitted power at the global scale. However, the strongest $5\text{-}\mu\text{m}$ thermal emission around 15°N can reach $\sim 1.9 \pm 0.6\%$ of the total emitted power at that latitude. The emitted power was $3.0 \pm 0.3\%$ higher in the NH than in the SH in the Cassini epoch. Such an asymmetry was not present in the Voyager epoch. Furthermore, Jupiter's emitted power increased $\sim 3.8 \pm 1.0\%$ on a global scale from the Voyager epoch to the Cassini epoch.

[35] Our analyses of atmospheric temperature reveal that the temporal variation of emitted power from the Voyager epoch to the Cassini epoch is mainly due to the warming of atmospheric layers around 200 mbar. The mechanisms of the temporal variation of tropospheric temperature and the related emitted power are unclear. We suggest that the temporal variation of cloud cover and some dynamical processes (e.g., waves, vortices, eddies, and storms) are possible mechanisms to drive the temporal variation of the large-scale atmospheric temperature and hence the temporal variation of emitted power on Jupiter, but long-term continuous observations and more theoretical studies are needed to understand the temporal variation in the Jovian atmosphere. On the other hand, the varying emitted power implies that the energy budget and its meridional distribution probably change with time on Jupiter. The potentially varying energy budget will inversely modify the atmospheric structures, large-scale circulation, and dynamical processes. Therefore, the coupling between the varying energy budget and the evolving atmospheric structure/dynamics, which makes Jupiter's atmospheric system very complicated, should be considered in the future exploration.

[36] Our follow-up studies, which are based on observations of reflected solar radiance in the visible band from the ISS and VIMS on Cassini, will help us measure the absorbed solar radiance on Jupiter during the Cassini epoch. Combining measurements of the emitted thermal radiance and absorbed solar energy, we can determine the energy budget and hence internal heat in the Cassini epoch. As well, Cassini measurements can be compared with previous measurements (i.e., Pioneer and Voyager) to detect and characterize the temporal variation of the energy budget and internal heat on Jupiter.

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