Temperature Variability in Titan's Upper Atmosphere: The Role of Wave Dissipation

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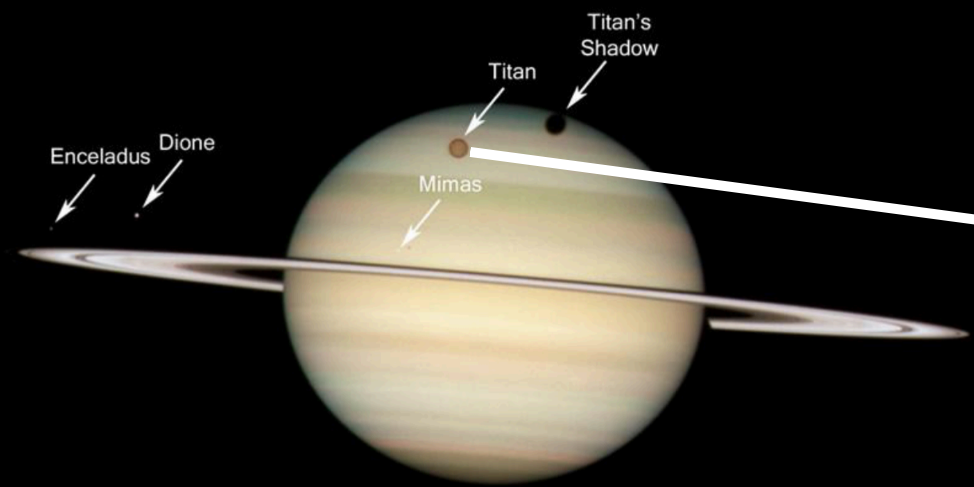
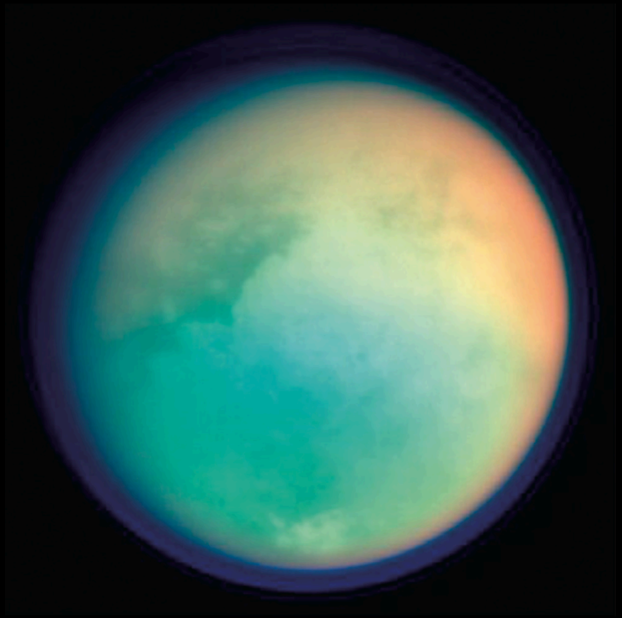
Outline

- ☛ Introduction
- ☛ Linear Gravity Wave Model
- ☛ Results
- ☛ Conclusions
- ☛ References

Saturnian System

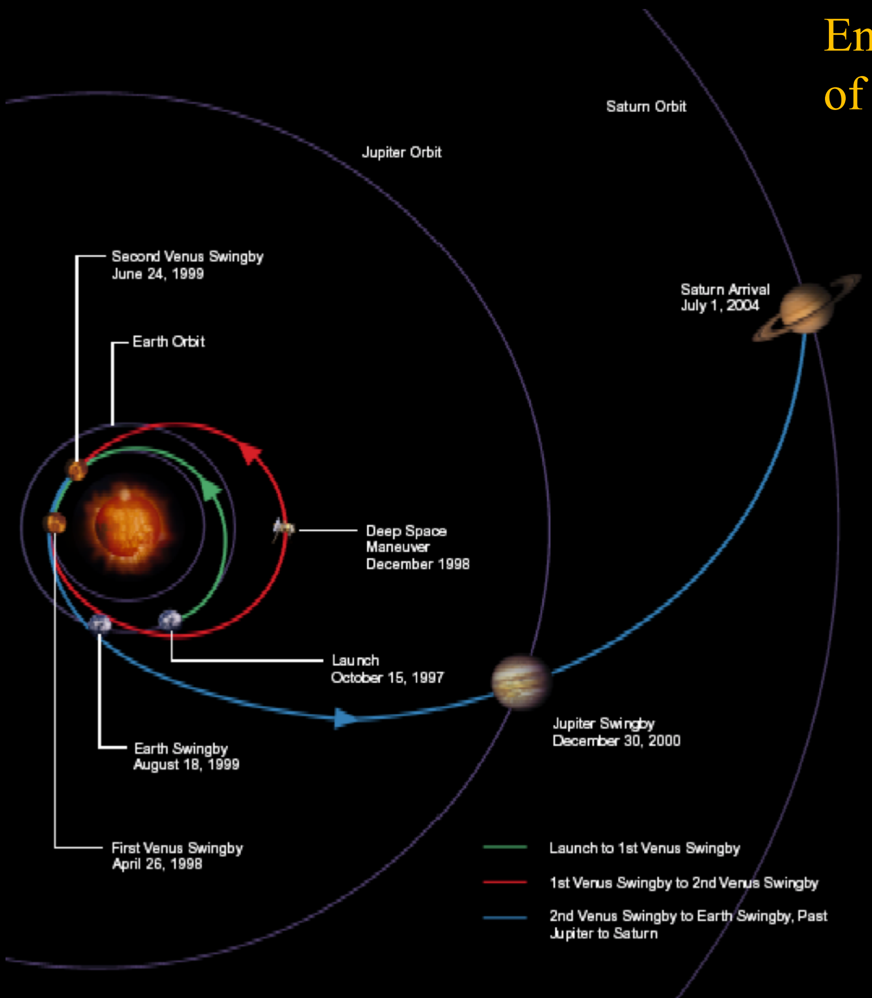
The largest satellite of Saturn, has a thick and permanent atmosphere that is mainly composed of N_2, CH_4, H_2, and a variety of hydrocarbons and nitriles.



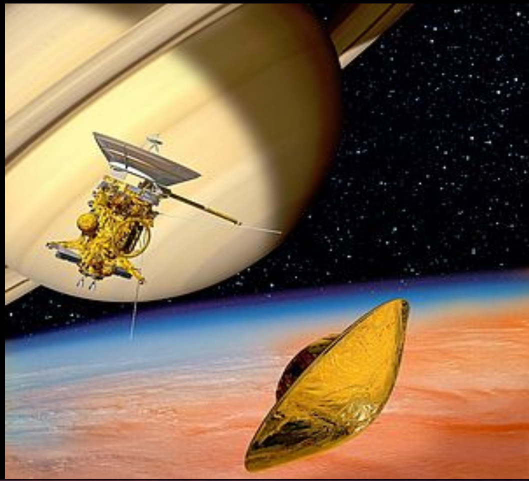


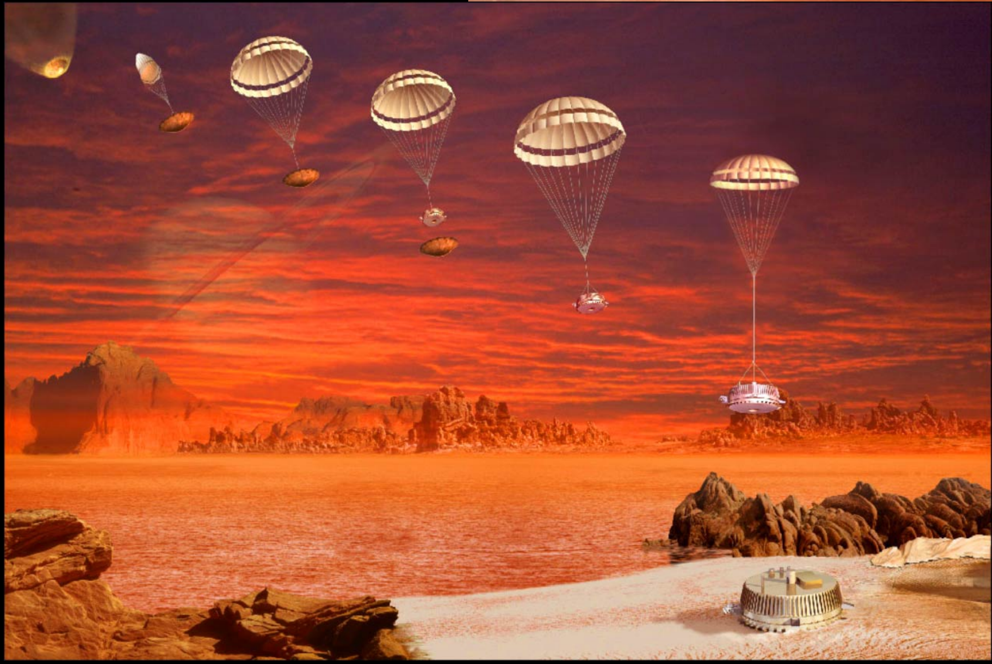
Cassini-Huygens

Cassini Interplanetary Trajectory

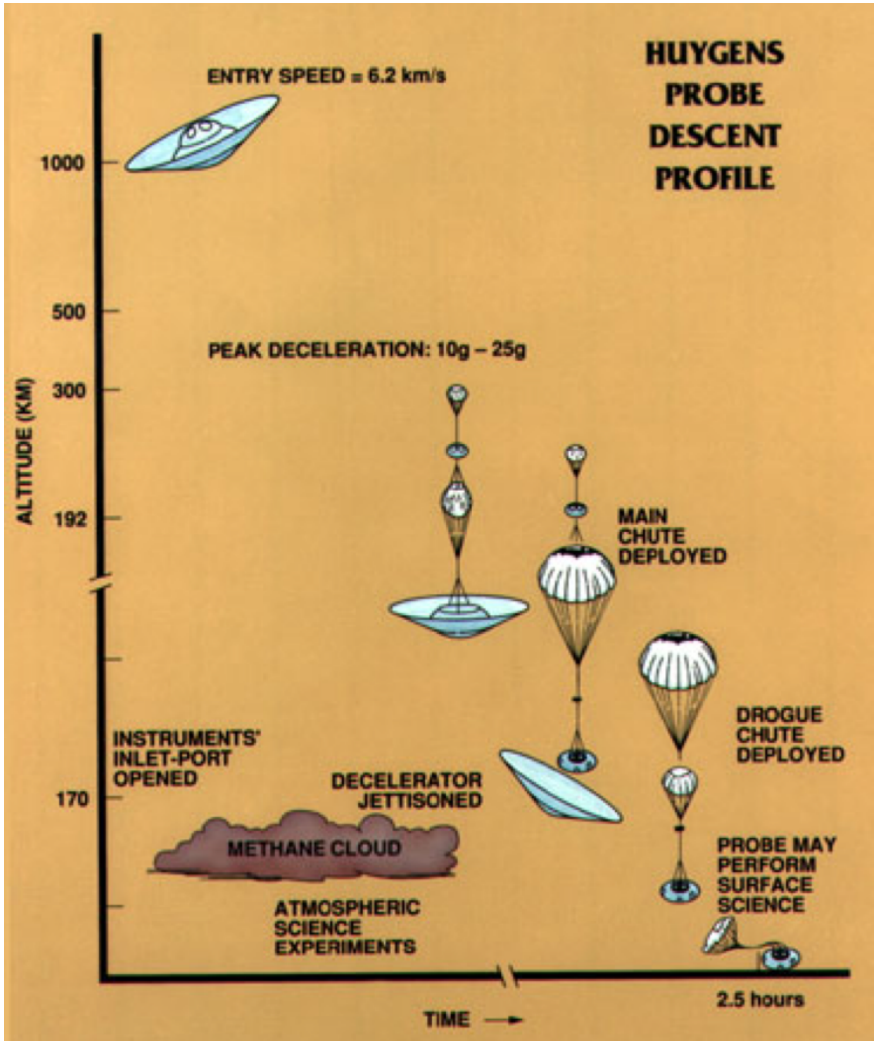


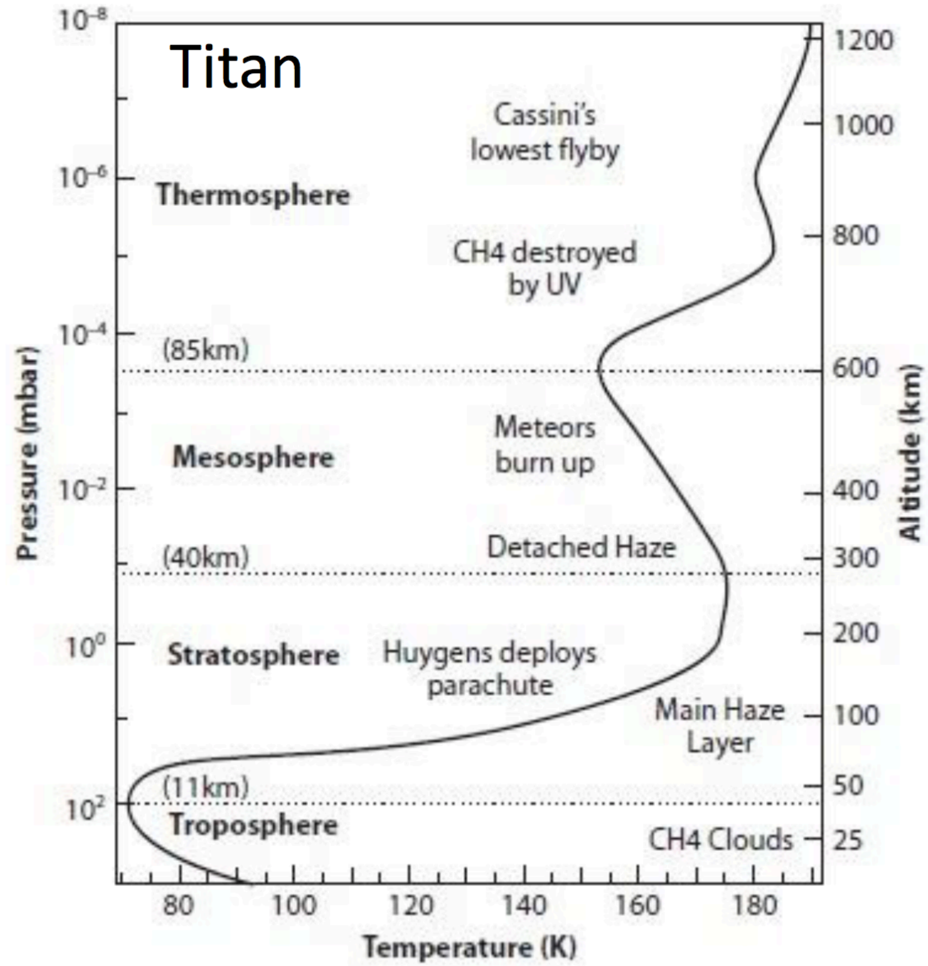
Entry, descent, and landing of Huygens (Jan. 14, 2005)





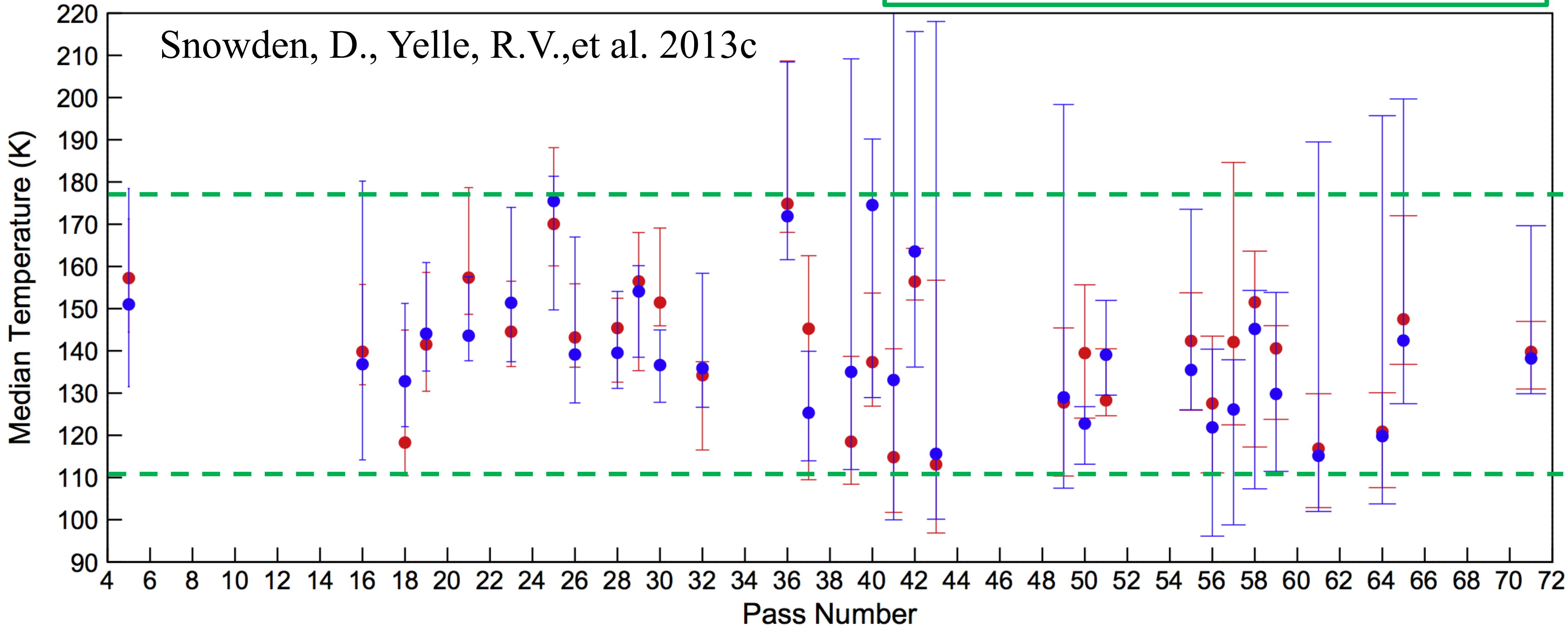
The Atmospheric Structures of Titan





Energy Crisis

Temperature variability over the range of 112-175K among 32 flybys

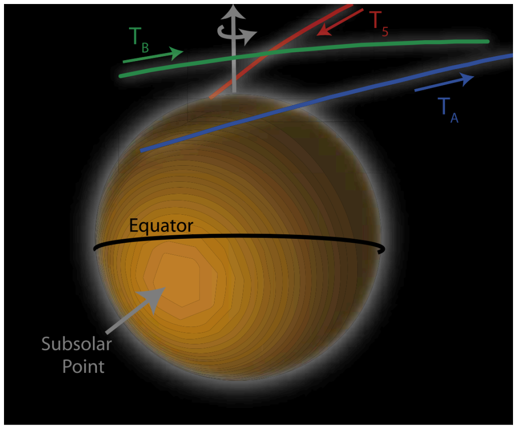


☛For this energy crisis phenomenon, there are some scenarios to explain:
Solar EUV radiation, charged particle precipitation, Joule Heating, HCN rotational line emission, **wave dissipation**.

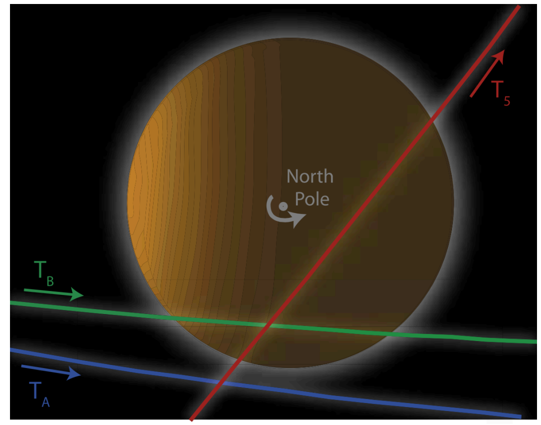
☛The energy crisis is known to be present in upper atmosphere of four outer giant planets.

Solar EUV Radiation

Three flybys: T_A(Oct.26,2004), T_B(Dec. 13,2004), T_5(Apr. 16, 2005)



Side View of Titan



North Pole View of Titan

The dayside temperature was lower than the nightside temperature!

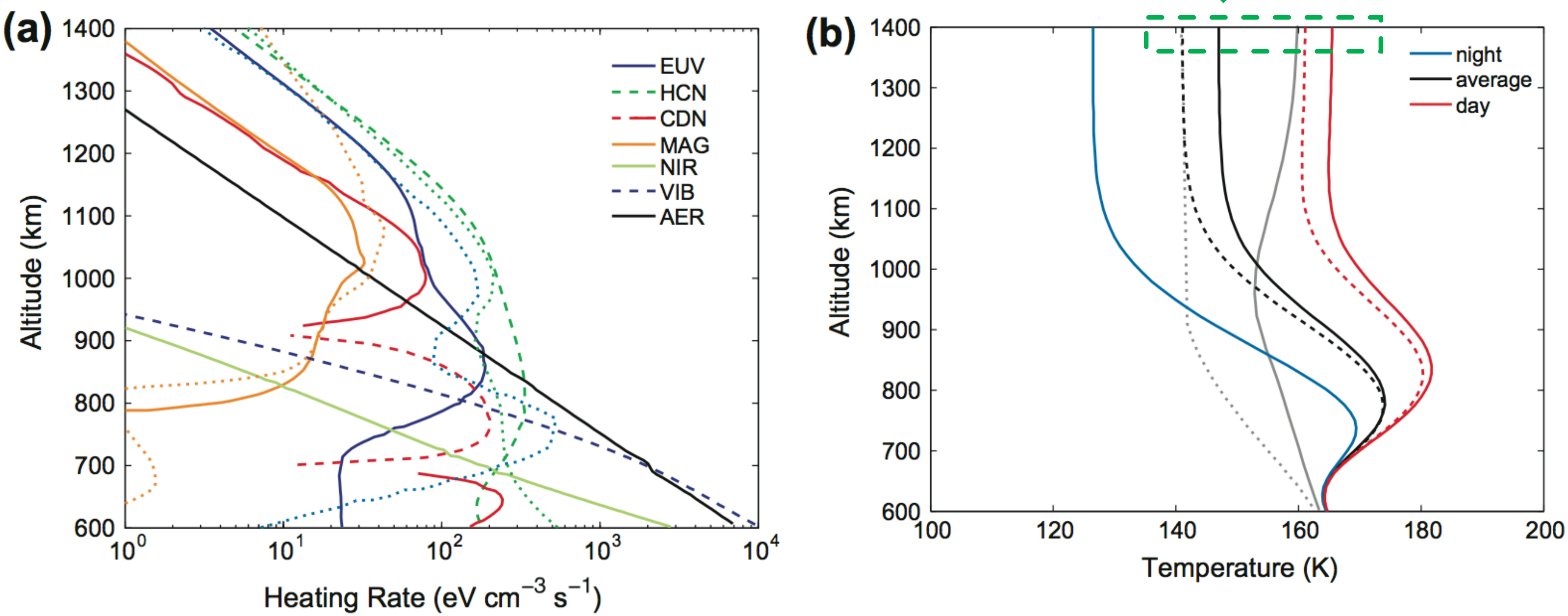
	T_A	T_B	T_5
	Temperature, K		
Combined data	152.8 ± 4.6	149.0 ± 9.2	157.4 ± 4.9
Ingress	150.0	Not enough data	162.3
Egress	157.4	149.0	154.1
	Eddy Diffusion Coefficient, $cm^2\ s^{-1}$		
Combined data	$(5.2^{+5.0}_{-2.9}) \times 10^9$	$(1.0^{+1.0}_{-0.58}) \times 10^{10}$	$(3.9^{+1.0}_{-0.9}) \times 10^9$
Ingress	2.3×10^9	Not enough data	3.0×10^9
Egress	1.2×10^{10}	1.0×10^{10}	4.9×10^9
Homopause altitude, km	1250 ± 60	1280 ± 120	1180 ± 30
Exobase altitude, km	1442 ± 7	1409 ± 14	1401 ± 2
Thickness of exobase layer, km	85 ± 2	81 ± 4	86 ± 3

de La Haye, Waite, Johnson et al.2007

Charged Particle Precipitation from Saturn's Magnetosphere

It only results in a ~7K increase in temperature above 1000km altitude!

At the exobase(1400km), the diurnally averaged temperature with and without magnetospheric heating is 141 and 147 K, the average dayside temperature is 161 and 168 K.

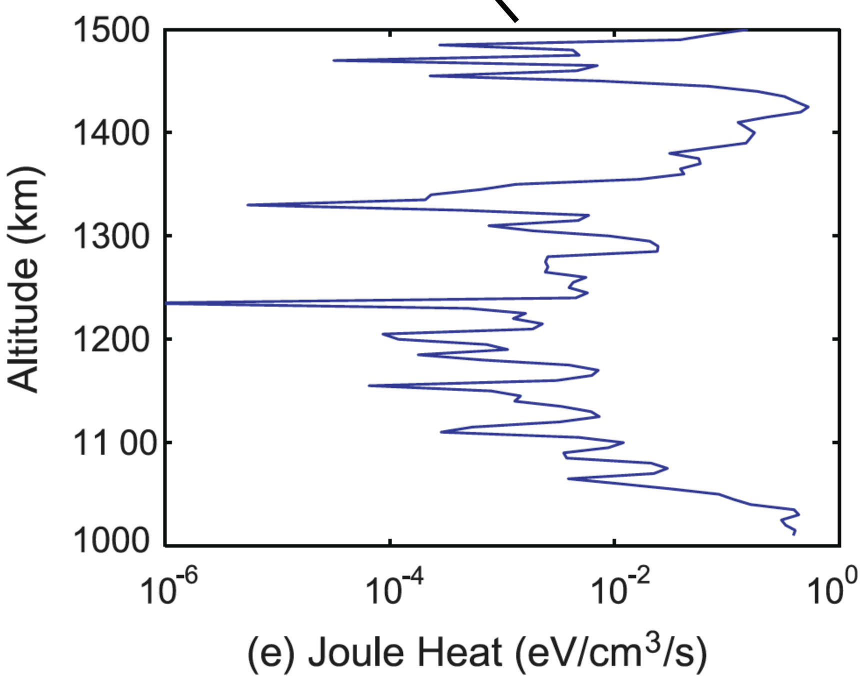


Snowden, Yelle et al. 2014

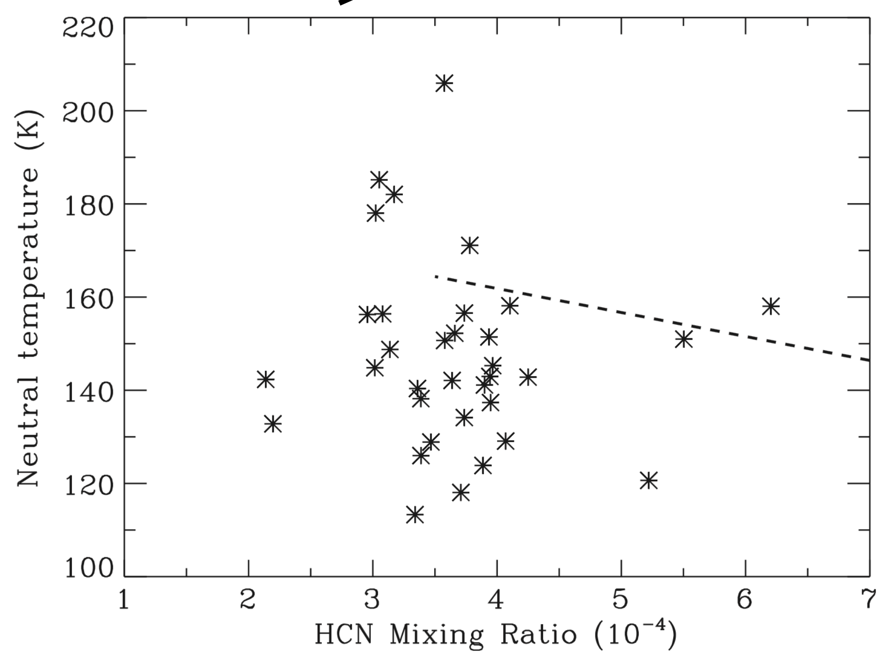
Joule Heating and HCN Rotational Line Emission

The Joule heating rate is less than 1 eV cm^{-3} s^{-1} at all altitudes, and is insufficient to account for the observed temperature variability!

It indicate that a decrease in HCN volume mixing ratio about twice leads to an increase in temperature from 145 to 165 K above 1200km.



Snowden&Yelle et al. 2014

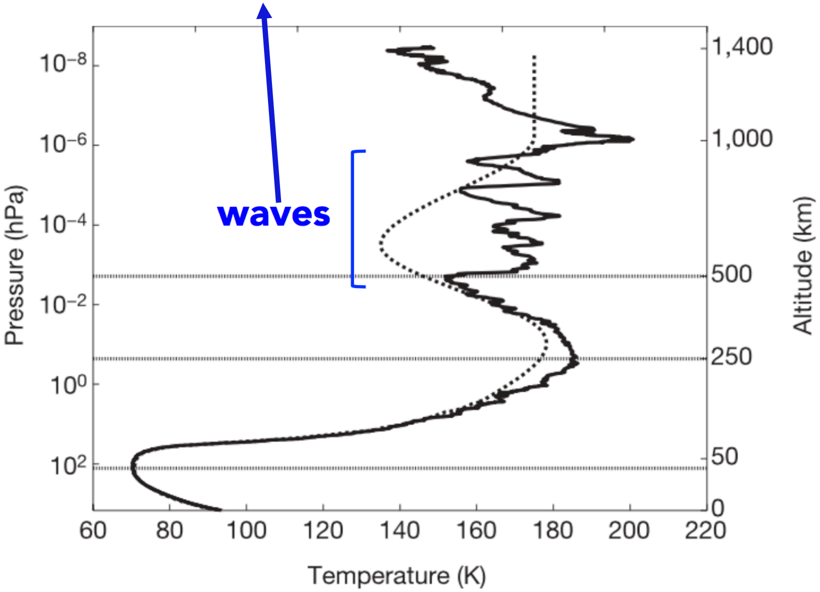


Cui, Cao, Lavvas et al. 2016

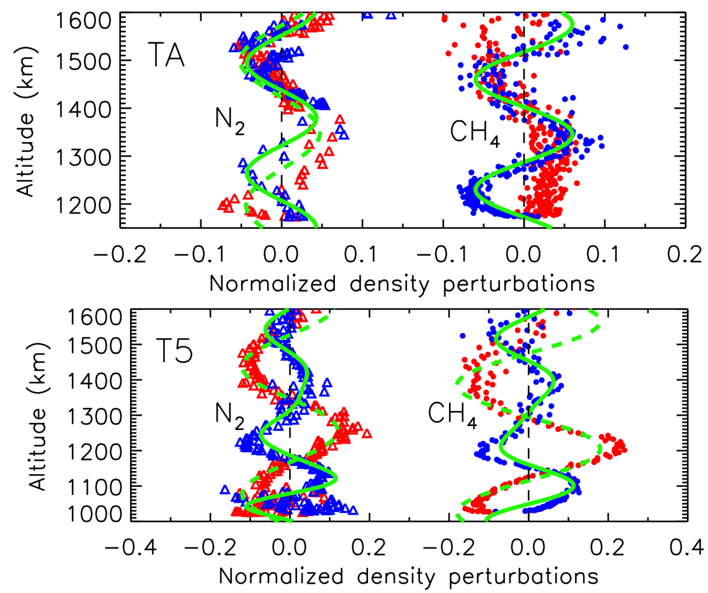
Wave Dissipation

Wave structures were revealed by the Huygens Atmosphere Structure Instrument (HASI) data;

Typical density perturbations of 10% in the upper atmosphere were inferred from the INMS measurements of N_2 and CH_4;



Fulchignoni et al. 2005



Muller-Wodarg et al.2006

- ☛The analysis of INMS data in Cui et al. 2013 showed that the observed waves are **upward propagating gravity waves** with a characteristic wavelength of 700 km and a wave period of 10h;
- ☛Muller-Wodarg et al.2006 obtained an energy flux of 3×10^{9} eV cm^{-2} s^{-1} at 1200km;
- ☛Snowden & Yelle et al. 2014 just estimated that the maximum heating rate due to viscous dissipation of waves was about 30 eV cm^{-3} s^{-1} and the maximum cooling rate due to heat flux to be -9 eV cm^{-3} s^{-1} .

Linear Gravity Wave Model

Model Description:

☛We opt to use **anelastic approximation** since it can filter out acoustic waves that have not been observed in Titan’s atmosphere.

☛We assume that:

1.The background atmosphere is plane-parallel and hydrostatically balanced;
2.The background wind is zero or constant;
3.Coriolis effect can be ignored;

☛The resulting system of wave equations are:

$$\frac{D\rho}{Dt}=-\rho\nabla\cdot\vec{V}$$

Mass Continuity Equation

$$\nabla\cdot\vec{V}'-\frac{w'}{H_\rho}=0$$

$$\frac{D\vec{V}}{Dt}=-\frac{1}{\rho}\nabla p+g+\frac{\mu}{\rho}\left[\nabla^2\vec{V}'+\boxed{\frac{1}{3}\nabla(\nabla\cdot\vec{V}')}\right]$$

Neglect!

N-S equation

$$\left[\frac{\partial}{\partial t}+u_0\frac{\partial}{\partial x}-\nu\nabla^2\right]u'=-\frac{1}{\rho_0}\frac{\partial p'}{\partial x}$$

$$\left[\frac{\partial}{\partial t}+u_0\frac{\partial}{\partial x}-\nu\nabla^2\right]v'=-\frac{1}{\rho_0}\frac{\partial p'}{\partial y}$$

$$\left[\frac{\partial}{\partial t}+u_0\frac{\partial}{\partial x}-\nu\nabla^2\right]w'=-\frac{1}{\rho_0}\frac{\partial p'}{\partial z}-\frac{\rho'}{\rho_0}g$$

$$\frac{D\theta}{Dt}=\frac{\theta}{T}\frac{\nu}{Pr}\nabla^2T'$$

$$\theta=T\left(\frac{p_s}{p}\right)^{R/c_p}$$

$$\left[\frac{\partial}{\partial t}+u_0\frac{\partial}{\partial x}-\frac{\nu}{Pr}\nabla^2\right]T'-\frac{1}{c_p\rho_0}\left[\frac{\partial}{\partial t}+u_0\frac{\partial}{\partial x}\right]p'=-\Gamma w'$$

$X=X_0+X'$
$X=u,w,T,p,\rho$

$$\frac{p'}{p_0}=\frac{\rho'}{\rho_0}+\frac{T'}{T_0}$$

Equation of state

θ is potential temperature

☛Assuming wave perturbations are in form of $X' = \delta X(z)e^{i(k_x x + k_y y - \omega_0 t)}$, $\delta X(z)$ is expressed as WKB solutions in form of :

$$\delta X(z)=\Delta X(z_0)\left(\frac{k_{zr}(z)}{k_{zr}(z_0)}\right)^{\frac{1}{2}} exp\left[\int_{z_0}^{z}\left(ik_z+\frac{1}{2H_\rho}\right)dz\right]$$

☛Then, we can get:

$$\frac{d^2w'}{dz^2}-\frac{1}{H_\rho}\frac{dw'}{dz}+\left[\frac{1}{2H_\rho^2}\frac{dH_\rho}{dz}+\frac{1}{4H_\rho^2}+k_z^2\right]w'=0$$

This term is neglected due to slow varying background temperature and anelastic approximation!

☛However, according to the above wave equations, we can get:

$$\frac{d^2w'}{dz^2}-\frac{1}{H_\rho}\frac{dw'}{dz}+\left[\frac{1}{H_\rho^2}\frac{dH_\rho}{dz}-k_h^2+\frac{k_h^2N^2}{\hat{\omega}(\hat{\omega}+i\beta)}\right]w'+\left[\frac{1}{T_0}\frac{dT_0}{dz}+\frac{(\gamma-1)g\tilde{\omega}_0}{c_s^2(\hat{\omega}+i\beta)}\right]\left(\frac{w'}{H_\rho}-\frac{dw'}{dz}\right)=0$$

☛We can obtain the dispersion relation as

$$k_z^2=\frac{k_h^2N^2}{\hat{\omega}(\hat{\omega}+i\beta)}-\frac{1}{4H_\rho^2}\left(1-2\frac{dH_\rho}{dz}\right)-k_h^2$$

☛Where $\hat{\omega}=\tilde{\omega}_0-i\nu\alpha$, $\beta=\left(1-\frac{1}{Pr}\right)\nu\alpha$ and $\alpha = \frac{1}{X'}\nabla^2 X'$, $\tilde{\omega}_0 = \omega_0 - u_0 k_x$ is the intrinsic wave frequency. $k_h = \sqrt{k_x^2 + k_y^2}$ is the horizontal wavenumber. $H_\rho = \left(-\frac{1}{\rho_0}\frac{\partial \rho_0}{\partial z}\right)^{-1}$ and $H_p = \left(-\frac{1}{p_0}\frac{\partial p_0}{\partial z}\right)^{-1}$ are the density and pressure scale height. $\Gamma = \frac{\partial T_0}{\partial z}+\frac{g}{c_p}$ is the atmosphere static stability. $N = \sqrt{\frac{g\Gamma}{T_0}}$ is the Brunt-Vaisala frequency.

☛Polarization relations:

$$u' = -\frac{ik_x}{k_h^2}\left(-ik_z+\frac{1}{2H_\rho}\right)w'$$

$$T' = -\frac{i}{\hat{\omega}+i\beta}\left[\Gamma+\frac{\tilde{\omega}_0\hat{\omega}}{c_p k_h^2}\left(-ik_z+\frac{1}{2H_p}\right)\right]w'$$

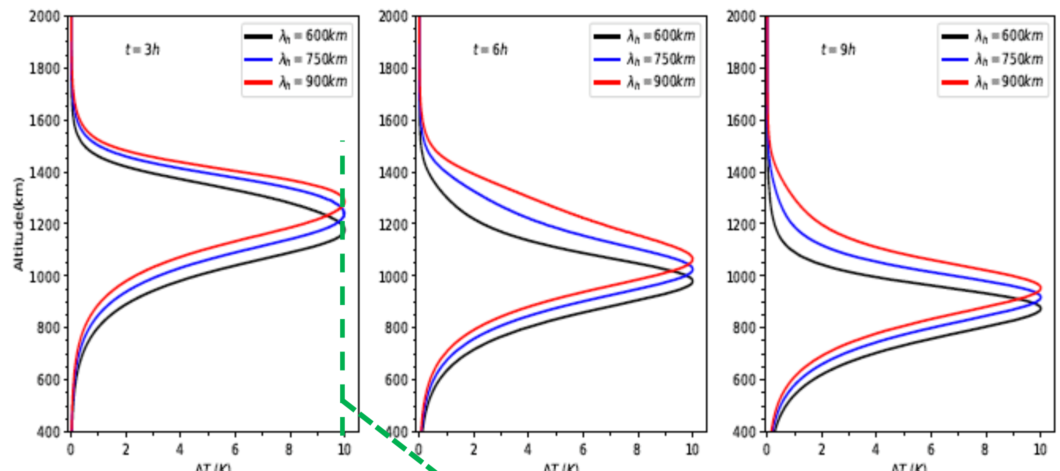
$$p' = -\frac{i\rho_0\hat{\omega}}{k_h^2}\left(-ik_z+\frac{1}{2H_p}\right)w'$$

$$\frac{\rho'}{\rho_0} = i\left\{\frac{\Gamma}{T_0(\hat{\omega}+i\beta)}-\frac{\hat{\omega}}{k_h^2}\left[\frac{1}{RT_0}-\frac{\tilde{\omega}_0}{T_0 c_p(\hat{\omega}+i\beta)}\right]\left(-ik_z+\frac{1}{2H_p}\right)\right\}w'$$

☛ τ ranged from ~80 min to 10h.(Cui. et al.2013)

Table 1. Gravity wave parameters and wave damping altitudes

Period τ [h]	λ_h [km]	c_h [ms^{-1}]	ΔT_{max} [K]	z_{max} [km]	λ_z (z_{max}) [km]
3	600	55.6	10.0	1176	323.5
3	750	69.4	10.0	1241	468.9
3	900	83.3	10.0	1290	628.3
6	600	27.8	10.0	979	124.4
6	750	34.7	10.0	1025	161.1
6	900	41.7	10.0	1067	202.0
9	600	18.5	10.0	876	77.5
9	750	23.1	10.0	917	99.1
9	900	27.8	10.0	952	121.5



These two waves satisify the observed vertical wavelengths range of 170km-360km (Muller-Wodarg et al.2006)

ΔT is fixed at 10K (Muller-Wodarg et al.2006)

Figure 1. Wave amplitude of tem -hour waves. The location of maximum wave amplitude is the r diffison.

Wave Heating and Cooling

The maximum wave energy fluxes are comparable to the value **1.2×10^9 eV cm^{-2} s^{-1}** estimate by Muller-Wodarg et al.2006;
But the results may be a coincidence:
They considered a planetary scale wave $(\lambda_h = 12000km, \tau = 1\ h_{Titan})$
and calculated by:

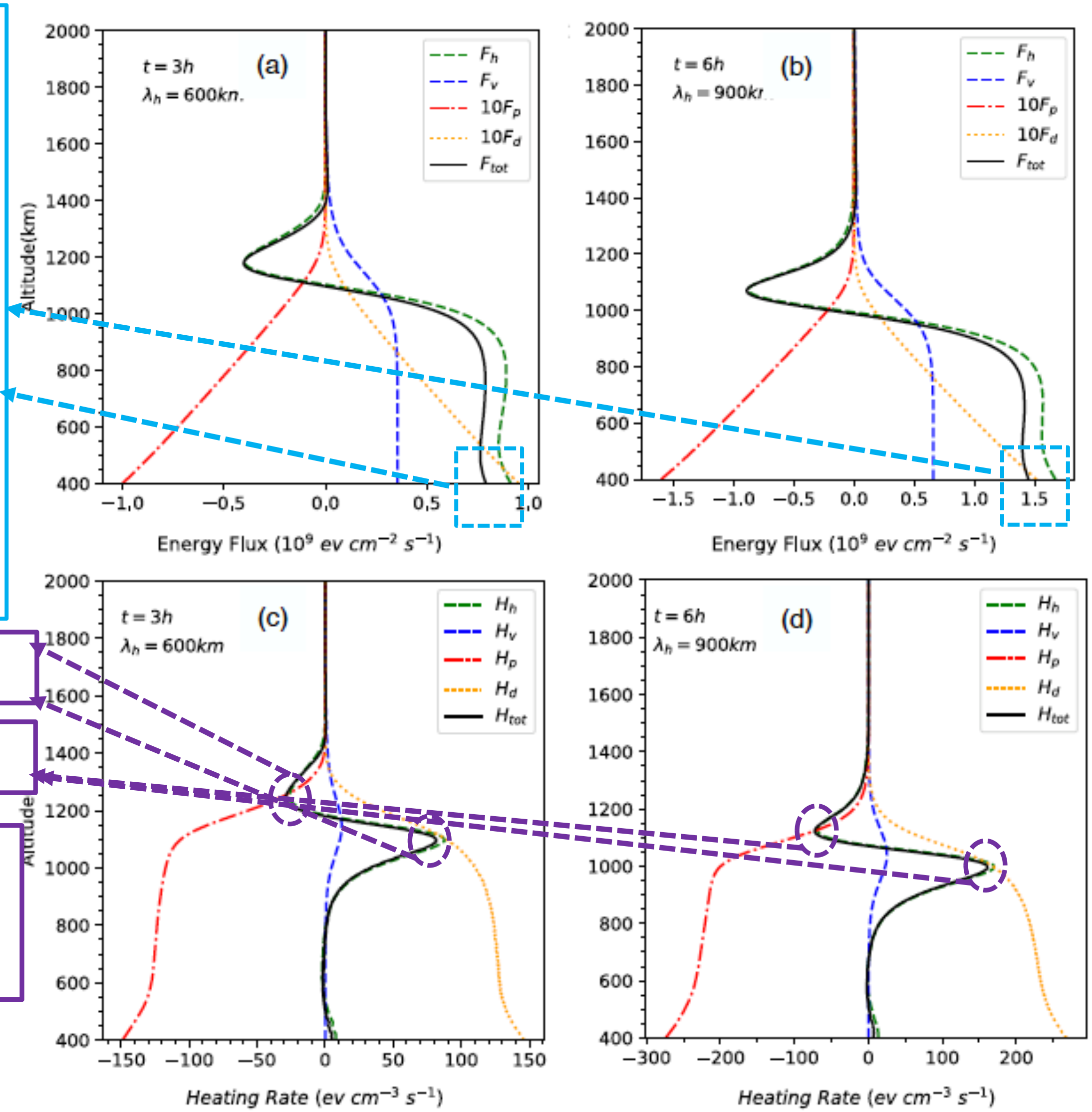
$$|F_z^w| \le \frac{1}{2}\rho_0\omega_0\frac{k_z}{k_h^2}\Delta W^2$$

This formula requires Boussinesq approximation. (Matcheva et al. 1999)

MHR: 80 eV cm^{-3} s^{-1} MCR: -30 eV cm^{-3} s^{-1}

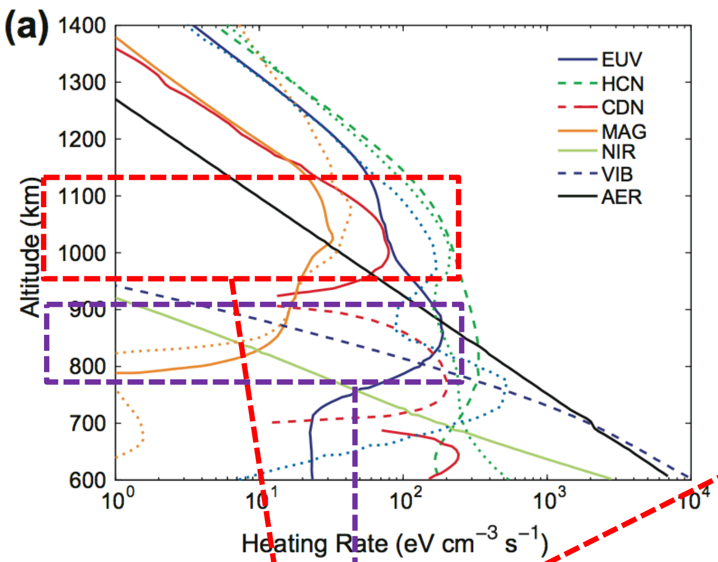
MHR:160 eV cm^{-3} s^{-1} MCR:-70 eV cm^{-3} s^{-1}

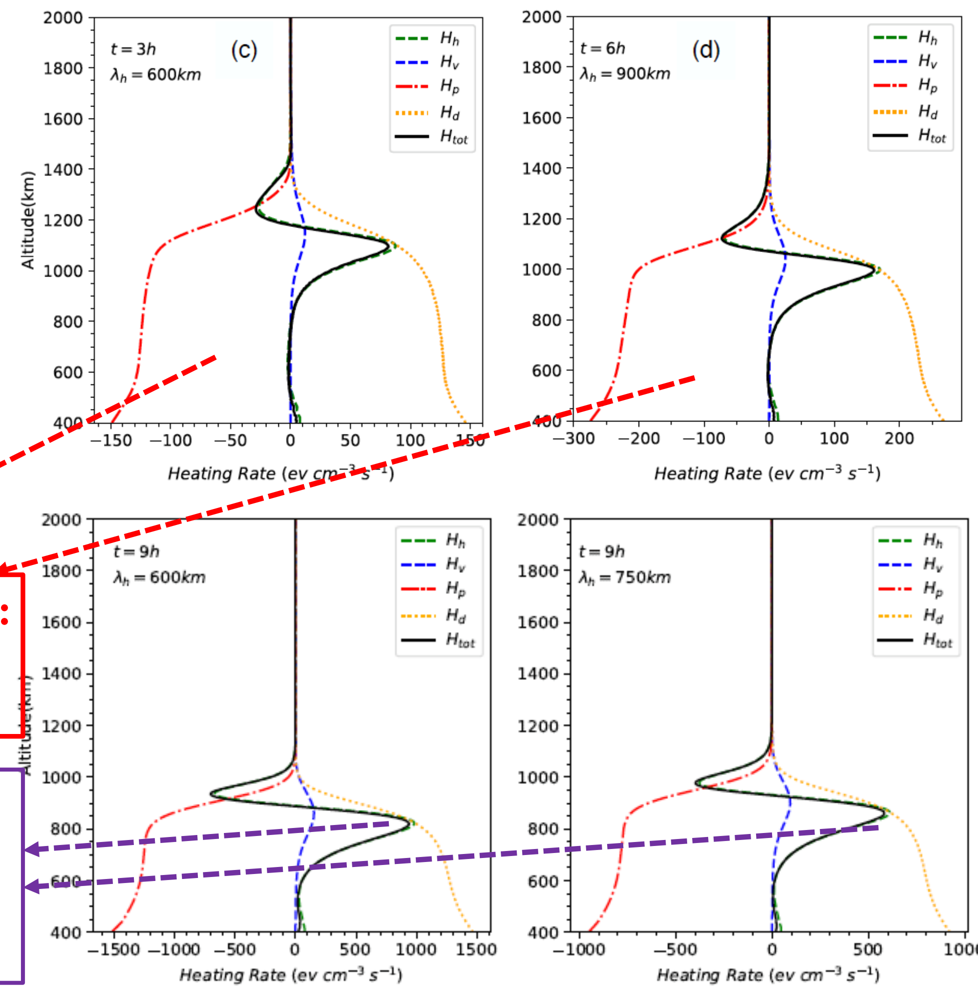
MHR/MCR of these two waves much larger than 30 eV cm^{-3} s^{-1} and -9 eV cm^{-3} s^{-1} estimated by Snowden & Yelle et al.2014



Discussion

Compare Wave Heating/Cooling Rate to Solar EUV Energy Deposition Rate





Solar EUV heating (25%)/ MHR of wave:

75 eV cm^{-3} s^{-1} / 80 eV cm^{-3} s^{-1} (1100km)

50 eV cm^{-3} s^{-1} /160 eV cm^{-3} s^{-1} (1000km)

Solar EUV heating peak value(25%):

700 eV cm^{-3} s^{-1} (740-870km)

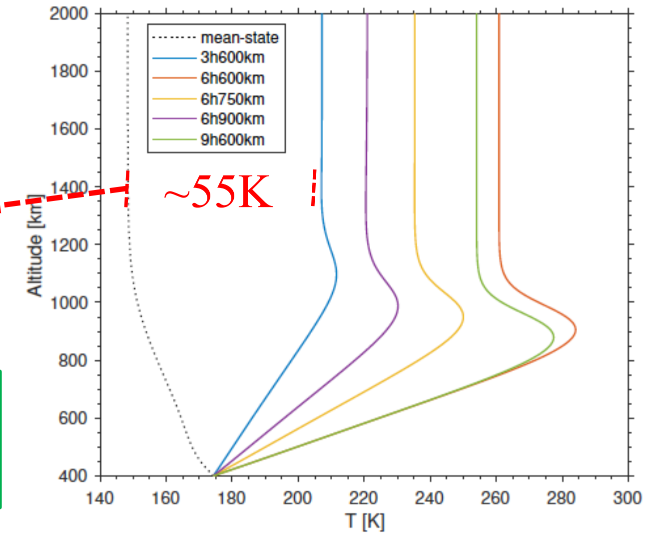
Heating rate of wave 9h600km,9h750km

400-1000 eV cm^{-3} s^{-1} (800-900km)

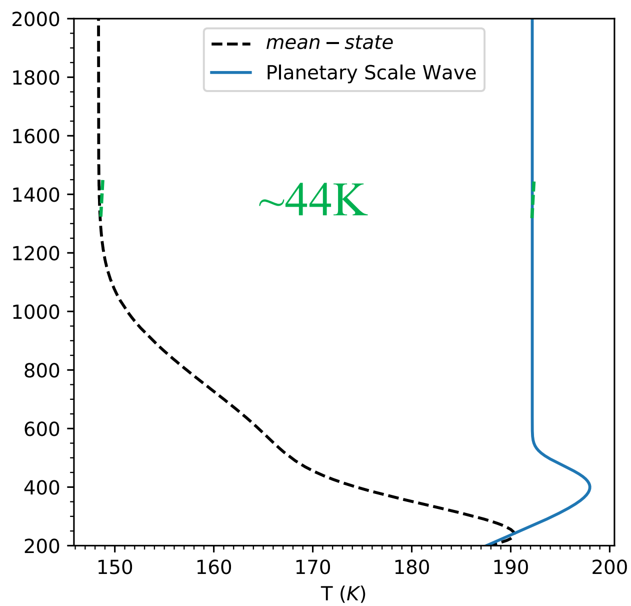
The variability of thermal structure by wave heating/cooling

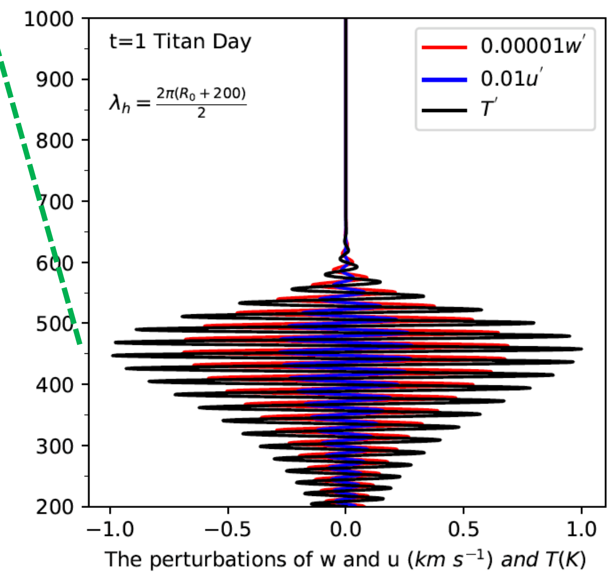
$$F_{tot}=k_m \frac{\partial T}{\partial z} \qquad k_m=27.21\times10^{-5}T_0^{0.8}\ J(mKs)^{-1}$$

Temperature variation by waves close to the observed 60K. However, the negative gradient of the mean-state temperature requires **downward** energy flux to maintain!



Planetary Scale Wave (t=1 Titan Day (16day), λ_h = 8718km): The direction of energy flux is **upward**(z>~450km)





Conclusions

☛ Solar EUV radiation, charged particle precipitation, Joule Heating, HCN rotational line emission, none of them contributes to the observed temperature variability;(~60K)

☛ Our calculations of GW's max heating rate larger than solar EUV heating;

☛ Temperature variation by GW close to the observed 60K, but the directions of energy fluxes are opposite to the gradient of the mean-state temperature;

☛ The Planetary Scale Wave may be conform to it, this needs further research.

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