A General Stability Theory of Planetary Atmospheres

Vulcano, 2012

Smadar Bressler

Nir J Shaviv

Giora Shaviv

Outline

1. Introduction
2. Some definitions
3. Radiative transfer models
4. Our model
5. Results
6. What can be done with our results
7. Summary and conclusions

Introduction

We are all used to think that an increase of greenhouse gas concentrations in planetary atmospheres, results in a temperature rise.

> Most of the observed increase in global average temperatures since the mid-20th century is *very likely* due to the observed increase in anthropogenic GHG concentrations.[8]

IPCC climate change 2007: fourth synthesis Report

Doubling the CO_2

NOAA states that, from paleontologic studies, it is infered that doubling the CO_2 concentration may raise the Earth's surface temperature by ~5K

"An estimate from the tropical ocean, far from the influence of ice sheets, indicates that the tropical ocean may warm 5°C for a doubling of carbon dioxide."

http://www.ncdc.noaa.gov/paleo/globalwarming/temperature-change.html

Atmospheric absorption

Before the industrial period, CO_2 concentration was 280ppm

Today the atmospheric CO_2 concentration exceeds 390ppm

Is this concentration change responsible for the claimed climate change?

What is the sensitivity of Earth-Like-Planets' T_{atm} and T_{surf} to chemical change?

What controls planetary temperatures?

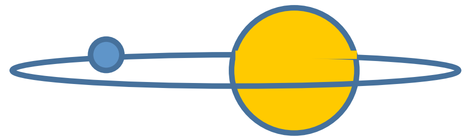
(When the central star is the only available energy source)

RADIATION MS Central star and distance to ELP

Surface and air contribution:

Emission

Albedo



CHEMISTRY Atmospheric composition:

Spectral fingerprint

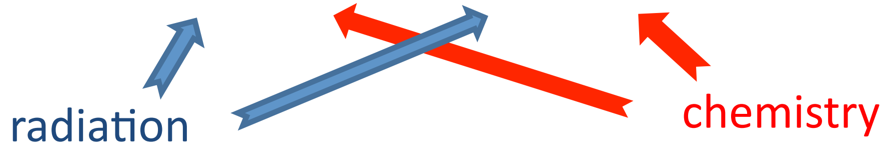
Greenhouse effect

Anti-Greenhouse effect

Our study

We investigate the direct effect of atmospheric concentration change (x) on the optical depth in the short and long wavelengths (τ_{vis} and τ_{fir}) and thus on the planet's surface temperature (T_{surf}), neglecting sequential effects:

$$\frac{\partial T_{surf}}{\partial X} = \frac{\partial T_{surf}}{\partial \tau_{vis}} \frac{\partial \tau_{vis}}{\partial X} + \frac{\partial T_{surf}}{\partial \tau_{fir}} \frac{\partial \tau_{fir}}{\partial X}$$



We use a unique radiative transfer model developed for calculating the T_{atm} and T_{surf} response to a change in atmospheric composition by two iteration schemes.

Some definitions

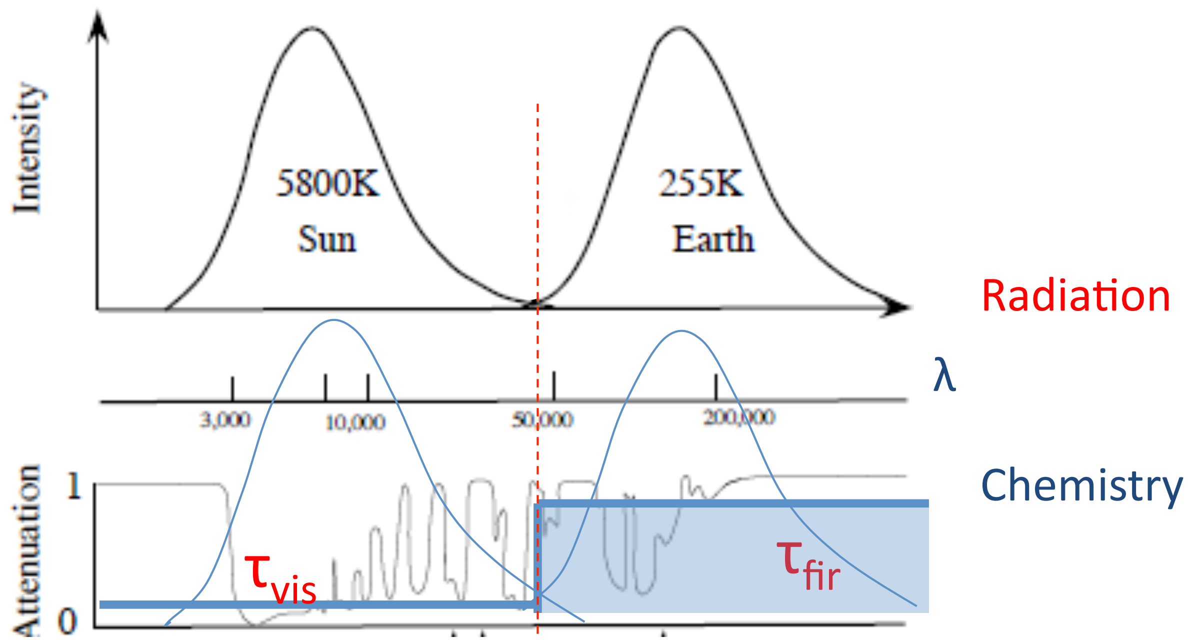
The importance of τ

τ , the optical depth of the atmosphere, is defined as:

$$\tau_{\lambda} = \int_0^Z \kappa_{(\lambda,T,P)} \rho dz$$

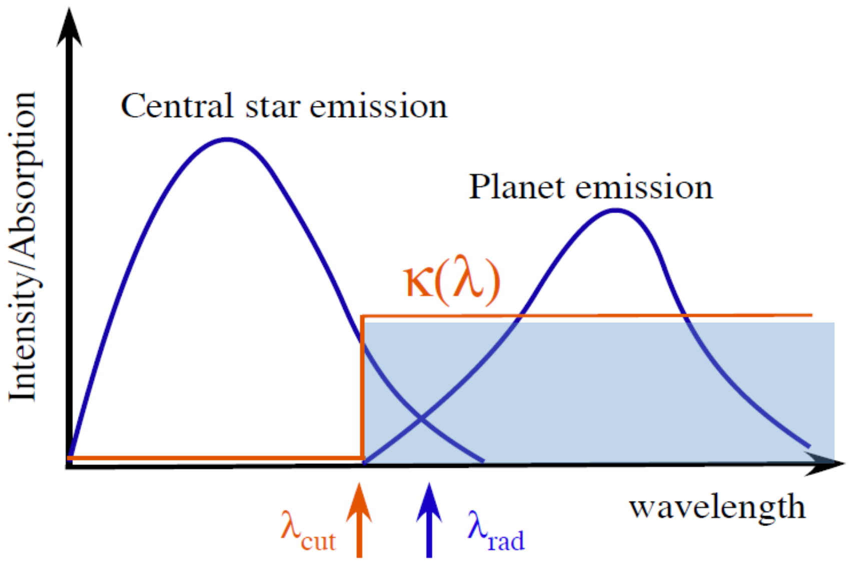
It is the parameter which connects the optical properties of the atmosphere with its chemical composition.

we define two regions of average τ:



The semi-grey approximation

The semi-grey approximation simplifies the treatment of the atmospheric absorption, using only two average τ's and a λ_{cut}.



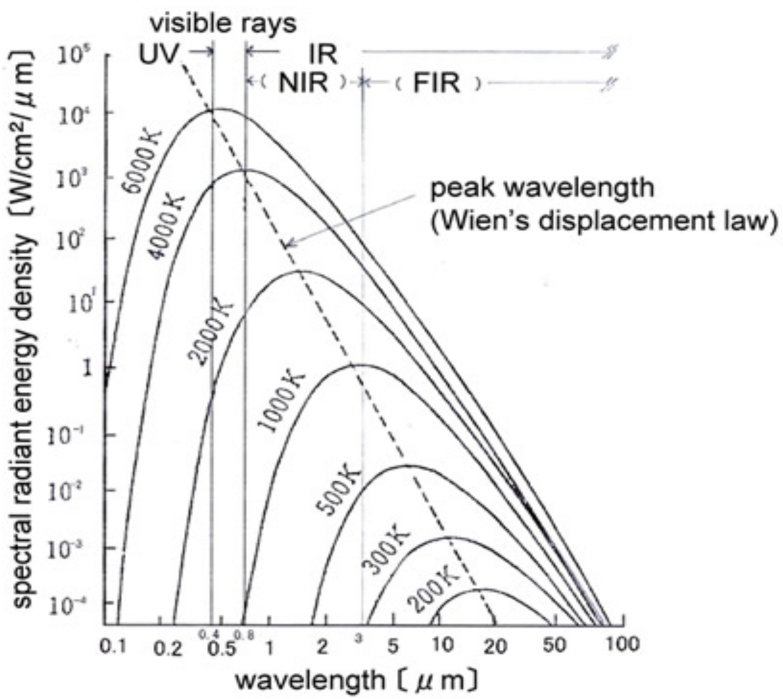
Another characteristic value is λ_{rad}, which is the equi-intensity value of the earth and sun's BB functions.

The definition of λ_{rad}

$$\frac{(1-a(\lambda))}{4}\frac{R_\odot^2}{d^2}I_\odot(\lambda_{rad}) = I_\oplus(\lambda_{rad})$$

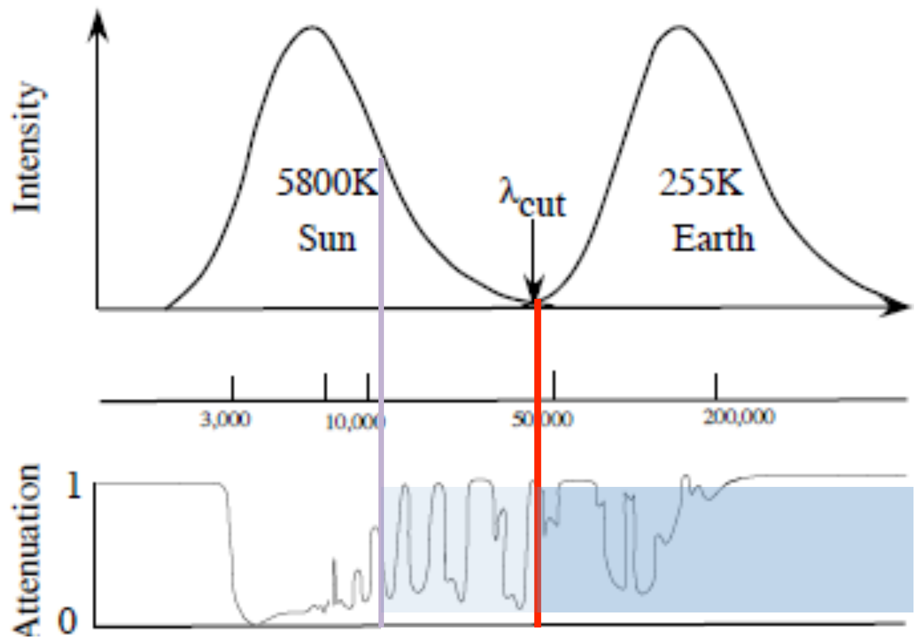
a=albedo
R = solar radius
d = distance ⊕⊙

When the temperature changes, so does the Planck function, and λ_{rad} shifts accordingly.



http://www.enseki.or.jp/e_tokusei.html

The choice of λ_{cut}



For the Earth, the literature assumes that $\lambda_{cut} \equiv \lambda_{rad} = 50{,}000$Å.
Shaviv et al (2011) are the first to introduce that $\lambda_{cut} \neq \lambda_{rad}$.

These definitions will help us model the greenhouse effect.

Tsurf and the Greenhouse effect

T_{surf} is the surface temperature of the Earth.
In radiative equilibrium, with no atmosphere:

$$\sigma T^4_{surf} = \sigma T^4_{\oplus equil} = 1/4*(1-a)*F_{\odot} \Rightarrow T_{\oplus equil} = 255K = -18^oC$$

$F_{\odot}$ (solar const.) = 1367W/m^2 ($T_{\odot}$=5780K)
a(avg. albedo) = 0.3
Factor for quick rotation = ¼

Greenhouse effect (GHE):

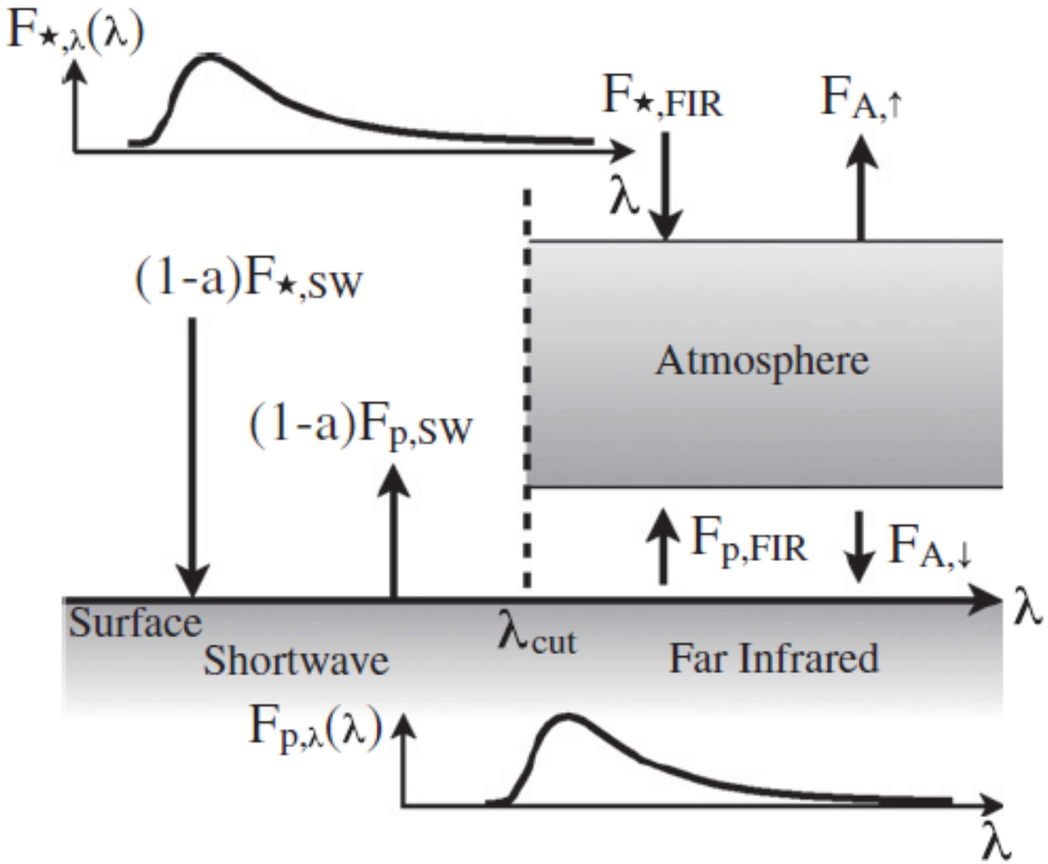
$$T_{surf} > T_{equil} \Rightarrow \partial T_z / \partial z < 0 \qquad z = \text{height}$$

$$T_{\oplus GH} = 288K = +15^oC$$

Anti - Greenhouse effect (aGHE):

$$T_{surf} < T_{equil} \Rightarrow \partial T_z / \partial z > 0$$

Greenhouse Effect

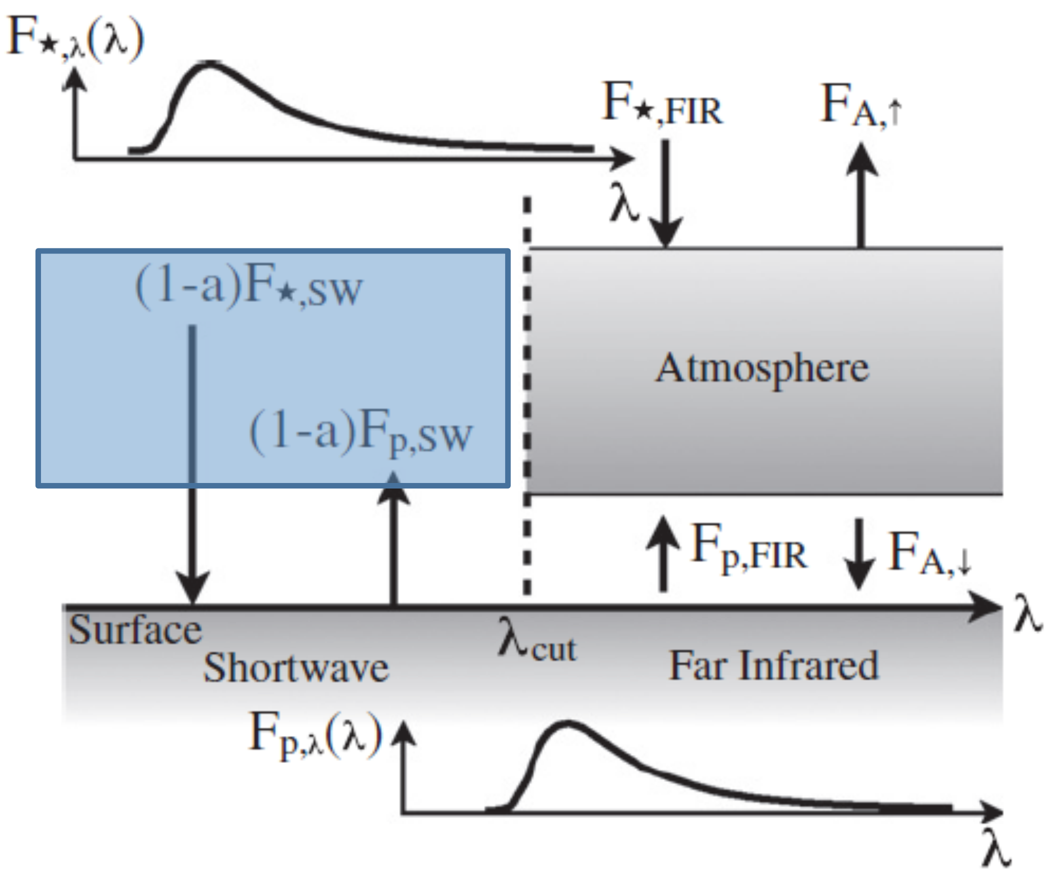


Taken from: The Maximal Runaway temperature of ELPs
N.J.Shaviv, G.Shaviv, R.Wehrse; Icarus, (2011) **216**, 403

Anti-greenhouse effect

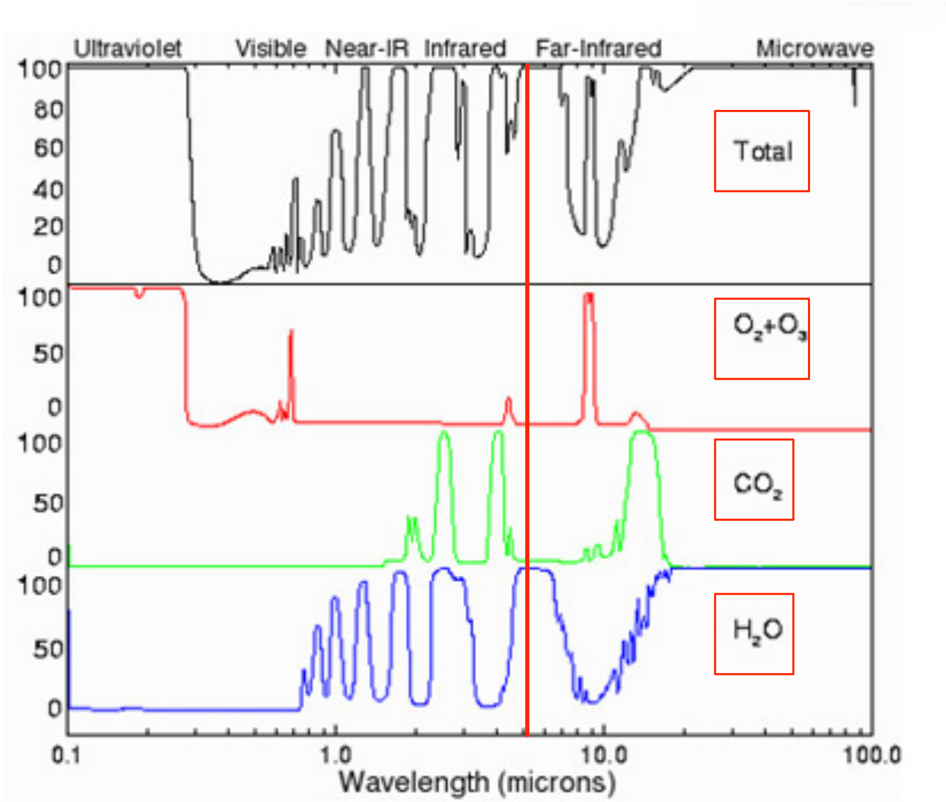
All models: scattering in the SW (aerosol scattering, σ)

Our model: absorption in the SW (molecular absorption,κ)



Major greenhouse contributors

1-% Transmission



70% $H_2O_{(g)}$
20% CO_2
10% CH_4

It is seen that the molecular absorption extends into the SW

http://devconsultancygroup.blogspot.com/2011/10/global-cooling-has-already-started.html

Radiative transfer models

The equation of radiative transfer

The equation of radiative transfer of the general form below, is used for calculating $I_{T(\lambda,z)}$ for each atmospheric layer, thus yielding $T(z)_{atm}$ and T_{surf}:

$$\frac{\mu}{\rho}\frac{\partial I_{T(\lambda,z)}}{\partial z_{T(\lambda,z)}} = (\kappa_{T(\lambda,z)} + \sigma_{T(\lambda,z)})I_{T(\lambda,z)} - S_{T(\lambda,z)}$$

1. $\kappa_{T(\lambda,z)}$ and $\sigma_{T(\lambda,z)}$ are the absorption and isotropic scattering coeff.
2. $(\kappa_{T(\lambda,z)} + \sigma_{T(\lambda,z)})I_{T(\lambda,z)}$ is the absorbed and scattered radiation
3. $S_{T(\lambda,z)} = (\kappa_{T(\lambda,z)}B_{T(\lambda,z)} + \sigma_{T(\lambda,z)}J_{T(\lambda,z)})/(\kappa_{T(\lambda,z)} + \sigma_{T(\lambda,z)})$ the atmospheric source function
4. The mean intensity $J(z,\lambda) = \oint_{4\pi} I(z,\lambda,\omega)d\Omega$
5. $\mu = \cos\theta$ for plane parallel atmosphere

Radiative transfer models

1. Line-by-line (LBL) models – calculate W/m^2, from attenuated energy in atmosphere during transmission.

→ Used by the IPCC to explain global warming

---

2. Full radiative transfer models – calculate ΔT_{atm} by using the equation of radiative transfer:

a. In Local Thermodynamic Equilibrium (LTE) for the *fir* and no absorption in the vis.

→ G. Simpson (1927) - using the diffusion approximation

b. But, in reality: LTE in the *fir* and non-LTE absorption in the *vis*

→ Our model for radiative transfer assumes steady-state

LBL models

all models divide the atmosphere (troposphere), into horizontal layers, in which some radiation is absorbed and some is transmitted (stratified atmosphere).

The τ of all layers is assumed to be constant for a given λ, and each layer is defined by a single radiation temperature.

LBL models use *one downward stream* of radiation:

a. for the *vis* - TOA insolation

b. for the *fir* - Self emission with given $\kappa B_{(T,\lambda)}$ from each atmospheric layer

$$I_{\nu(\mathrm{atm})} = I_{\nu(\mathrm{TOA})} - I_{\nu(\mathrm{TOA})} e^{-\tau_\nu} + \kappa_\nu B_{\mathrm{T},\nu}$$

LBL model, cont'd.

The so found flux (W/m^2) is used as input in GCM's to get $T_{atm} + \Delta T_{atm}$.

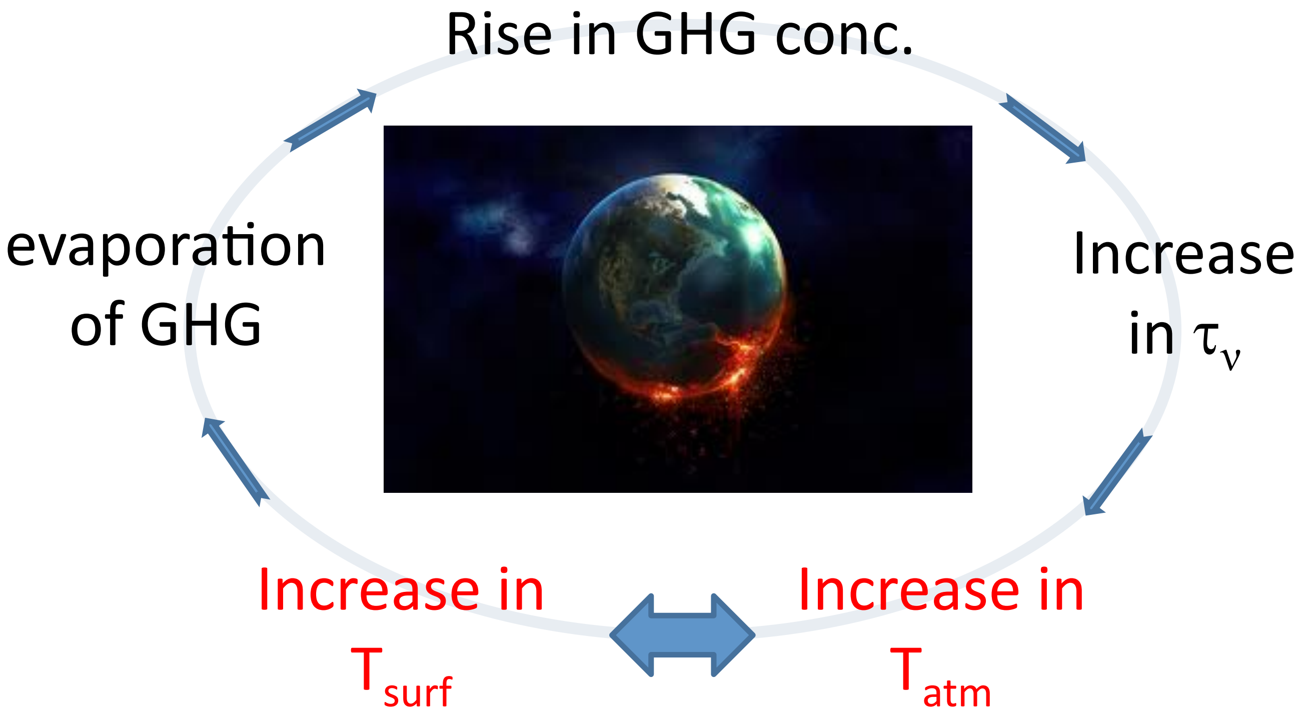
A main assumption of the LBL model is a fixed (T(z), P(z)) profile. T (z) is given and *NOT* iterated for, and thus it always rises with τ.

The transmission is calculated only from the downward radiation in each layer. It is *not* balanced by an upward stream.

What are the consequences of these assumptions?

Runaway Greenhouse

C. Sagan (1960) and T. Gold (1964)



The LBL model, constantly raises T_{atm} by the absorbed energy in the atmosphere.

This treatment necessarily leads to positive feedback and to runaway!!

http://www.highwallpapers.com/wallpaper/knowing-burning-earth-1306.html

From the IPCC report

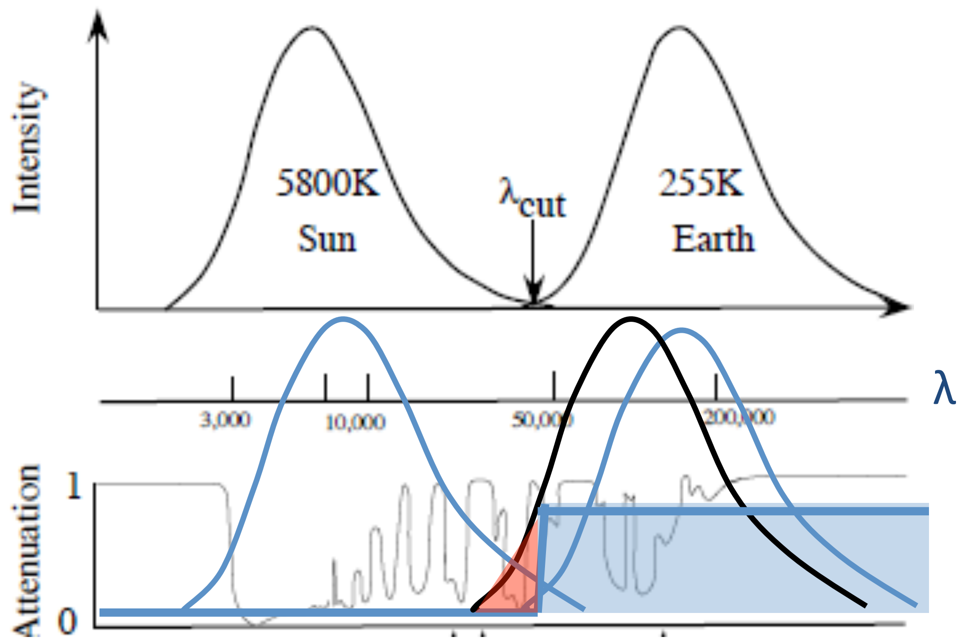
Warming reduces terrestrial and ocean uptake of atmospheric CO_2, increasing the fraction of anthropogenic emissions remaining in the atmosphere. This positive carbon cycle feedback leads to larger atmospheric CO_2 increases and greater climate change for a given emissions scenario, but the strength of this feedback effect varies markedly among models. *{WGI 7.3, TS.5.4, SPM; WGII 4.4}*

So why don't we burn down?

Since this model does not readjust T_{atm} to the new temperature, thus avoiding also the consistency of the radiation field. T_{atm} rises forever, burning down the Earth!

First suggested by J.F. Kasting, (1988) but calculated for the first time by N.J. Shaviv et al (2011), is the effect of radiation escape from the *vis*, following the shift of the planetary Planck-function upon heating.

This stops the positive feedback!!



Simpson's model, 1927

As early as 1927, G. Simpson has calculated pioneering models for the Earth's atmosphere, based on the radiative transfer equation.

His basic assumption for the calculation was
Local Thermodynamic Equilibrium (LTE) in the *fir*

- In LTE, radiation is in thermodynamic equilibrium with matter .
- LTE exists in optically thick atmospheres, such as in the *fir* range of the Earth's atmosphere, $\tau \geq 1$.

Assuming LTE, J=B. Radiative transfer is calculated by the diffusion approximation as defined below, and *the temperature gradient drives the flux in the upward direction*:

$$H_\nu = \frac{1}{2}\frac{dB_\nu}{d\tau_\nu}\cdot\frac{2}{3} = \frac{1}{3}\frac{dB_\nu}{d\tau_\nu} = -\frac{1}{3}\frac{dB_\nu}{\kappa_\nu \rho \, dz}$$

The Simpson Paradox

From Simpson's solution to the radiation equation, a paradox was derived:

$$T_p \approx \left[\left(1 + \frac{3\tau}{4}\right) \frac{(1-a)}{4} \left(\frac{R_\star}{d}\right)^2 \right]^{1/4} T_\star$$

$$\tau \approx 10^5 \Rightarrow T_p > T_*$$

This is a thermodynamic inconsistency!

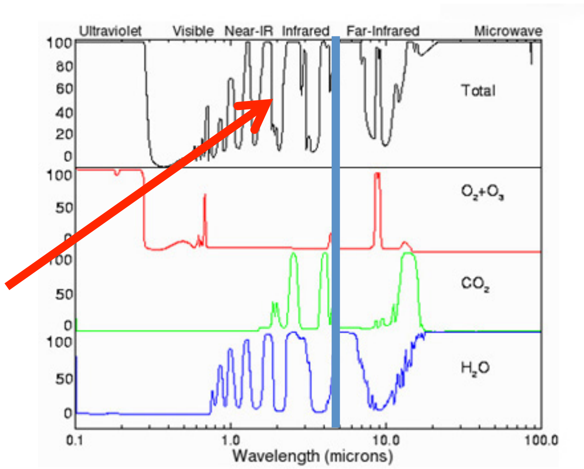
Simpson assumed LTE for $\lambda > \lambda_{cut}$ and $\tau_{vis}=0$ for $\lambda < \lambda_{cut}$, and arrived at a divergent solution.

What went wrong?

Simpson’s Assumptions

N.J.Shaviv et al, Icarus(2011), 216 403

1. No absorption at $\lambda < \lambda_{cut}$ in the optically thin *vis* range.



$\tau_{vis} \neq 0$

2. No leakage of the planetary emission through the *vis* range.

3. LTE assumption despite windows.

So how to calculate $\partial T_{surf} / \partial X$ correctly?

$$\frac{\partial T_{surf}}{\partial X} = \frac{\partial T_{surf}}{\partial \tau_{vis}} \frac{\partial \tau_{vis}}{\partial X} + \frac{\partial T_{surf}}{\partial \tau_{fir}} \frac{\partial \tau_{fir}}{\partial X}$$

Our model

Our model for radiative transfer

➢Our full λ-dependent radiative transfer model, adapted from stellar atmospheres, which includes the atmospheric response.

➢Our model assumes a 2-stream approximation for all λ's :

a. A downward stream as before
b. An opposing upward stream from the surface.

➢Our model imposes steady-state :

$$dQ(z)/dt \equiv 0$$

Our Model, cont'd

Radiation model: τ_{vis} and τ_{fir} are taken as free parameters.

Temperature model:

1. We use τ_{vis} and τ_{fir} to calculate $T(z)_{atm}$ and T_{surf}.

2. We use two Iteration schemes for the Temperature by the method of steepest descent:

a. Iteration for $T(z)_{atm}$ in all atmospheric layers, at constant T_{surf}, until convergence.

b. Then, iteration to thermal equilibration of $T(z)_{atm}$ and T_{surf}, $Flux\uparrow = Flux\downarrow$.

Conditions and B.C.

1. We use a steady-state assumption. No convection or scattering is considered at this stage.

$$\frac{1}{C_V}\frac{dQ(z)}{dt} = \int_0^\infty [B(T(z),\lambda) - J(z,\lambda))]\kappa(z,\lambda)d\lambda - \nabla \cdot F_{conv} = 0$$

2. Boundary conditions:

a. TOA

$$I_-(Z) = \frac{1}{4}\frac{R_\odot^2}{d^2}B(T_\odot,\lambda)$$

(For fast rotating planets)

b. Surface

$$\int_0^\infty (1-a(\lambda))I_+(0,\lambda)d\lambda = \sigma T_{surf}^4$$

The equation for T_{atm} and T_{surf}

To understand the physics, we divide the radiative equation into two regions artificially:

$$\int_0^{\lambda rad} \kappa(T,z,\lambda) J(T,z,\lambda) d\lambda + \int_{\lambda_{rad}}^{\infty} \kappa(T,z,\lambda)[J(T,z,\lambda) - B(T,z,\lambda)] d\lambda = 0$$

$J_{\odot}(T=5800K) >> B_{\oplus}(T=288K)$

$J_{\odot}(T=288K) \approx B_{\oplus}(T=288K)$

In practice, this separation comes out of the calculation and is not imposed.

Heating and Cooling

Thus, we get:

$$\int_0^{\lambda_{rad}} \kappa(T, z, \lambda) J(T, z, \lambda) d\lambda > 0 \Longrightarrow \odot \text{ heating}$$

and

$$\int_{\lambda rad}^{\infty} \kappa(T, z, \lambda)[J(T, z, \lambda) - B(T, z, \lambda)] d\lambda < 0 \Longrightarrow \oplus \text{ cooling}$$

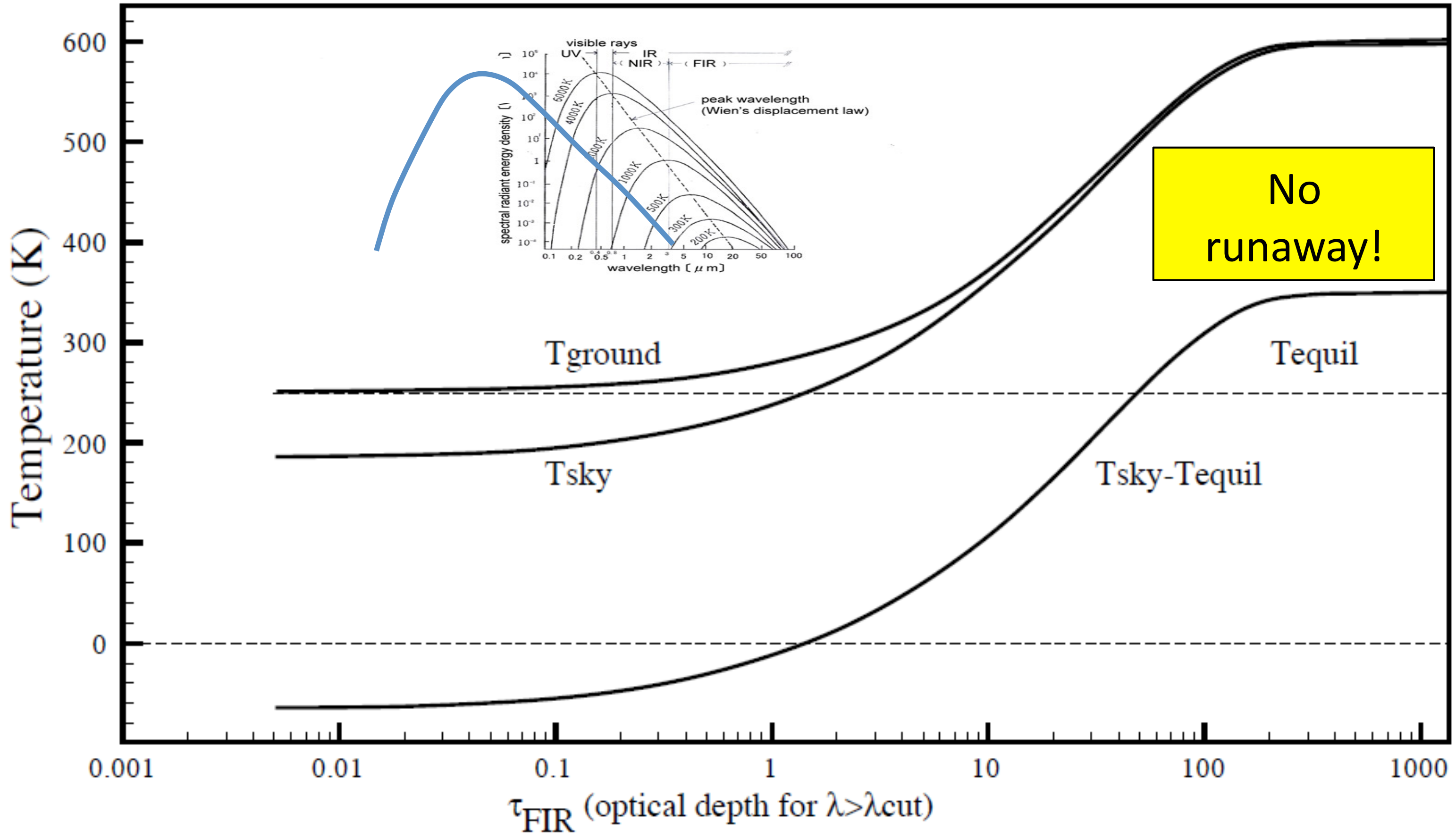
Our model yields T_{atm} and T_{surf} which are consistent with the radiation-field!

Our results

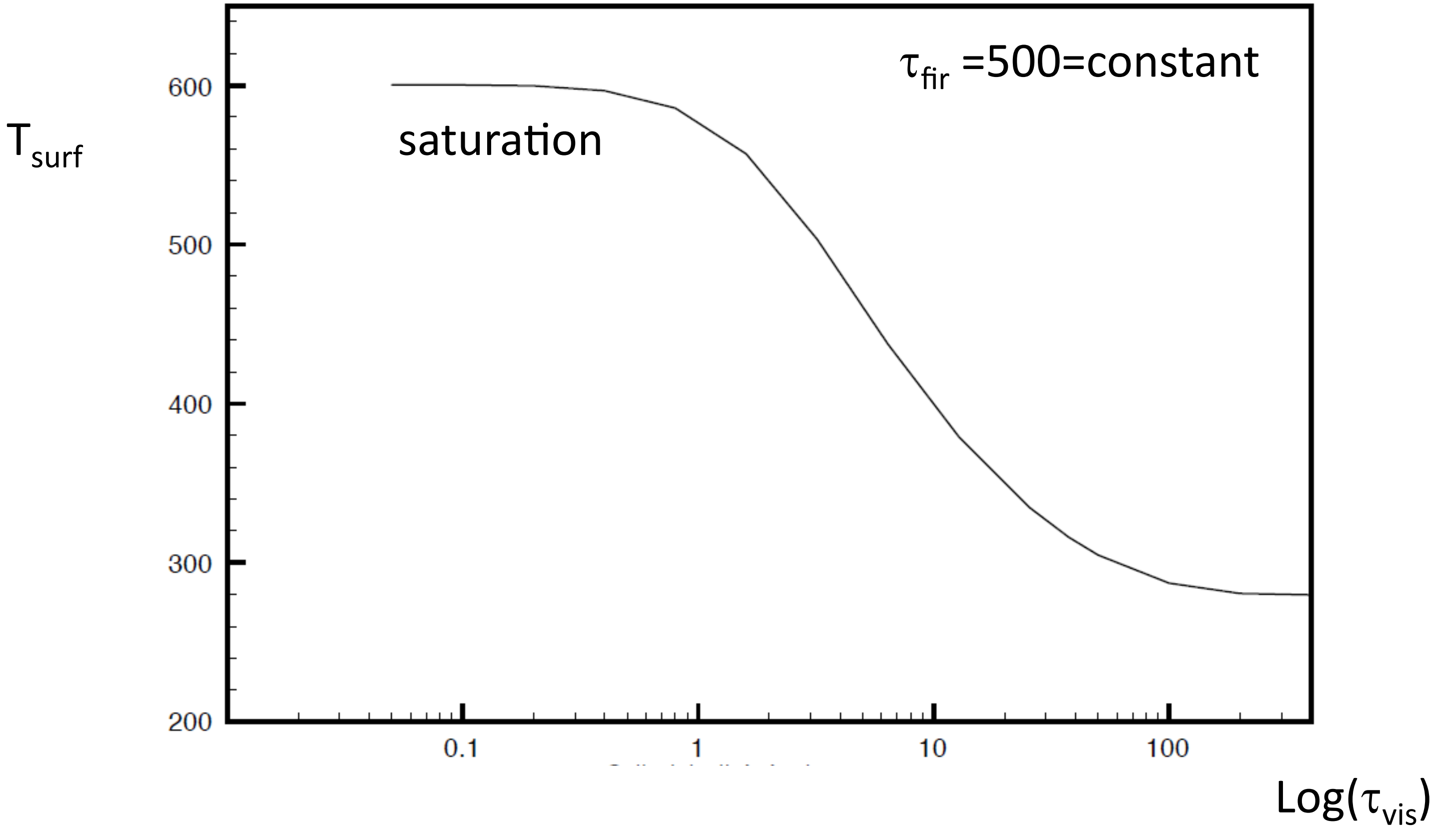
Saturation of T_{surf} at high values of τ_{fir}

after *N.J.Shaviv, et al; Icarus, (2011)* ***216****, 403*

As T_{surf} rises, more planetary radiation escapes through the visible range. This causes saturation of the GH effect.



Cooling at Rise of τ_{vis}



We saw that High τ_{fir} & low τ_{vis} yield saturation.

But, as τ_{vis} increases to O(1), heating is reduced because insolation is absorbed at high altitudes and doesn't reach the surface.

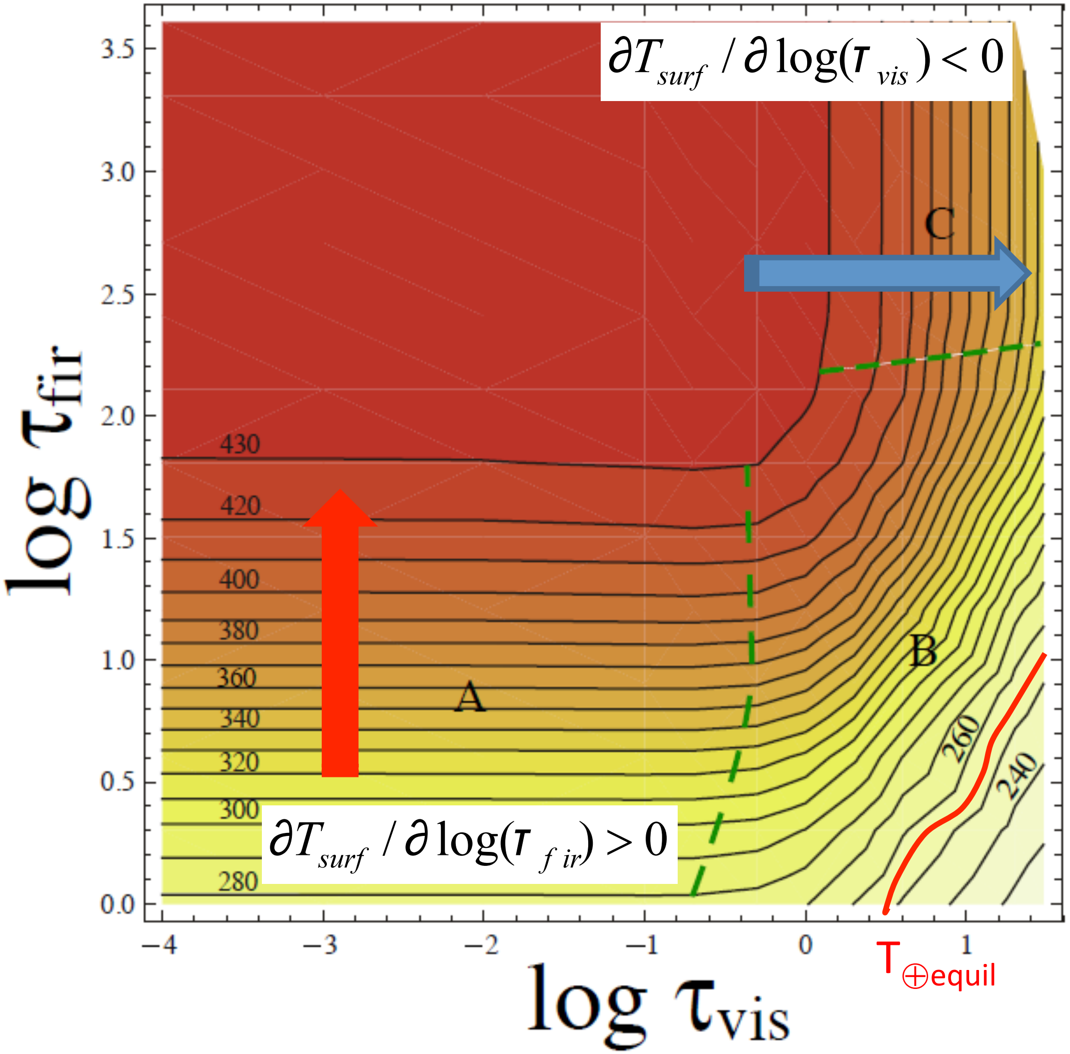
Summary until now

1. The GHE *does not* runaway, due to short-wave escape of radiation.

2. Increasing the *vis* absorption reduces surface temperature.

3. Our steady state model allows for these effects to be calculated.

The unified picture - $T_{surf}(\tau_{vis}, \tau_{fir})$



The unified radiative model: heating *and* cooling

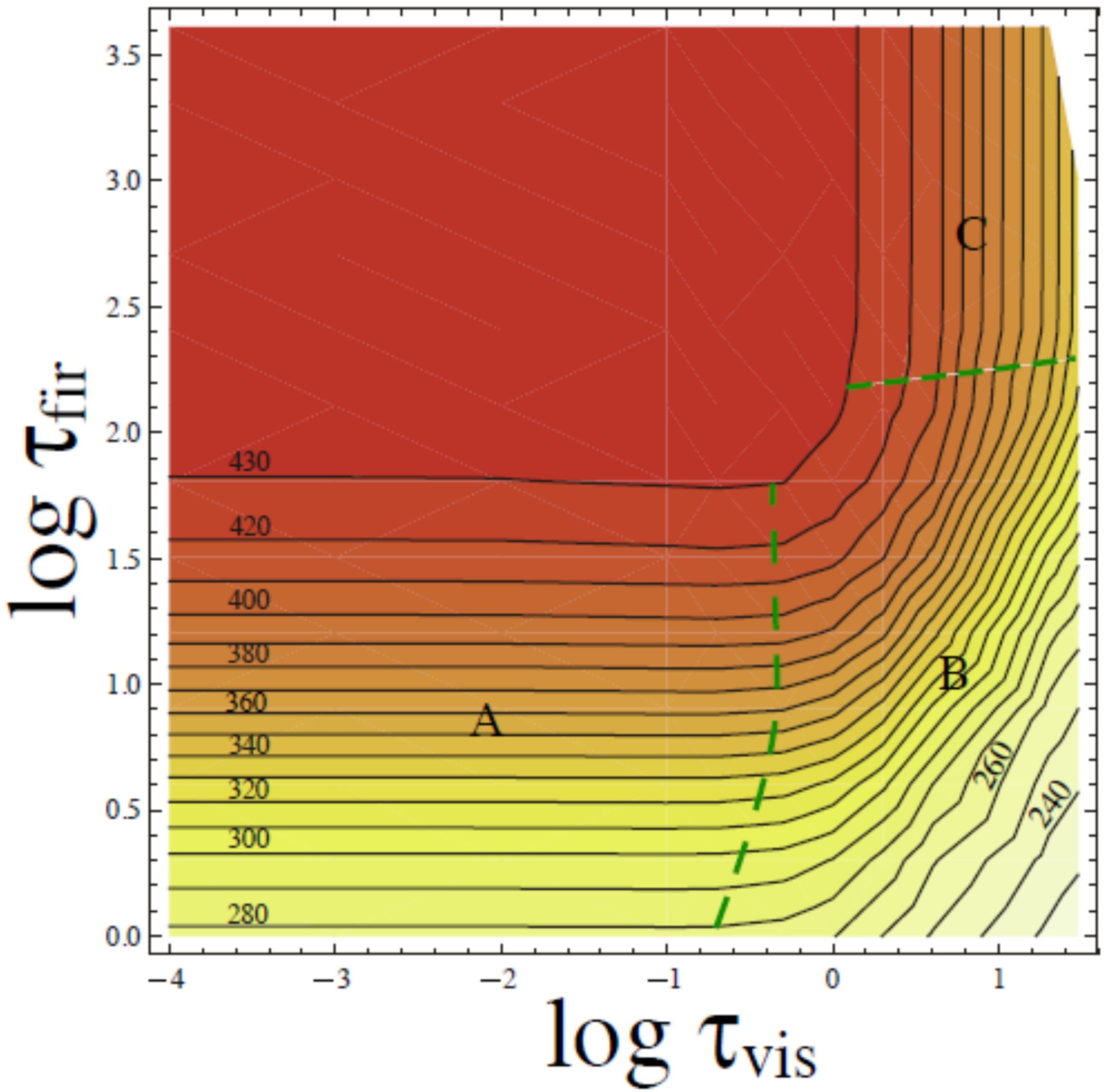
Stability region?

$\partial T_{surf} / \partial \log(\tau_{vis}) =$?

$\partial T_{surf} / \partial \log(\tau_{fir}) =$?

What can be done with our results?

A universal radiative transfer limit



For each planetary atmosphere we can draw a 3D graph with a maximal Tsurf, determined only by:

the astrophysical setup

and by λcut.

If this limit is exceeded, it is not a planet, it's a star!

No spectrum required for T_{lim}!

The only given parameters are:
the astronomical configuration and the planet's temperature

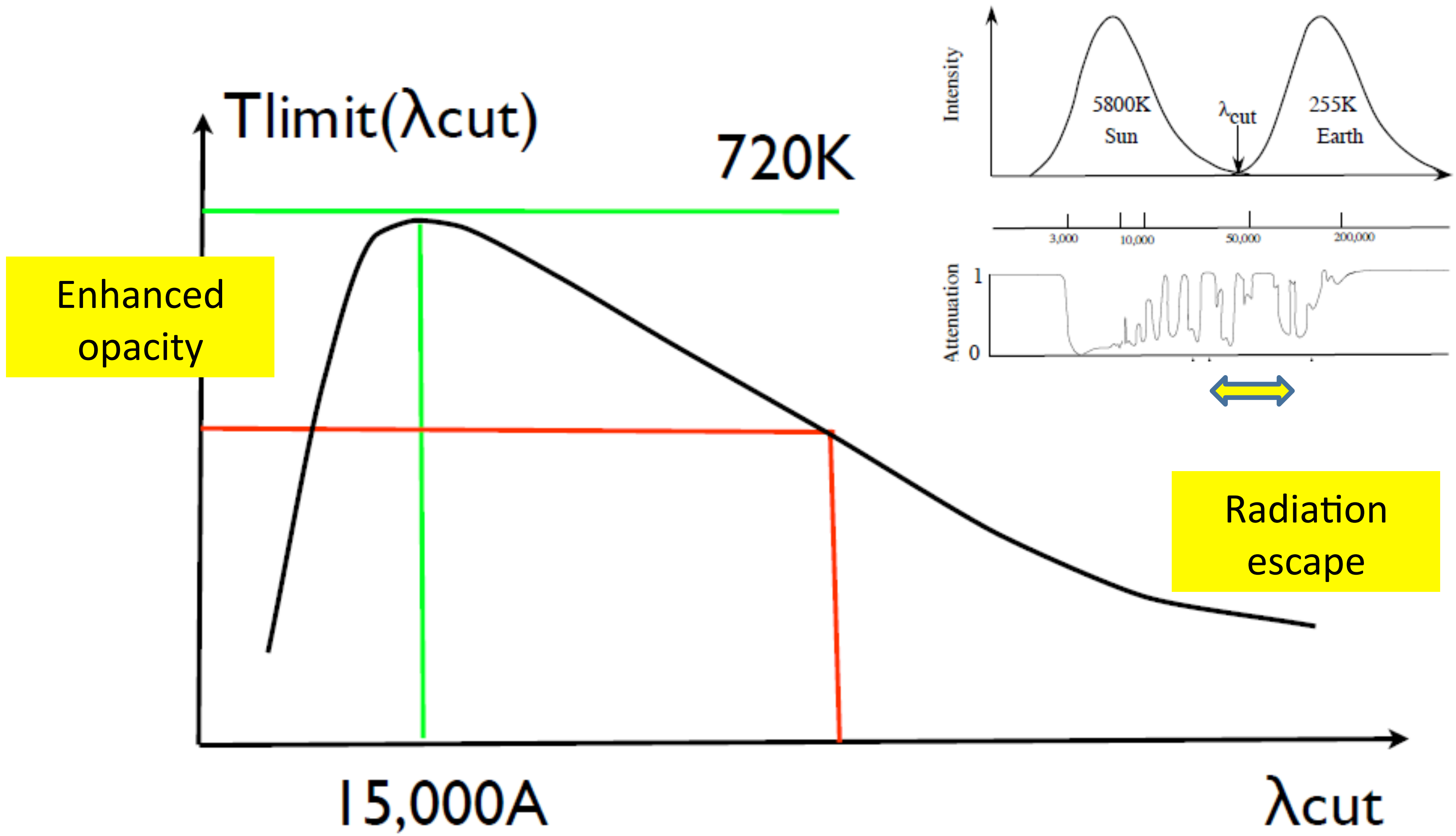
We look for the nearest equi-temperature line on the 3D plane.

The 3D plane is λcut sensitive. So the question is, is there an upper limit of Tsurf as function of λcut?

The upper limit is obtained from the shift of λcut to shorter wavelengths until *no radiation can escape* from the *vis* range.

This is the ULTIMATE limit on Tsurf without the spectral fingerprint!

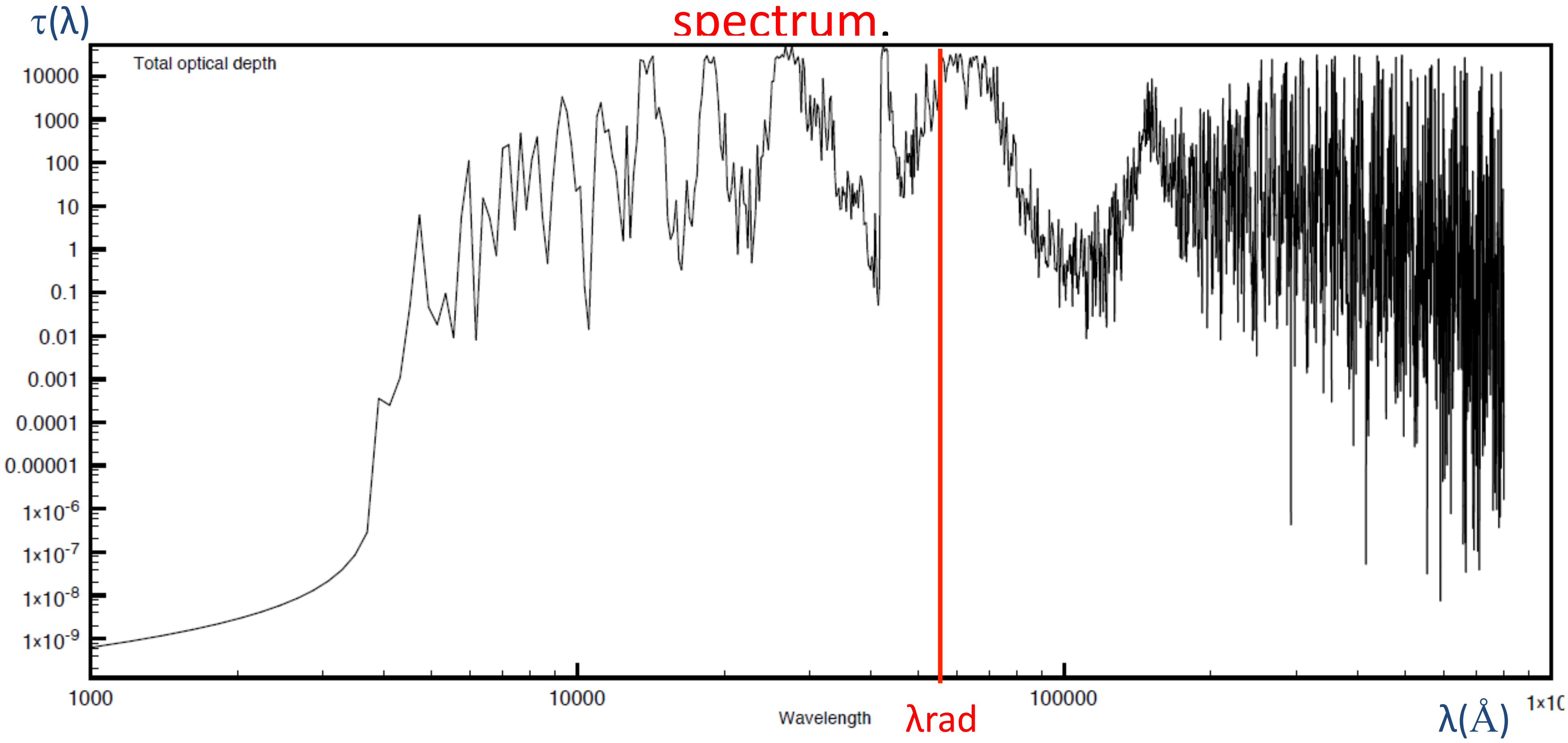
Ultimate temperature limit for Venus



In case λcut is known from the spectrum, things are extremely facilitated.

So Where is the Earth on this Graph?

In order to answer this question we have to calculate "average" τ_{vis} and τ_{fir} for the Earth from its absorption spectrum.



HITRAN 2008

Averaging for line absorption

For the average τ, it is necessary to average over the line absorption without changing the energy flux.

The mean is defined as:

$$<\tau>=\int_{\nu 1}^{\nu 2} \kappa B(T,\nu) d\nu / (\nu_2 - \nu_1)$$

The Planck mean (satisfies emission conservation):

$$\int_{\nu_1}^{\nu_2} \kappa_\nu B(T,\nu) d\nu = \langle \kappa_P \rangle_{\Delta\nu} \int_{\nu_1}^{\nu_2} B(T,\nu) d\nu$$

The Rosseland mean (requires diffusion):

$$\left\langle \frac{1}{\kappa_{Ross}} \right\rangle_{\Delta\nu} \int_{\nu_1}^{\nu_2} \frac{\partial B(T,\nu)}{\partial T} d\nu = \int_{\nu_1}^{\nu_2} \frac{\partial B(T,\nu)}{\partial T} \frac{1}{\kappa(\nu)} d\nu$$

Our semi-grey model

S.Bressler, N.J.Shaviv, G.Shaviv (2012) *to be published*

λ <λrad

$$\ln \langle \tau_{vis} \rangle = -\frac{\int_{\nu_1}^{\nu_2} B(T_{\odot},\nu) e^{-\tau(\nu,T_{atm})} d\nu}{\int_{\nu_1}^{\nu_2} B(T_{\odot},\nu) d\nu}$$

We take as the weighting function the attenuation of intensity

$I(\lambda) = B_{\odot}(\lambda)e-\tau(\lambda)$

λ >λrad

$$\tau_{fir} = \frac{4}{3}\left[\frac{\int_{\nu_1}^{\nu_2} B(T_{atm},\nu) d\nu}{\int_{\nu_1}^{\nu_2} \frac{B(T_{atm},\nu)d\nu}{1+3\tau(\nu)/4}} - 1\right]$$

We take as the weighting function the Simpson solution.

For $\tau(\lambda)$=const ➔ $\tau_{fir} = \tau$

$\lambda rad = 50{,}000$Å

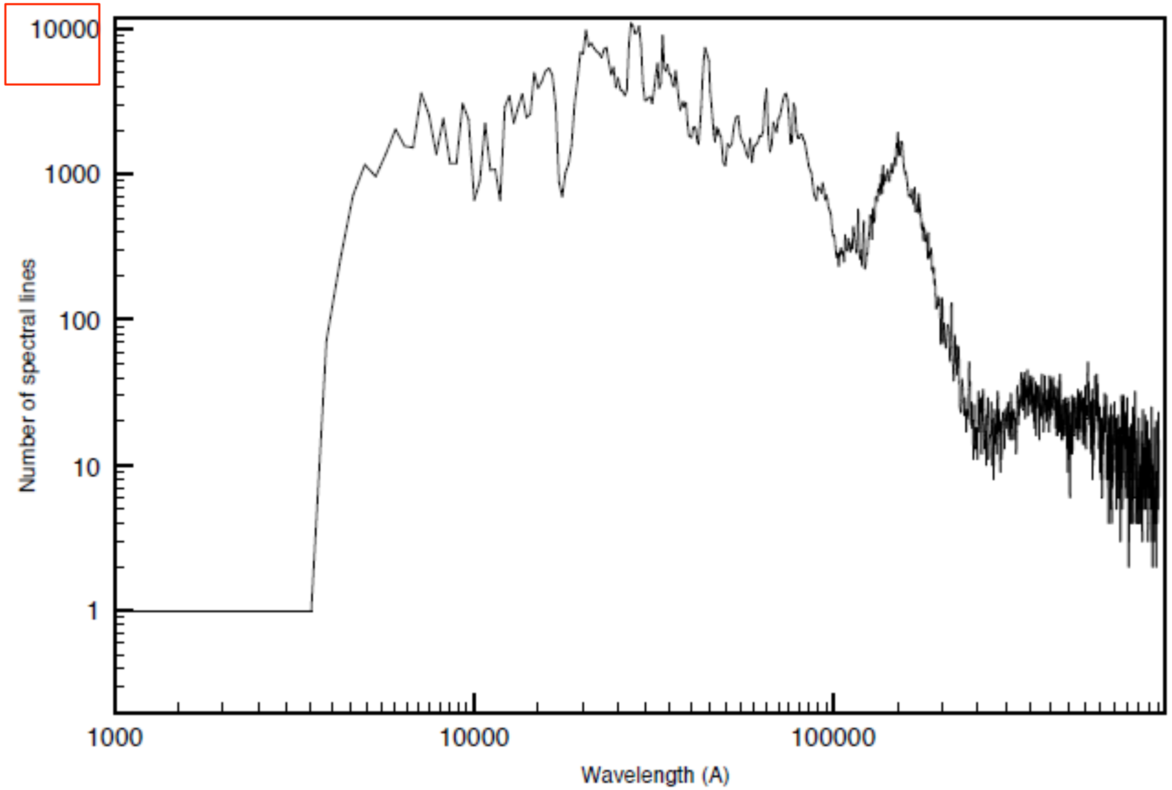
Constraints on the spectrum

- 848,001 wavelengths were chosen every 1Å in the range 10^3-$8x10^5$Å

- All Hitran2008 lines of the Earth's standard atmosphere, over $2x10^6$, are included in the calculation

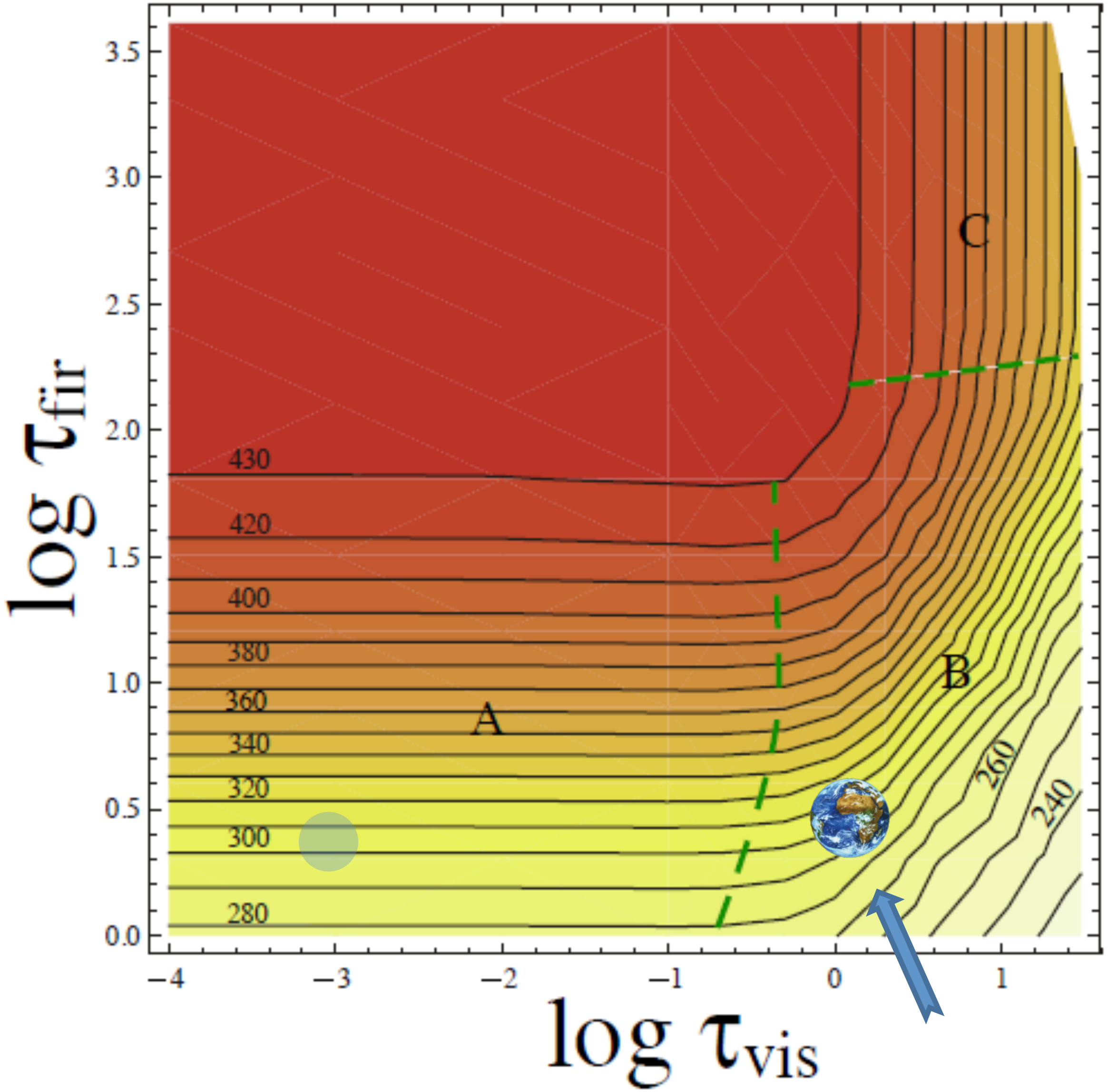
- The shape of the lines in the different layers were calculated by the Voigt function including Doppler and pressure broadening.

❖ At each wavelength, contribution from lines as far away as 200Å on each side of the line in the *vis* and 400Å on each side in the *fir* are included.



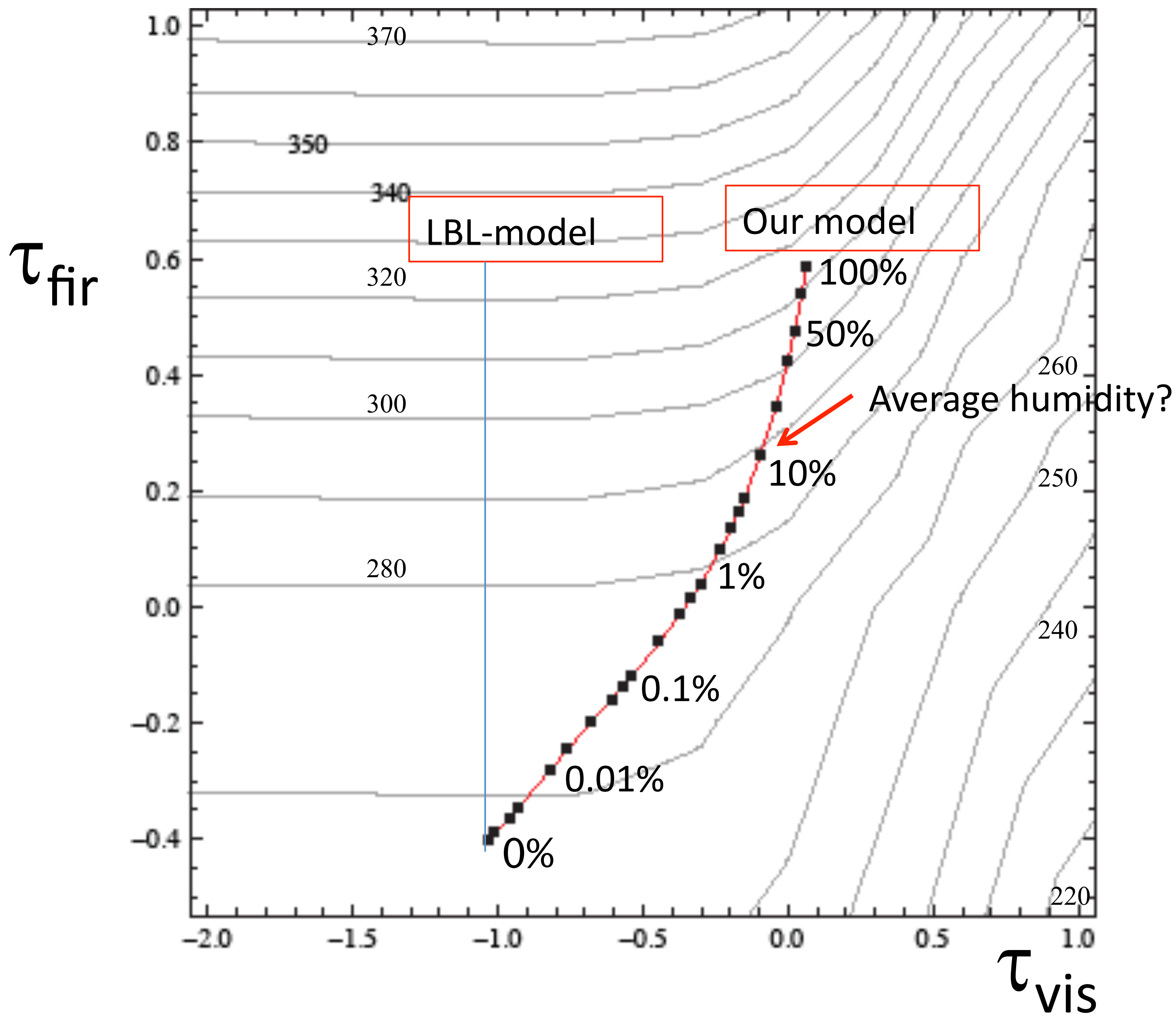
HITRAN 2008

We are here!

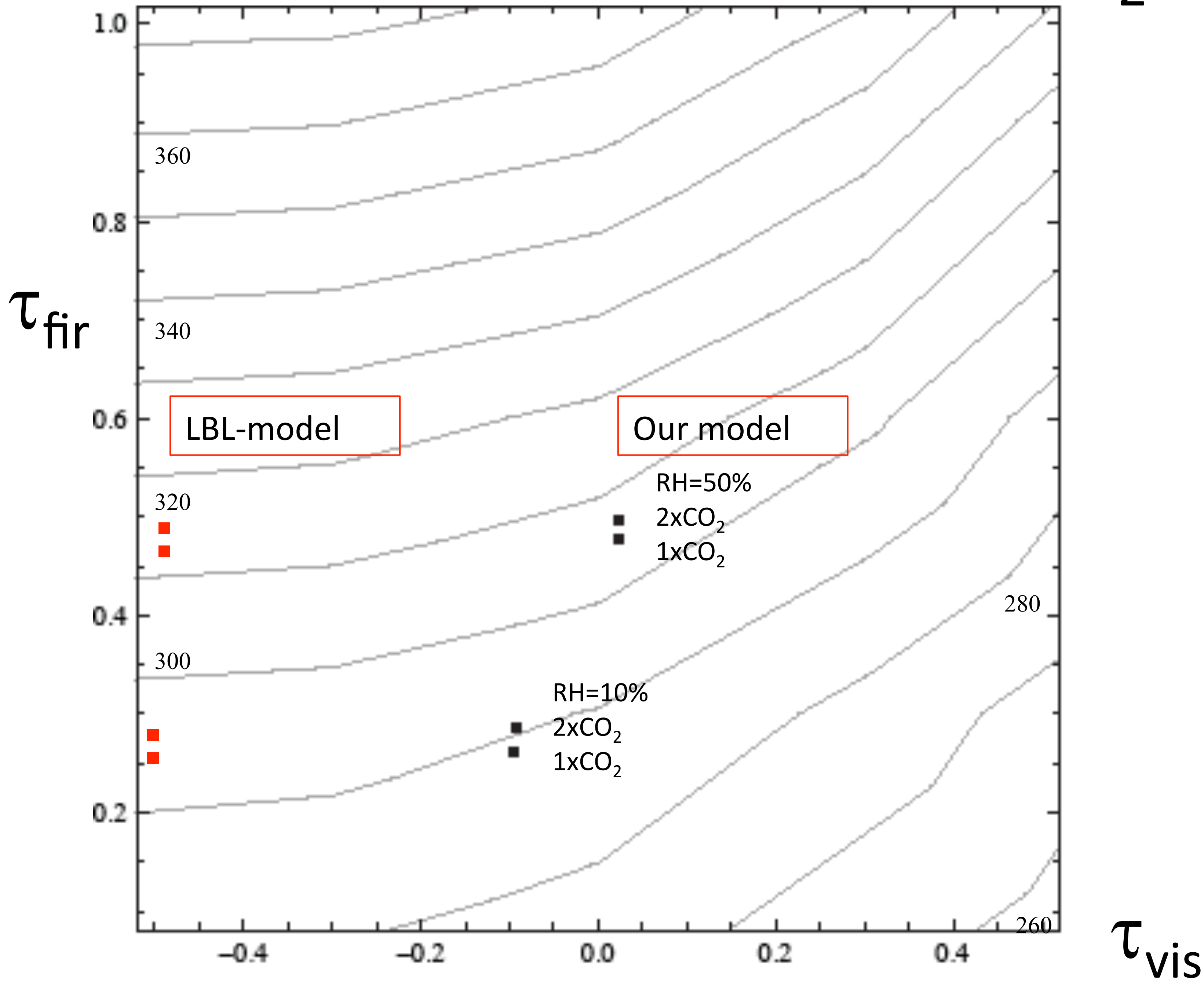


3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
log τfir
430
420
400
380
360
340
320
300
280
A
B
C
260
240
−4
−3
−2
−1
0
1
log τvis

Planetary Evolution: effect of relative humidity



Planetary Evolution: doubling CO_2



Relative humidity and CO_2

RH	CO_2-ppm	τvis	<τ>	τplanck	τfir	<τ>	τplanck
5	391.6	0.701015	2297.772	474.819	1.53127	294.06	462.429
10	391.6	0.801728	2763.181	657.5	1.82605	508.386	712.148
35	391.6	0.996608	3863.801	1173.869	2.656576	1188.99	1395.926
50	391.6	1.05252	4237.145	1370.059	2.99793	1464.409	1645.696
75	391.6	1.114919	4699.114	1623.032	3.467154	1821.849	1958.15
10	783.2	0.805433	3022.129	670.558	1.92976	530.665	792.682
50	783.2	1.05497	4473.348	1380.28	3.132385	1486.632	1726.34

τvis ≈1 and τfir ≈1

We expect exactly these values, and not a value of 10^3, as the average and the Planck mean yields, which causes complete saturation and unrealistic temperatures.

Summary and Conclusions

Model Summary

1. We presented our model for radiative transfer of planetary atmospheres in light of other models.

2. Our model's attitude is novel in the following ways:

a. We identified the different role of tauvis and taufir.

b. We use the radiative transfer equation for iteration for Tsurf.

c. We use the steady-state assumption

d. We find a universal dependency of Tsurf on τfir, τvis

e. We can analyze the effect on Tsurf of any gas on any planet, given its astronomic configuration and spectral fingerprint.

Conclusions

- ❖ Our Model allows for full radiative feedback in the atmosphere
  - ❖ we arrive at realistic values of tau from our semi-grey model.
    - ❖ T_{surf} saturates at an upper limit. T_{atm} was not discussed.
      - ❖ We can discriminate between planets and cool stars by this limit.
        - ❖ The Earth is located far from the limit in a relatively stable region.
      - ❖ High absorption in the visible region reduces heating
    - ❖ The effect of relative humidity is lower than obtained by the LBL model
  - ❖ The sensitivity of $\partial T_{surf} / \partial CO_2$ is less than obtained by the LBL model

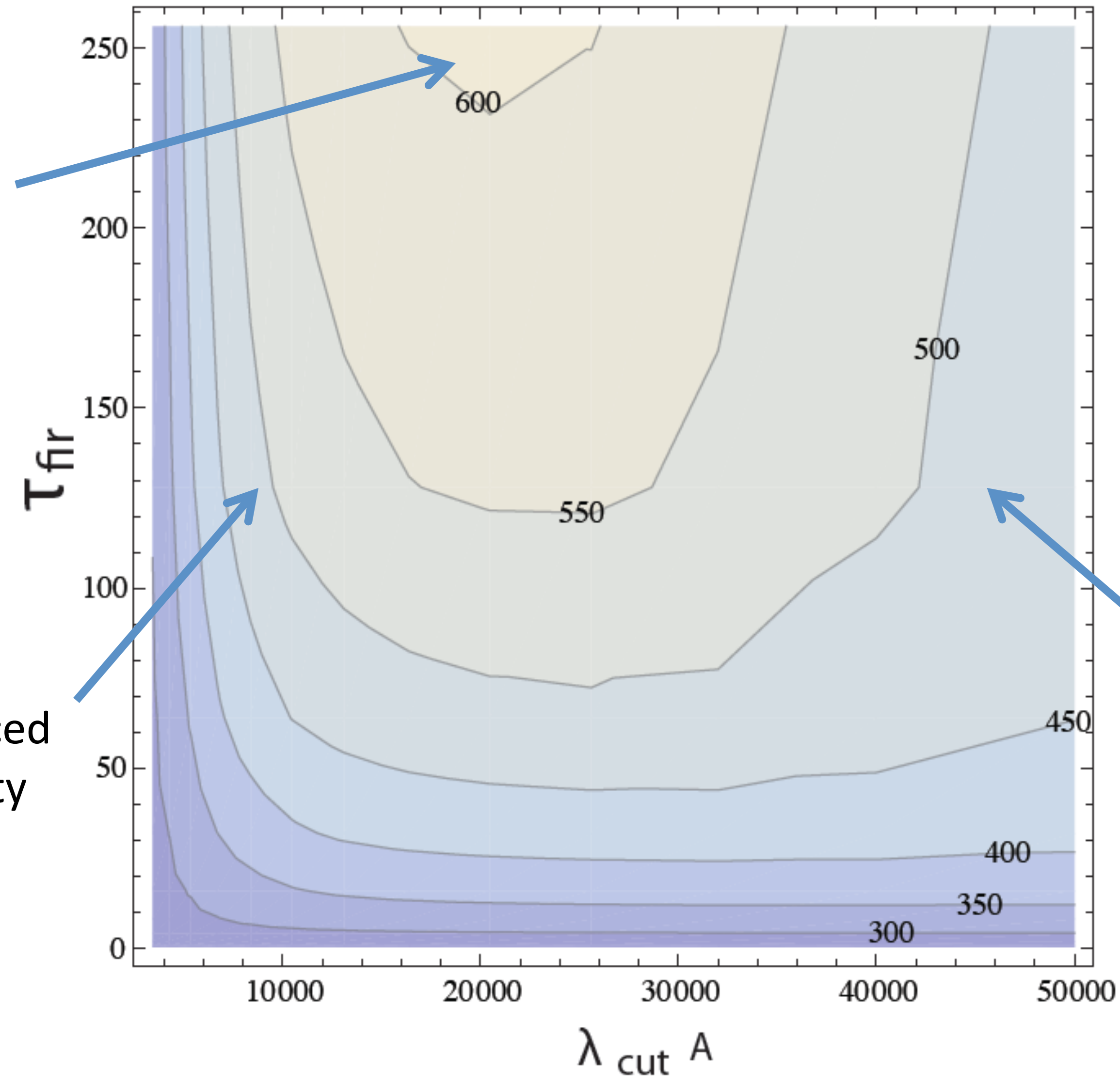
❖ Our model allows to assess the temperature sensitivity of planetary atmospheres to atmospheric concentration changes during planetary evolution

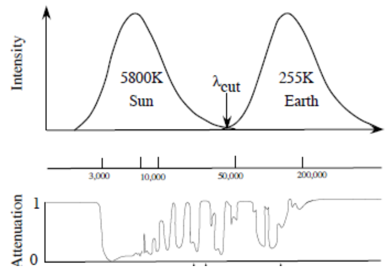
PRELIMINARY RESULTS – CLASSIFIED!!!

http://www.uiowa.edu/~nathist/EarthMonth.html

Saturation in the τ_{fir}/λ_{cut} plane

Saturation of τ_{fir}





Enhanced opacity

Radiation escape in SW

Convection

The Earth's atmosphere will transfer heat in a convective manner, only when the temperature gradient of the atmosphere is just above the adiabatic limit.

We can parameterize the adiabatic limit from our model, by translating the calculated $dT/d\tau_{fir}$, into a dT/dz gradient:

$$\frac{dT}{dz} = \frac{dT(\tau)}{d\ln\tau}\frac{d\ln\tau}{dz} = \frac{dT(\tau)}{d\ln\tau}\frac{1}{l}$$

$$l = (d\ln\tau/dz)^{-1}$$

is the linear scale.
the smaller it is, the grater is dT/dz.

The limiting temperature gradient has the steepest descent. Thus, a further increase of τ_{fir} beyond the adiabatic limit, will not change the onset of convection.

Temperature Calculation

The atmosphere is divided into 50 layers.

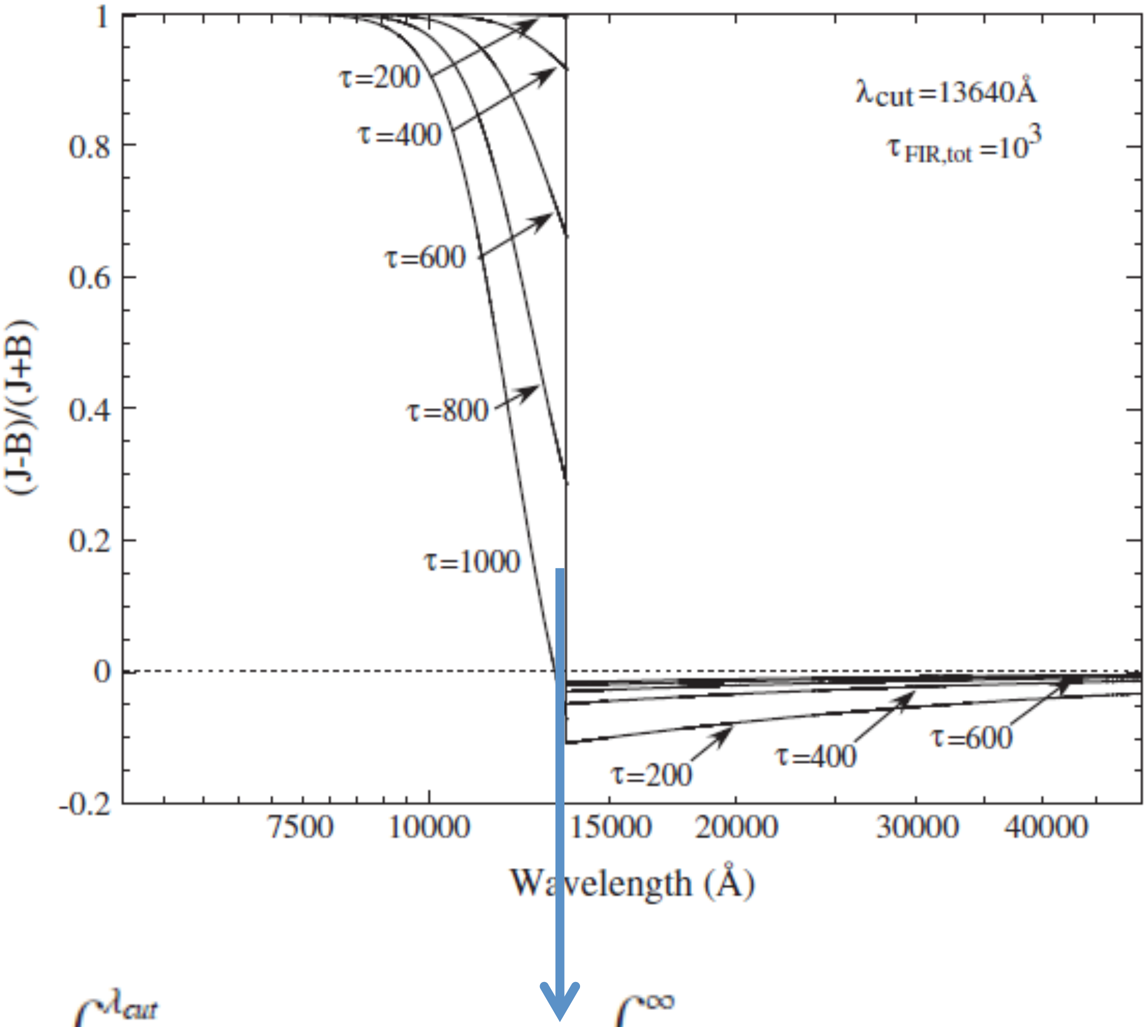
No linear scale is defined - the fraction of radiation through each spectral band is the same throughout the layers.

Elastic scattering only - no thermal redistribution is considered. $B_{T(\lambda,z)}$ is calculated from a single temperature, to allow for an analytic solution.

Iteration by steepest descent method (relative accuracy of 10^{-6}):

a. for the temperature in all atmospheric layers, at a constant surface temperature, until convergence.
b. then, iteration until a thermal equilibration of the atmosphere and surface is achieved.

J-B



$$\int_0^{\lambda_{cut}} \kappa(z,\lambda) J(z,\lambda) d\lambda \quad + \int_{\lambda_{cut}}^{\infty} \kappa(z,\lambda) \left[J(z,\lambda) - B(z,\lambda) \right] d\lambda = 0$$

Our model, cont'd.

The two stream approximation may be used for simplicity, due to the geometrically bi-polar nature of the source functions:

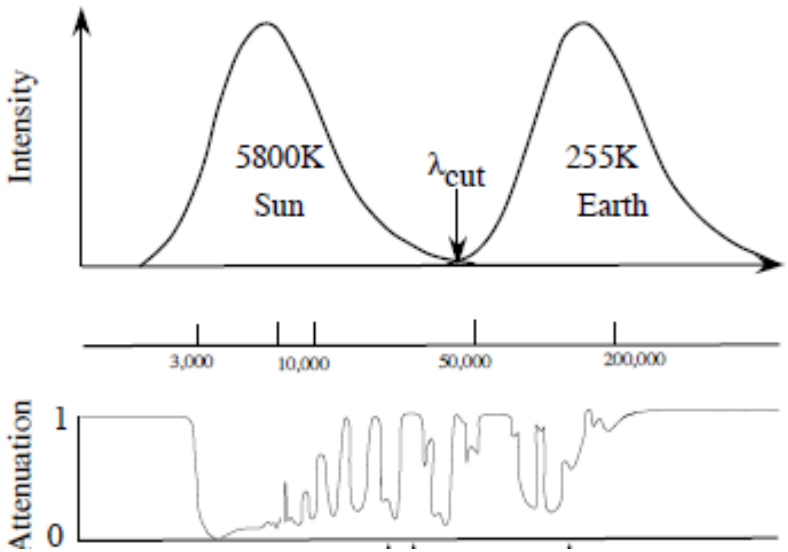
$$J(z,\lambda) = \left(I_+(z,\lambda) + I_-(z,\lambda)\right)/2$$

The radiative transfer equations, for the downward and upward fluxes are, respectively:

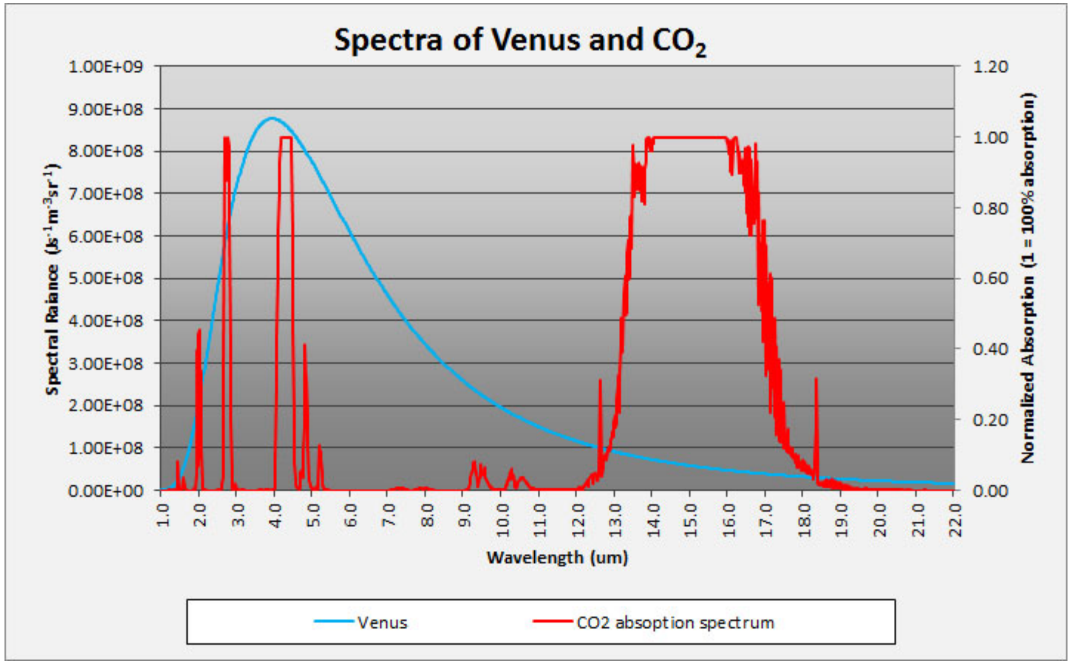
$$-\frac{dI_-}{d\tau} = -\kappa(x,\lambda,z)I_- - \cancel{\sigma(\lambda,z)I_-} + B(\lambda,T) + \cancel{\sigma(\lambda,z)J(\lambda,z)}$$

$$-\frac{dI_+}{d\tau} = -\kappa(x,\lambda,z)I_+ - \cancel{\sigma(\lambda,z)I_+} + B(\lambda,T) + \cancel{\sigma(\lambda,z)J(\lambda,z)}$$

The spectral complexity of planets

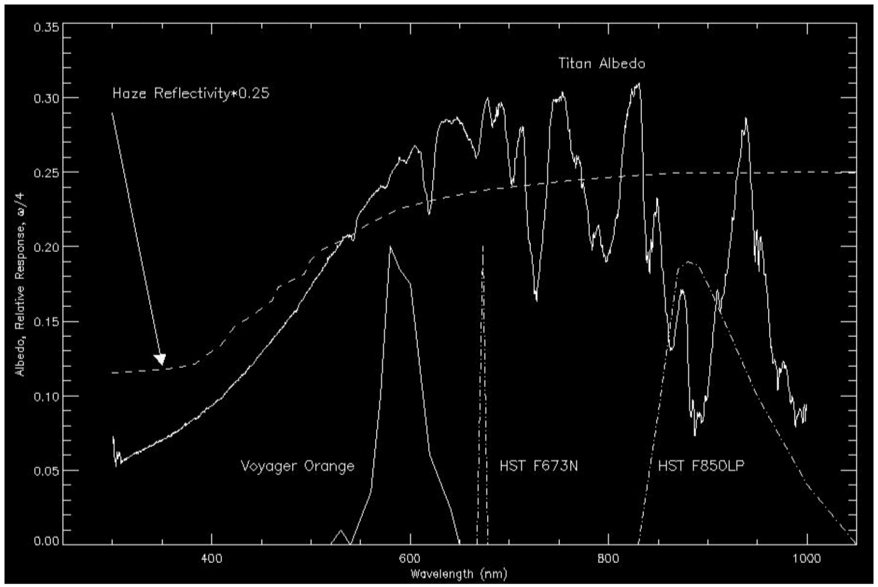


EARTH



http://www.scholarsandrogues.com/2011/05/06/venus-climate-v-co2-heating/

VENUS



TITAN

http://www.eas.purdue.edu/richardson/vgertitan.html

Models comparison

Simpson's model treats only the heating in the fir:

$$\int_{\lambda_{\mathrm{rad}}}^{\infty} \kappa(T, z, \lambda)[J(T, z, \lambda) - B(T, z, \lambda)]d\lambda = 0 \Longrightarrow \partial T_{surf} / \partial \tau_{\mathrm{fir}} > 0$$

LBL model treats the heating from absorption in the *fir* and *vis*:

$$I_{\nu(\mathrm{atm})} = I_{\nu(\mathrm{TOA})} - I_{\nu(\mathrm{TOA})} e^{-\tau_\nu} + \kappa_\nu B_{T,\nu} \Longrightarrow \begin{cases} \partial T_{surf} / \partial \tau_{vis} > 0 \\ \partial T_{surf} / \partial \tau_{\mathrm{fir}} > 0 \end{cases}$$

Our full model considers both the above, but also *vis* cooling:

$$\int_{0}^{\infty} \kappa(T, z, \lambda)[J(T, z, \lambda) - B(T, z, \lambda)]d\lambda = 0$$

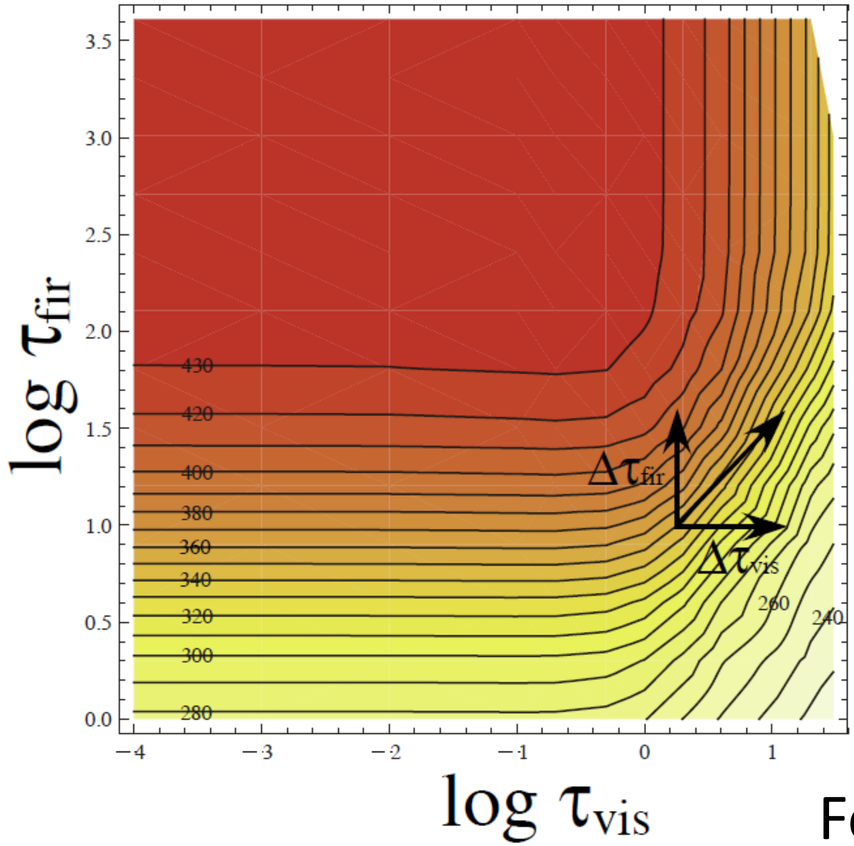
$$\partial T_{surf} / \partial \tau_{vis} < 0$$

Which is the molecular absorption anti-GHE cooling!!

And possibly also: $\partial T_{surf} / \partial \tau_{\mathrm{fir}} < 0$

The Greenhouse Index

The 3D-plane, allows to define a GH Index, reflecting the *change* in T_{surf} which depends on both τ_{vis} and τ_{fir}.



1. Let $(\partial\tau_{fir}/\partial\tau_{vis})_{Tsurf(\tau vis,\tau fir)} = \alpha_0$

2. Let $(\partial\tau_{fir}/\partial\tau_{vis})_{\Delta x(\tau vis,\tau fir)} = \alpha$

Then:

$$GHI(X,X')_{(\tau vis,\tau fir)} = \alpha - \alpha_0$$

Chemistry — Radiation

For GHI>0 we get heating and GH

For GHI<0 we get cooling and anti-GH

The GHI is a wonderful tool to track changes during planetary evolution!