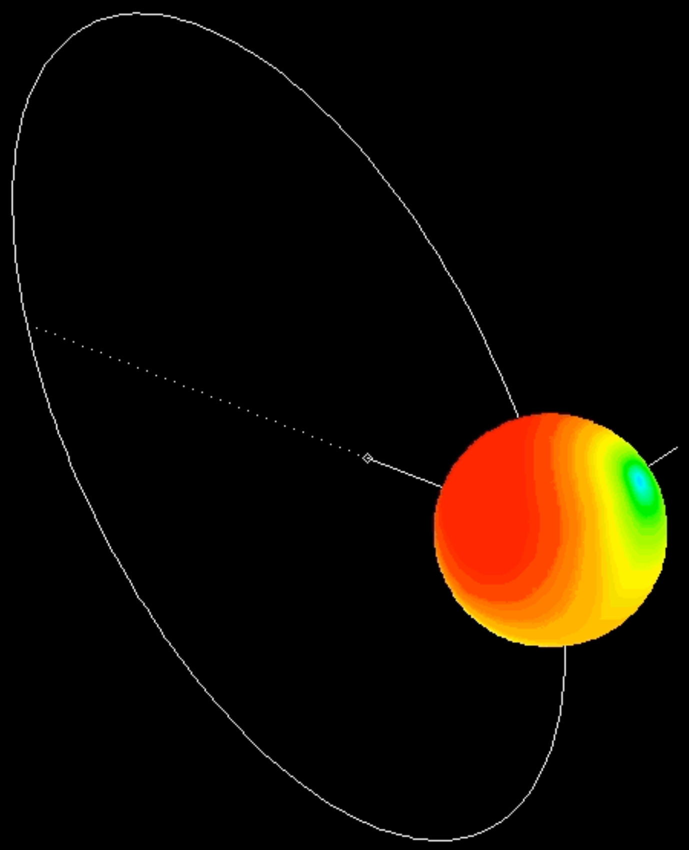
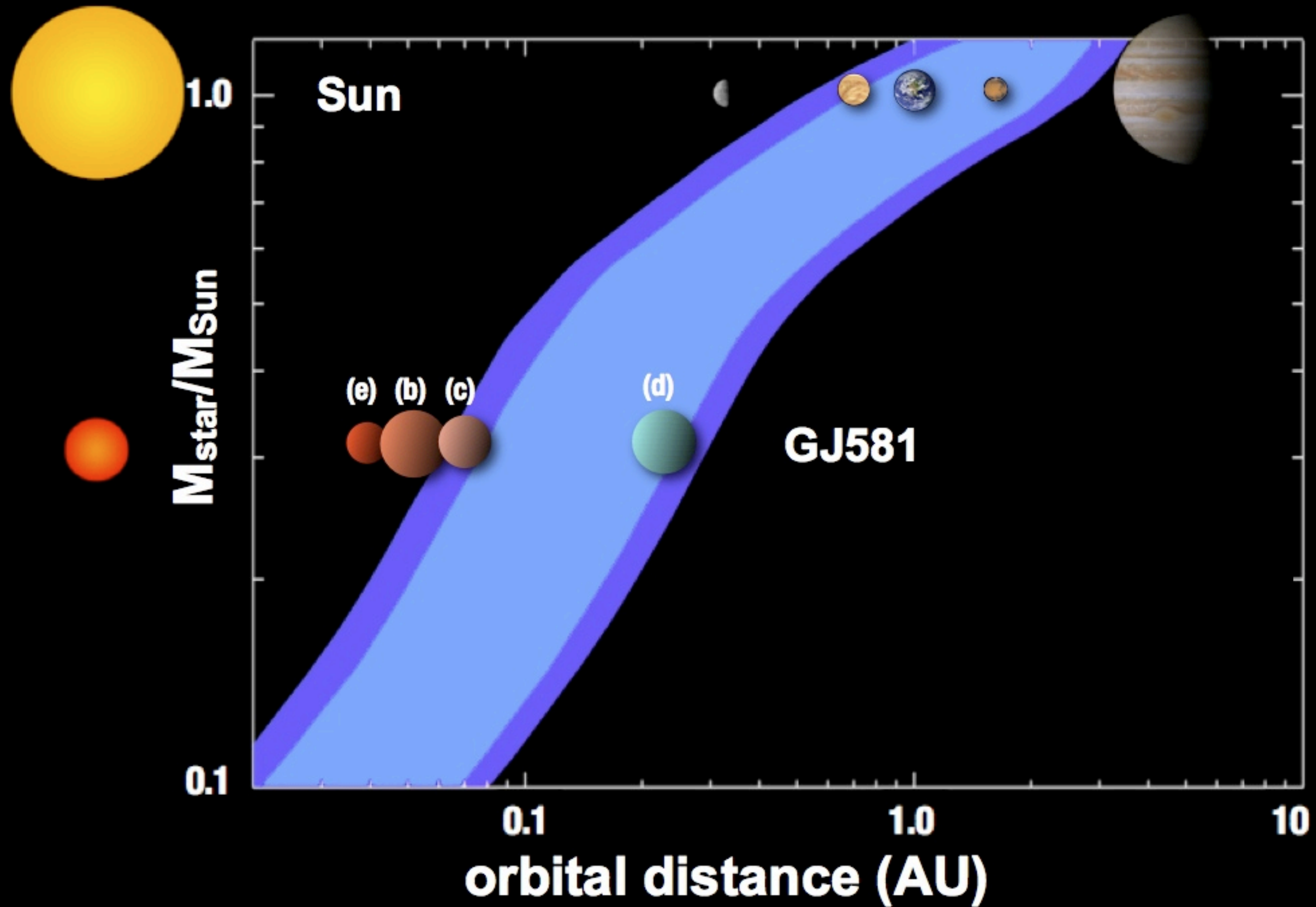
The atmospheres of short-period terrestrial exoplanets



E$_3$ARTHS group (Bordeaux): F. Selsis, A. Belu, M. Dobrijevic, I. Gomez-Leal, E. Hébrard, P. Hedelt, A.-S. Maurin, S. Raymond, O. Venot

LMD (Paris): R. Wordsworth, F. Forget, F. Codron

LISA (Créteil): Y. Bénilan et al.



RV GJ581: Udry et al., 2007; Mayor et al., 2009

HZ: Selsis, Kasting et al, 2007

Habitability around M stars

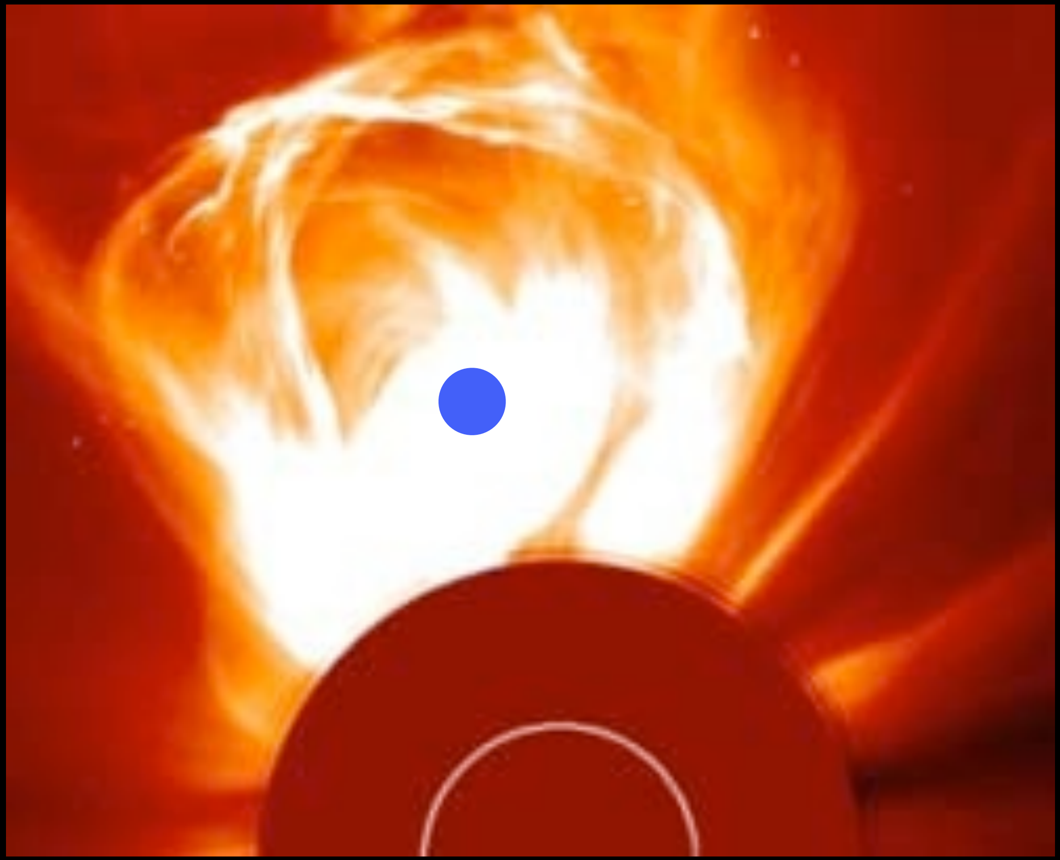
- Strong tidal interaction with the star. Slow rotation. Fast tidal locking if circular orbit. The atmosphere can freeze out on the dark hemisphere if heat redistribution (circulation, greenhouse effect) not efficient enough.

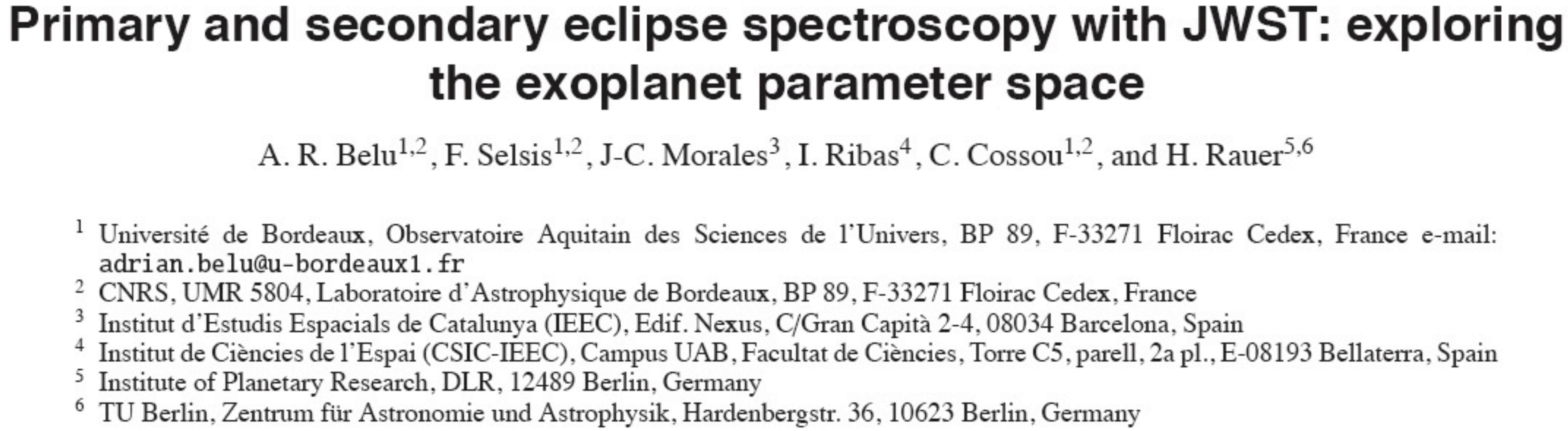
(A dense atmosphere can prevent synchronization, see Correia et al., 2008).

- Planets in the HZ are subjected to high and long-lasting X-EUV radiations, strong stellar winds (Scalo et al., 2007), frequent CMEs (Kodatchenko et al., 2007) and flares

➔Fast atmospheric escape

Do terrestrial planets in the HZ of M stars have an atmosphere ?





Primary and secondary eclipse spectroscopy with JWST: exploring the exoplanet parameter space

A. R. Belu[1,2], F. Selsis[1,2], J-C. Morales[3], I. Ribas[4], C. Cossou[1,2], and H. Rauer[5,6]

[1] Université de Bordeaux, Observatoire Aquitain des Sciences de l'Univers, BP 89, F-33271 Floirac Cedex, France e-mail: `adrian.belu@u-bordeaux1.fr`
[2] CNRS, UMR 5804, Laboratoire d'Astrophysique de Bordeaux, BP 89, F-33271 Floirac Cedex, France
[3] Institut d'Estudis Espacials de Catalunya (IEEC), Edif. Nexus, C/Gran Capità 2-4, 08034 Barcelona, Spain
[4] Institut de Ciències de l'Espai (CSIC-IEEC), Campus UAB, Facultat de Ciències, Torre C5, parell, 2a pl., E-08193 Bellaterra, Spain
[5] Institute of Planetary Research, DLR, 12489 Berlin, Germany
[6] TU Berlin, Zentrum für Astronomie und Astrophysik, Hardenbergstr. 36, 10623 Berlin, Germany

2 R_{Earth} planet
S/N for the strongest potential spectral features (e.g. 4.3 and 15 μm CO_2, 9.6 μm O_3) in emission and transmission

stellar photon noise only

instrumental and astrophysical sources of noise

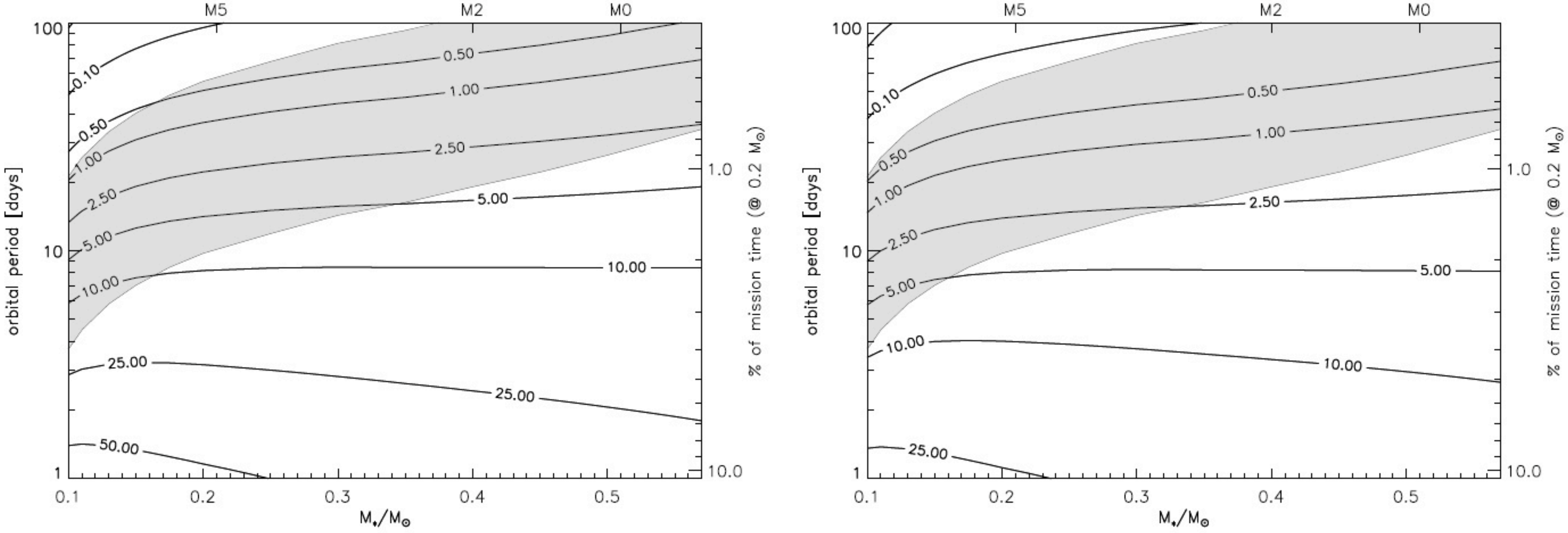
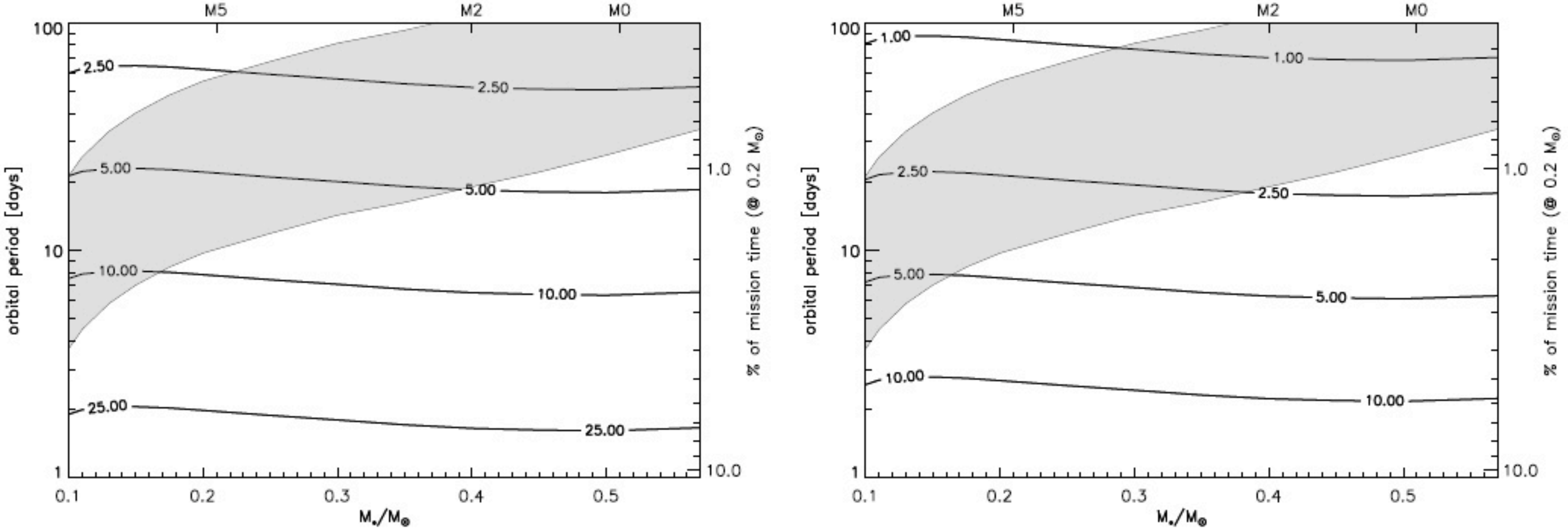


Fig. 15. S/N in emission for the 9.6 μm O_3 signature, with the *MIRI* instrument for a star situated at **6.7 pc**.



9.6 μm O_3, @ **6.7 pc**, in transmission, with MIRI

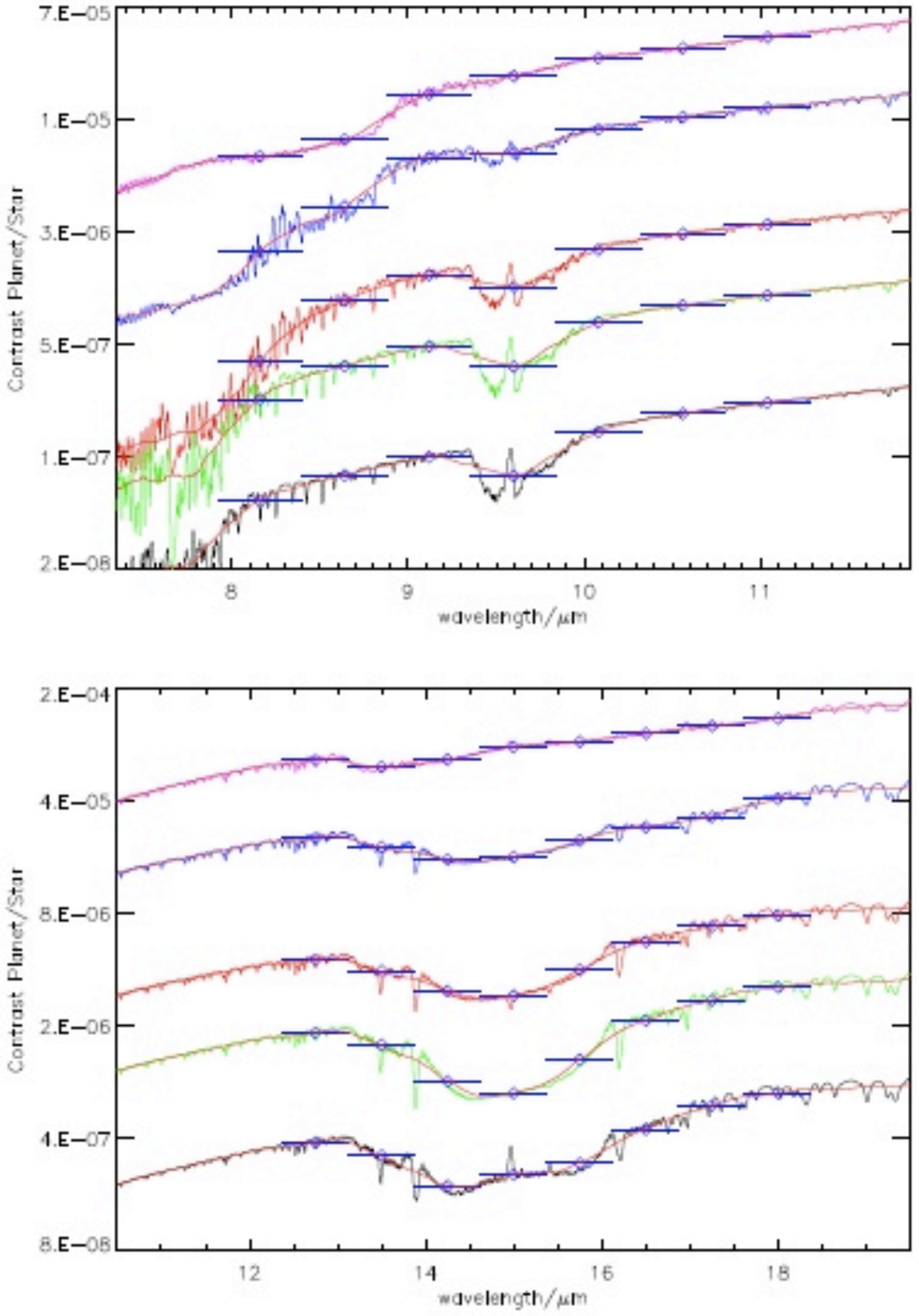
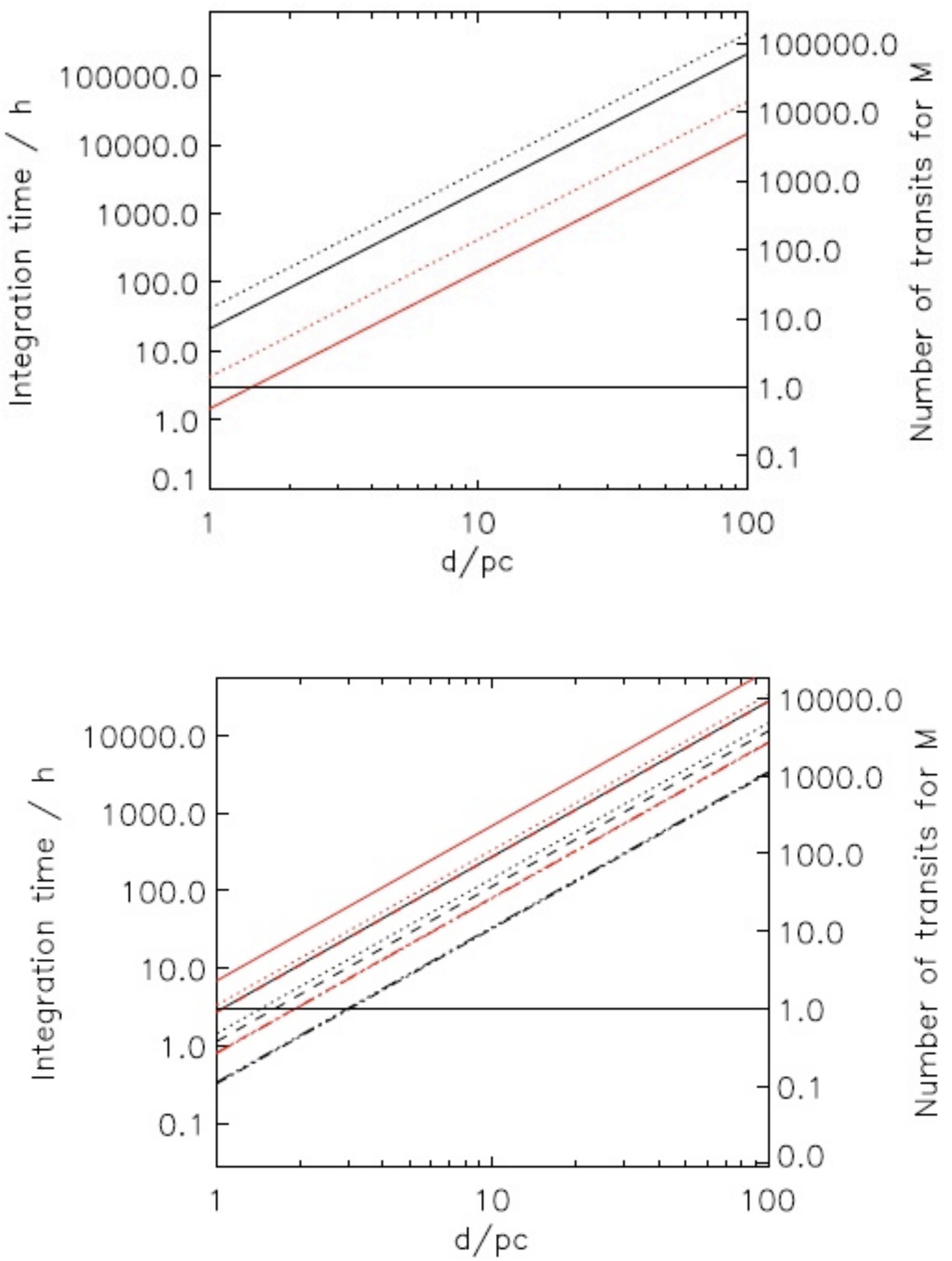
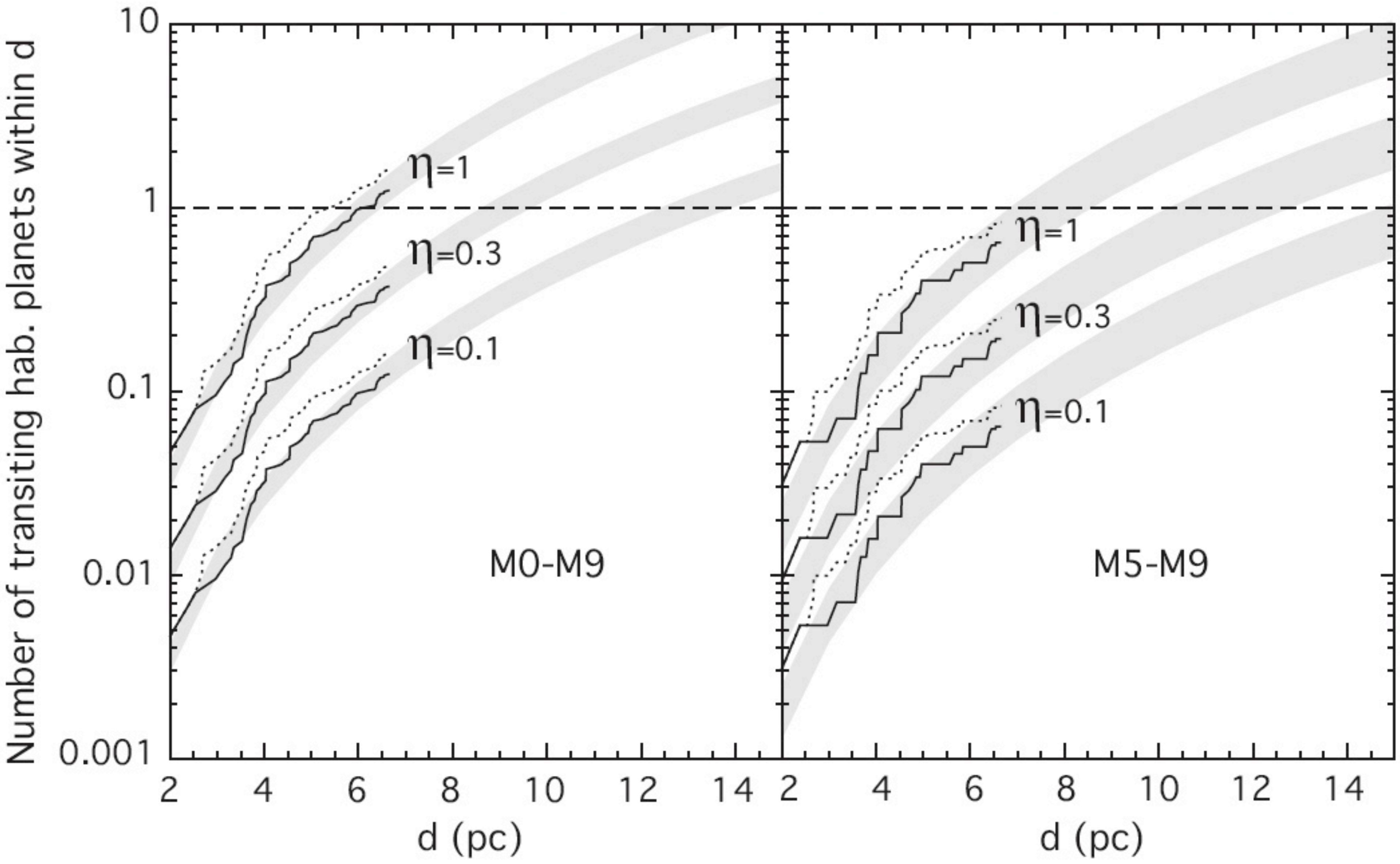


Fig. 6.— Contrast spectrum of the 9.6 μm ozone band and the 15 μm carbon dioxide band for Earth around Sun (black), AD Leo (red), M0 (green), M5 (blue), and M7 (magenta). Red: smoothed spectra to the same resolution, diamonds: binned to R=20.

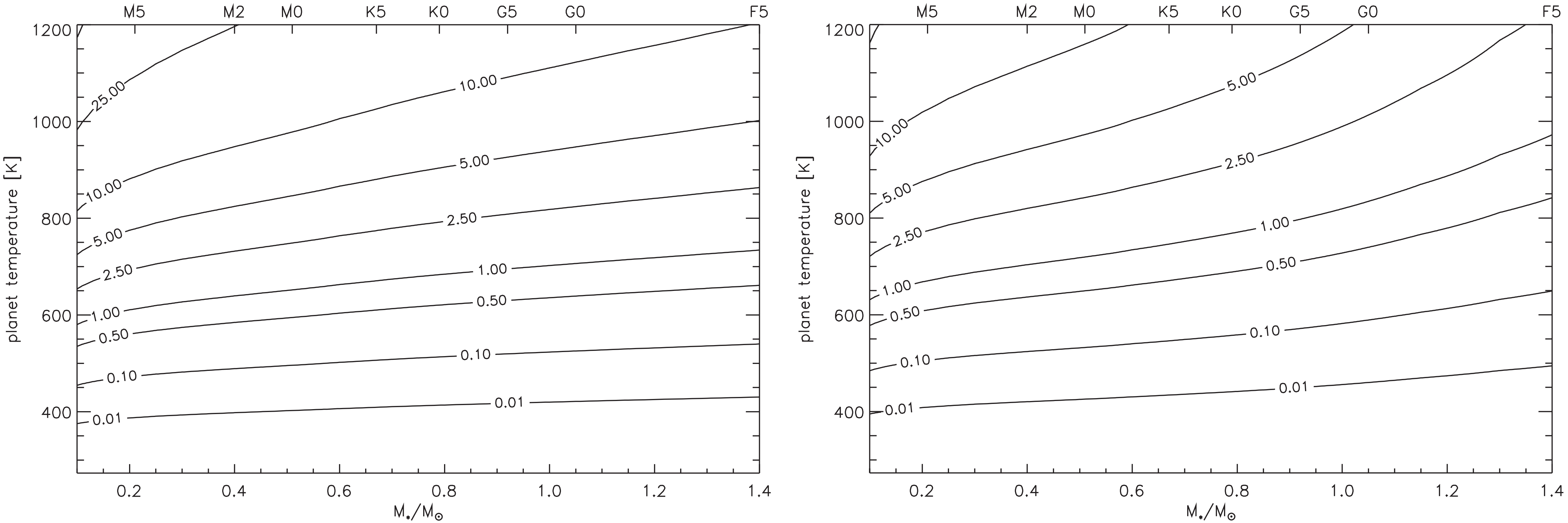


Rauer et al., 2010



Belu et al., A&A, 2010

what about hotter (not habitable) terrestrial planets ?



$\lambda = 3\ \mu$m, $\Delta\lambda = 1\ \mu$m, R=NIRspec, 1 single secondary eclipse, @10 pc

planets with P < 50 days and 5<M<20 M_{Earth} are found by RV around 30±10 % of G,K stars (Mayor et al., 2009)

If η similar for M stars (?), the closest transiting object of this kind could be found within 5 pc

The detection and basic characterization of dense atmospheres on hot+big rocky planets is an important objective for understanding the formation and survival of atmospheres.
In particular around M dwarfs that remain active (flares, high XUV, strong winds) longer than K, G stars.

But we need statistics.

Transiting objects within 10 pc are not going to give us statistics.

The detection and basic characterization of dense atmospheres on hot+big rocky planets is an important objective for understanding the formation and survival of atmospheres.
In particular around M dwarfs that remain active (flares, high XUV, strong winds) longer than K, G stars.

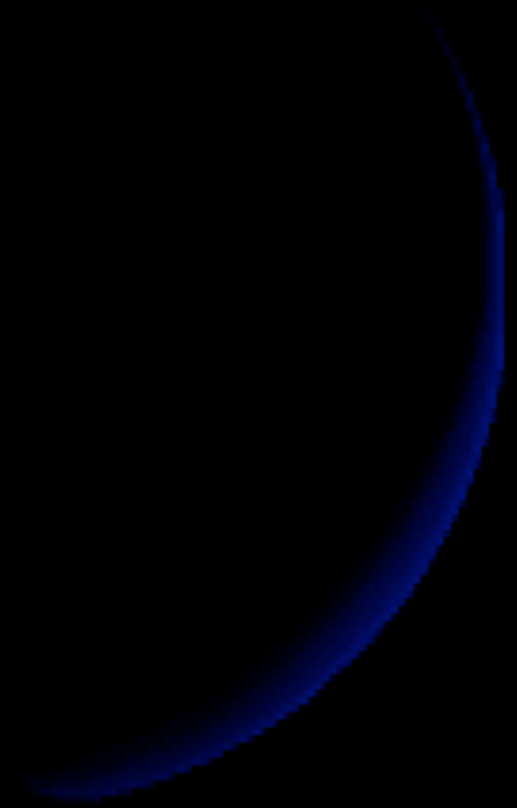
But we need statistics.

Transiting objects within 10 pc are not going to give us statistics.

Can we measure phase curves of *non-transiting* short-period terrestrial exoplanets ?

Animation made with the data from the Martian Climate Database

thermal emission

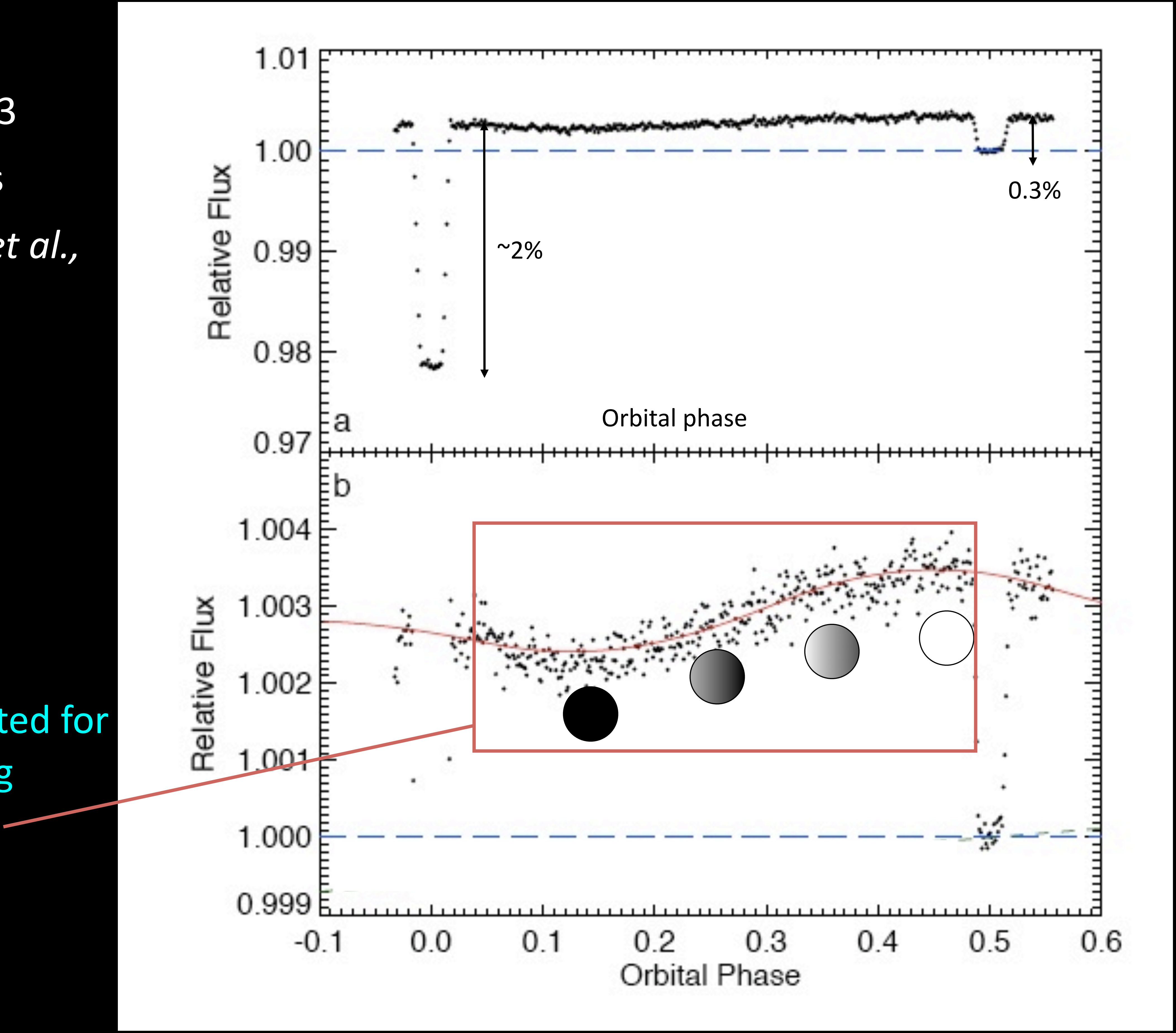


relected light

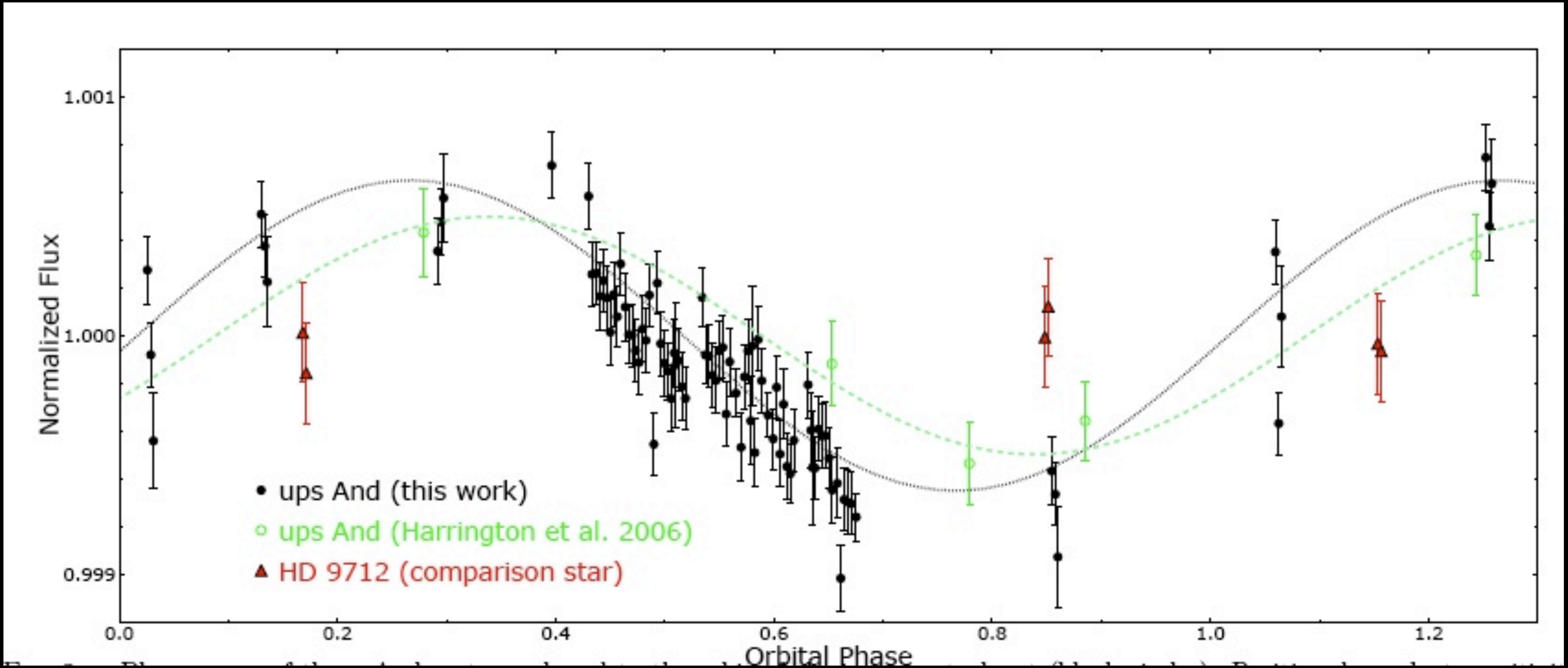
HD189733

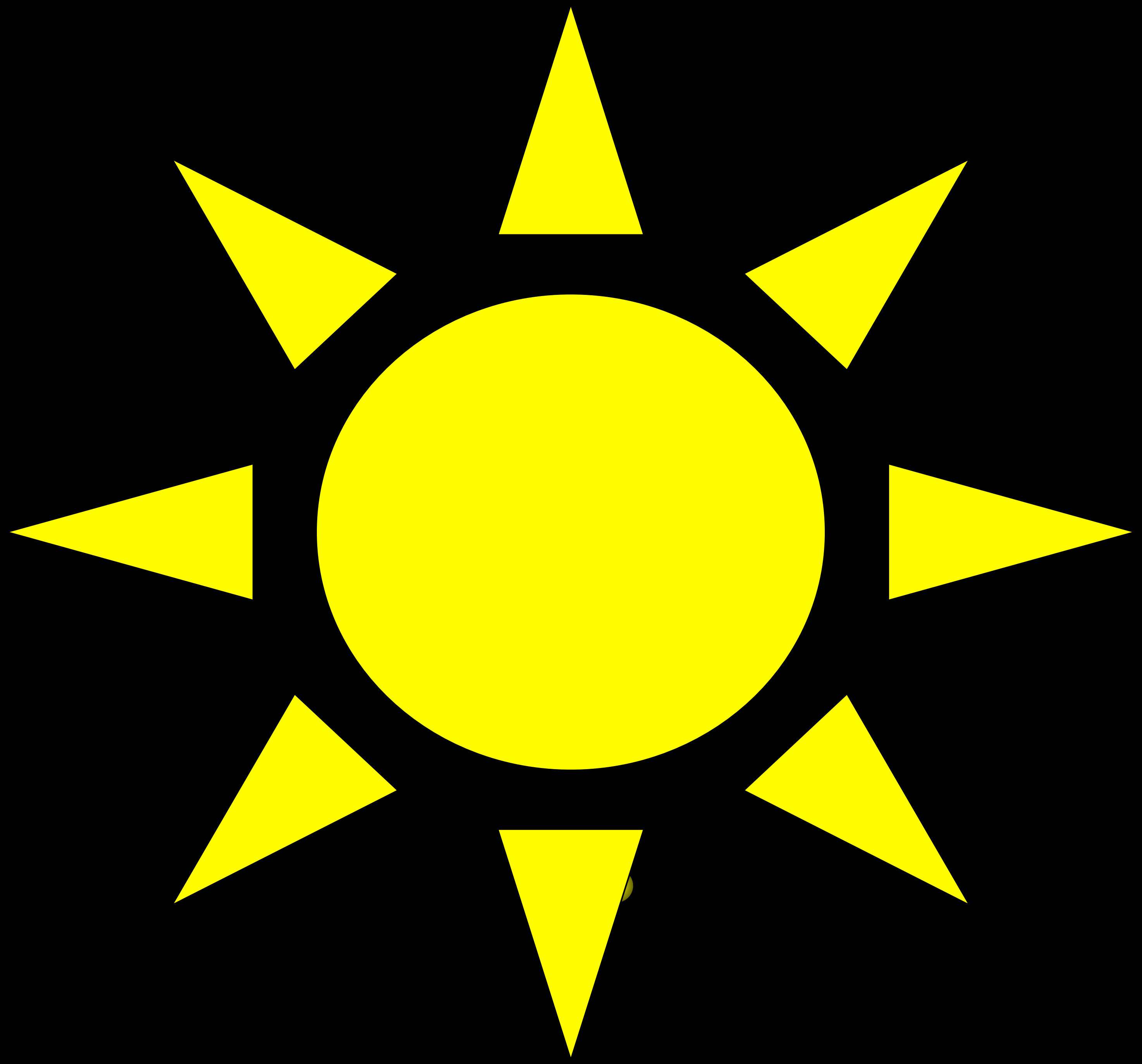
8 microns

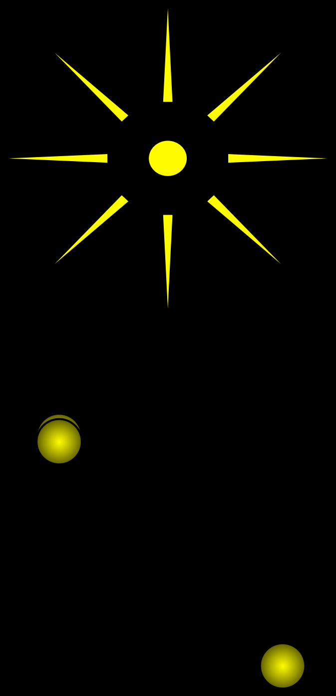
Knutson et al., 2008

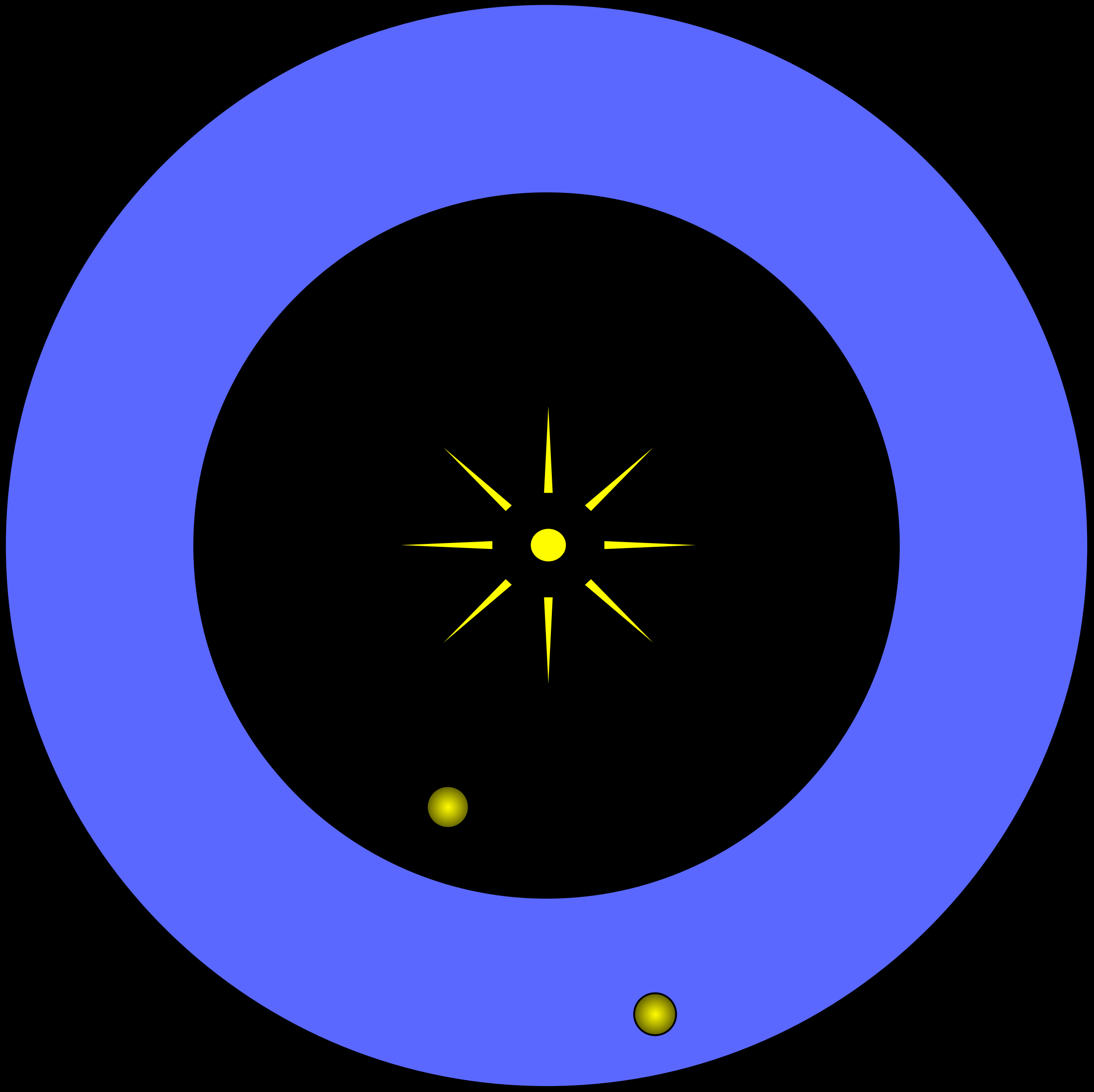


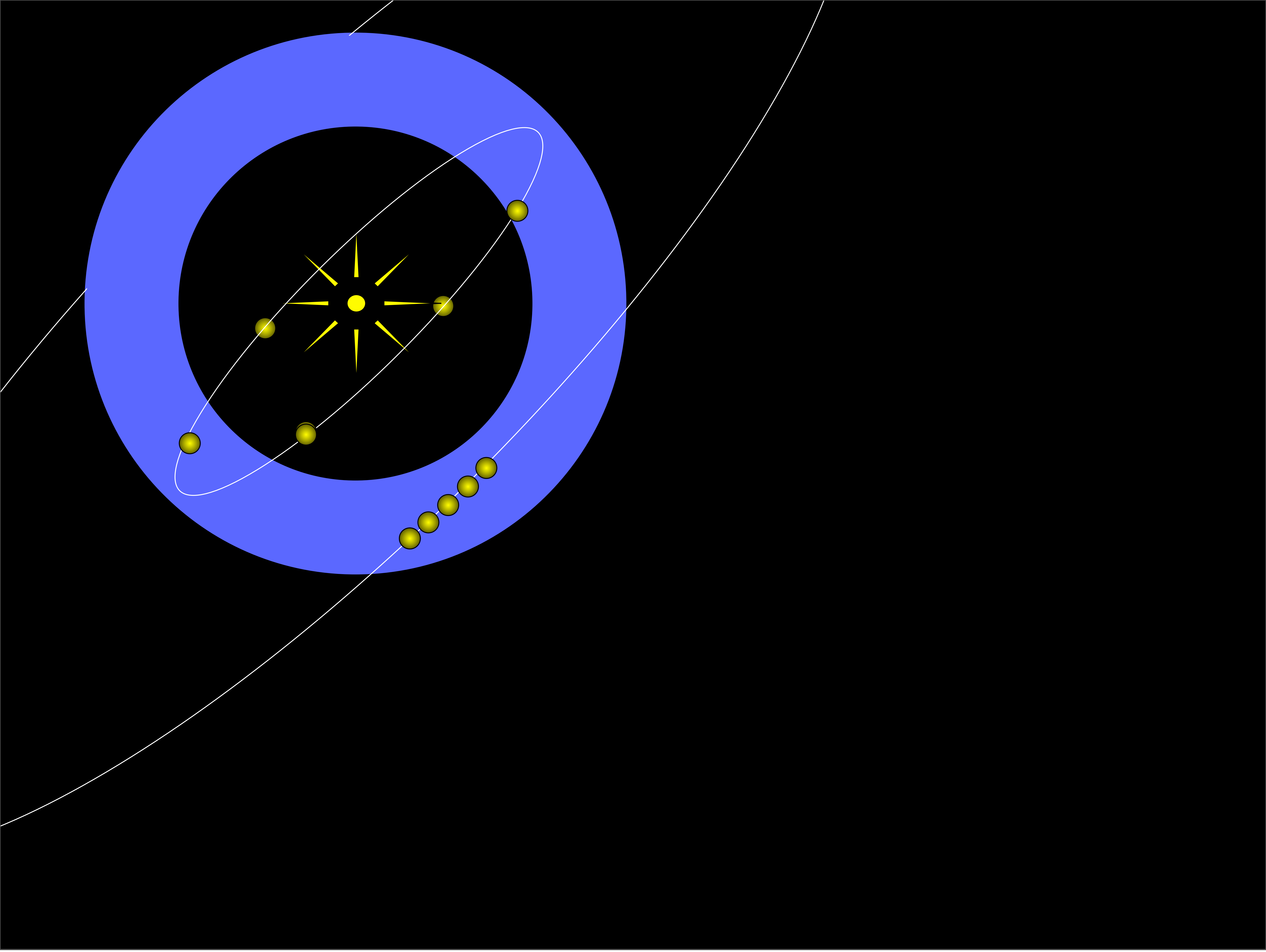
Can be detected for non-transiting planets


Normalized Flux
1.001
1.000
0.999
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Orbital Phase
● ups And (this work)
○ ups And (Harrington et al. 2006)
▲ HD 9712 (comparison star)



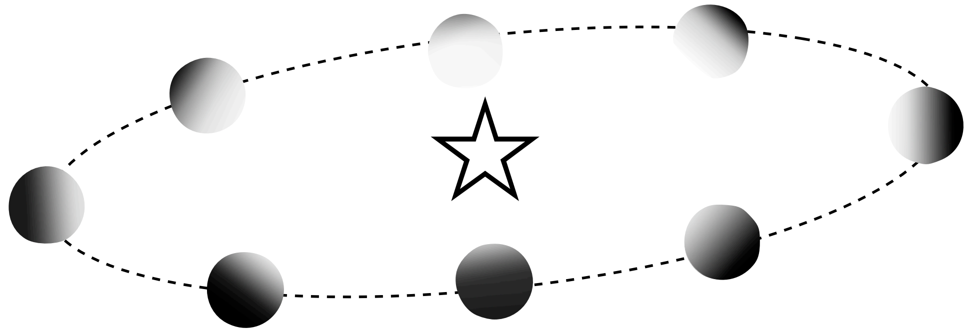


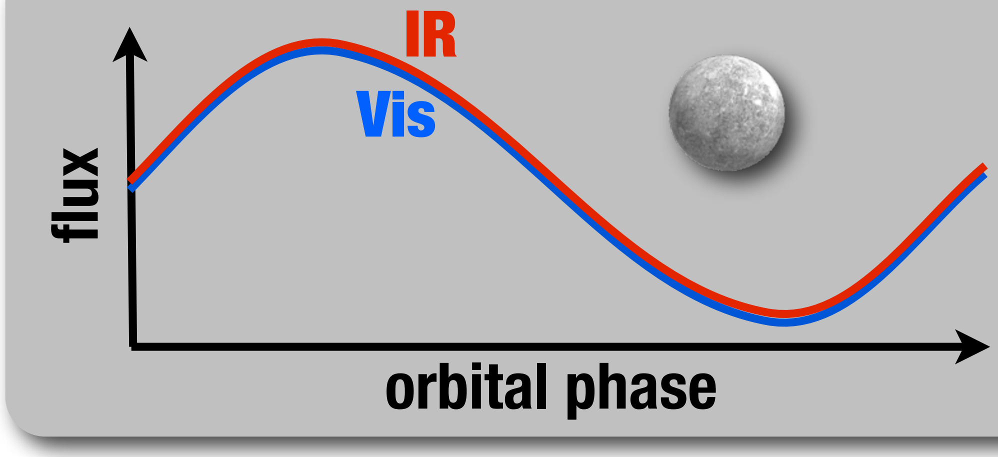




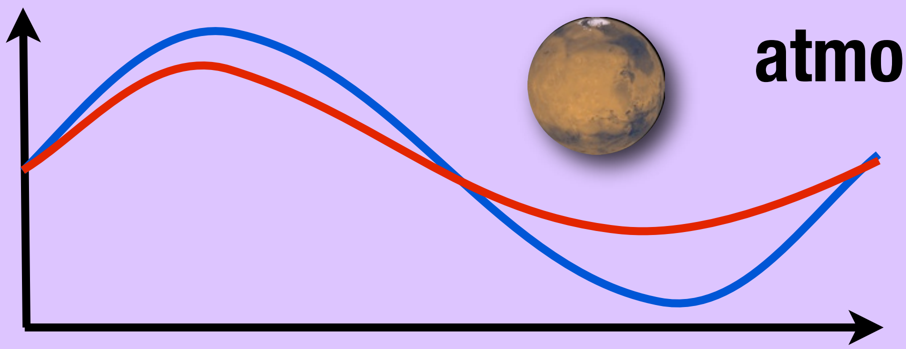
IR phase curve and climate characterization

(Selsis 2003)





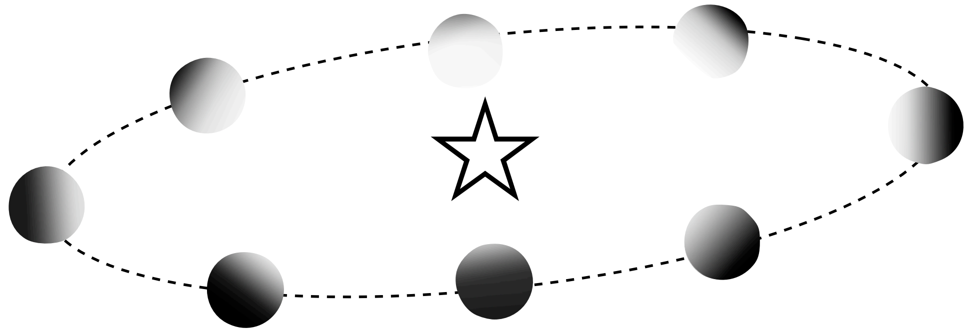
Airless planets

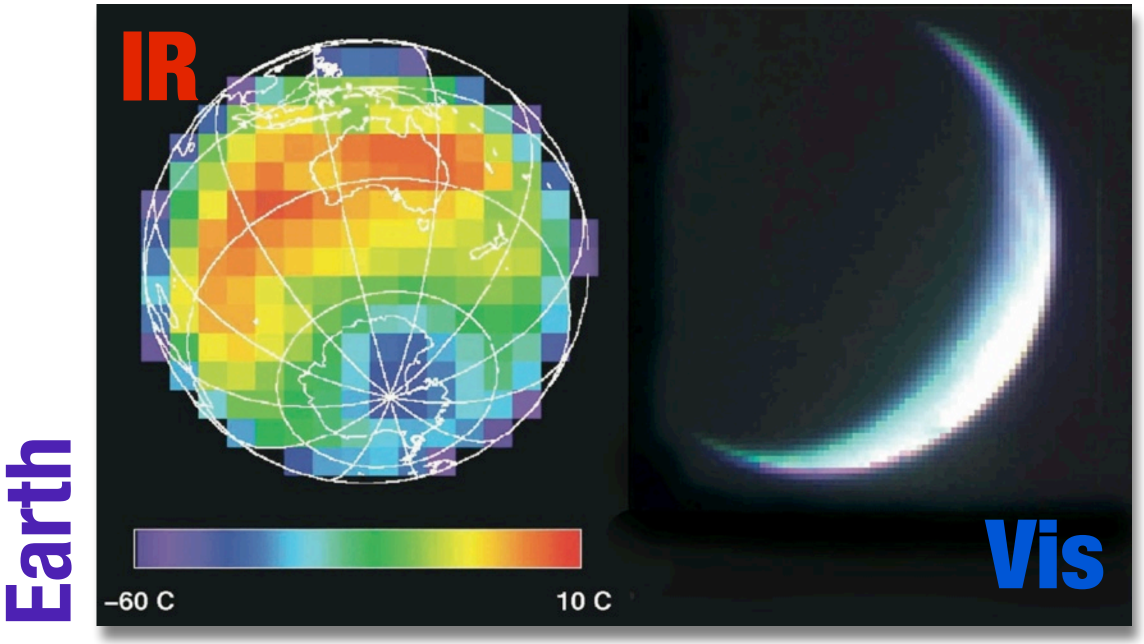


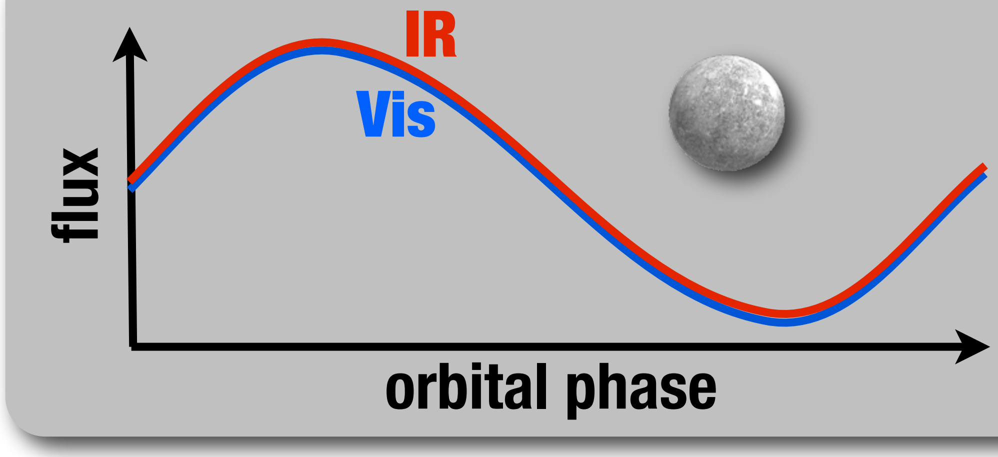
Tenuous atmospheres

IR phase curve and climate characterization

(Selsis 2003)

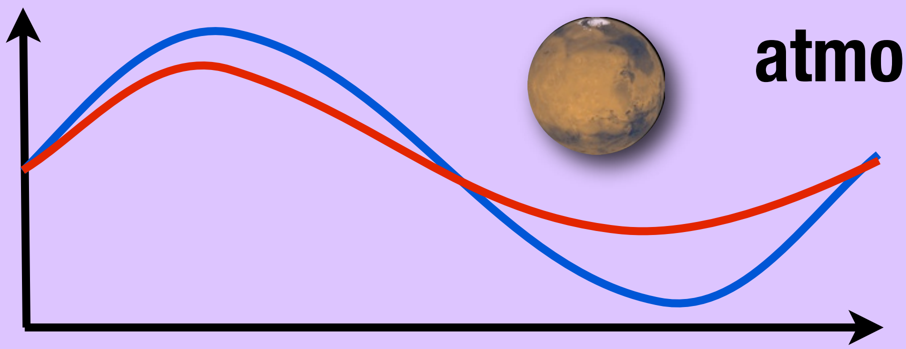


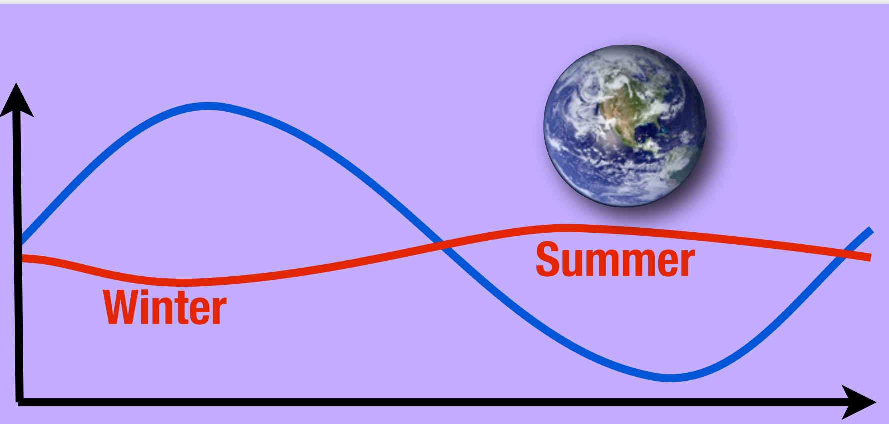


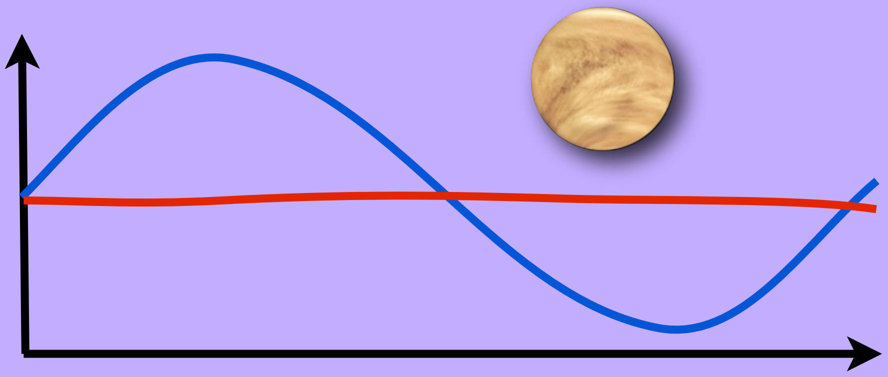


Airless planets

Tenuous atmospheres

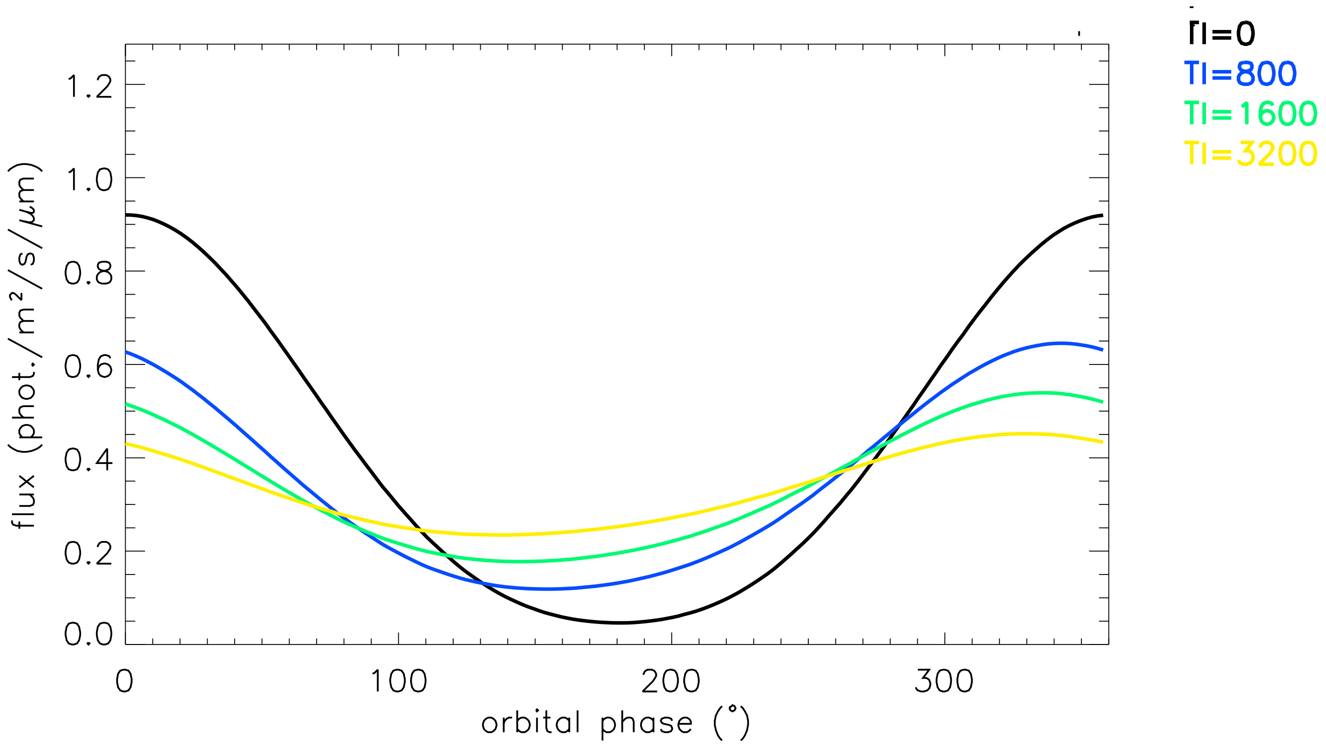


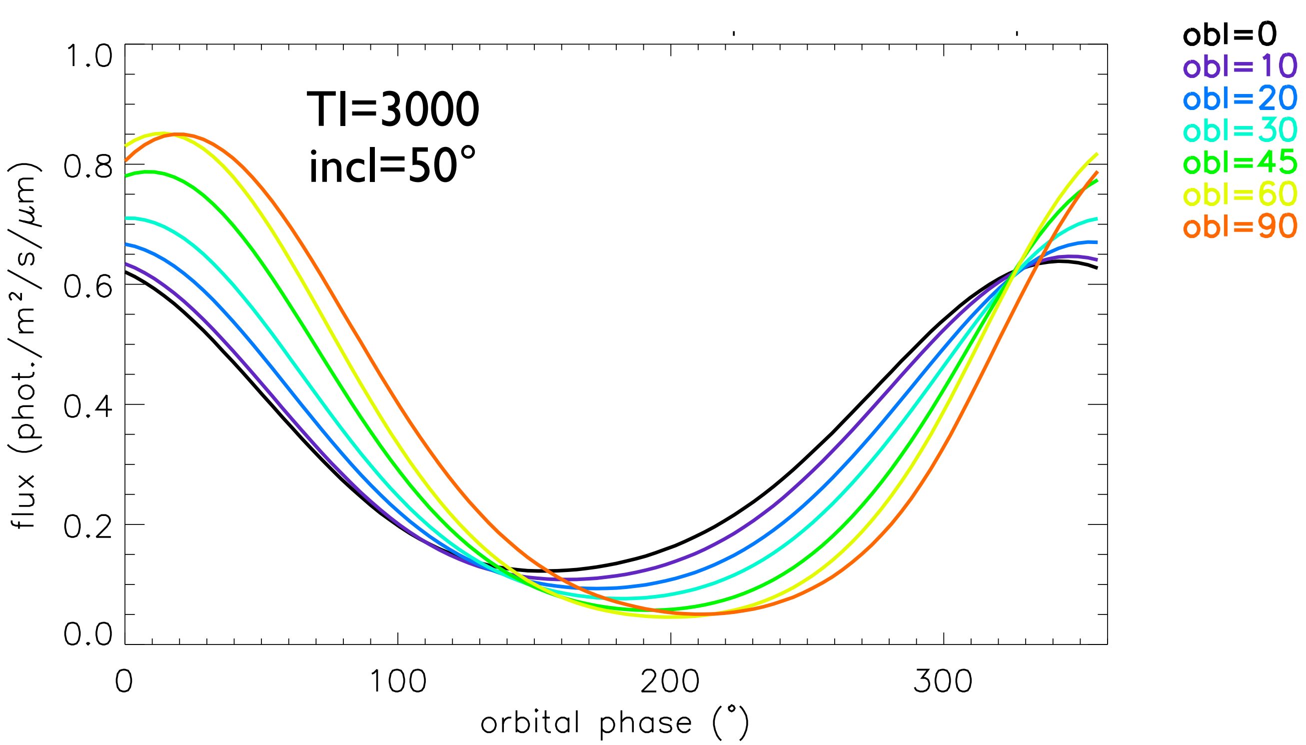




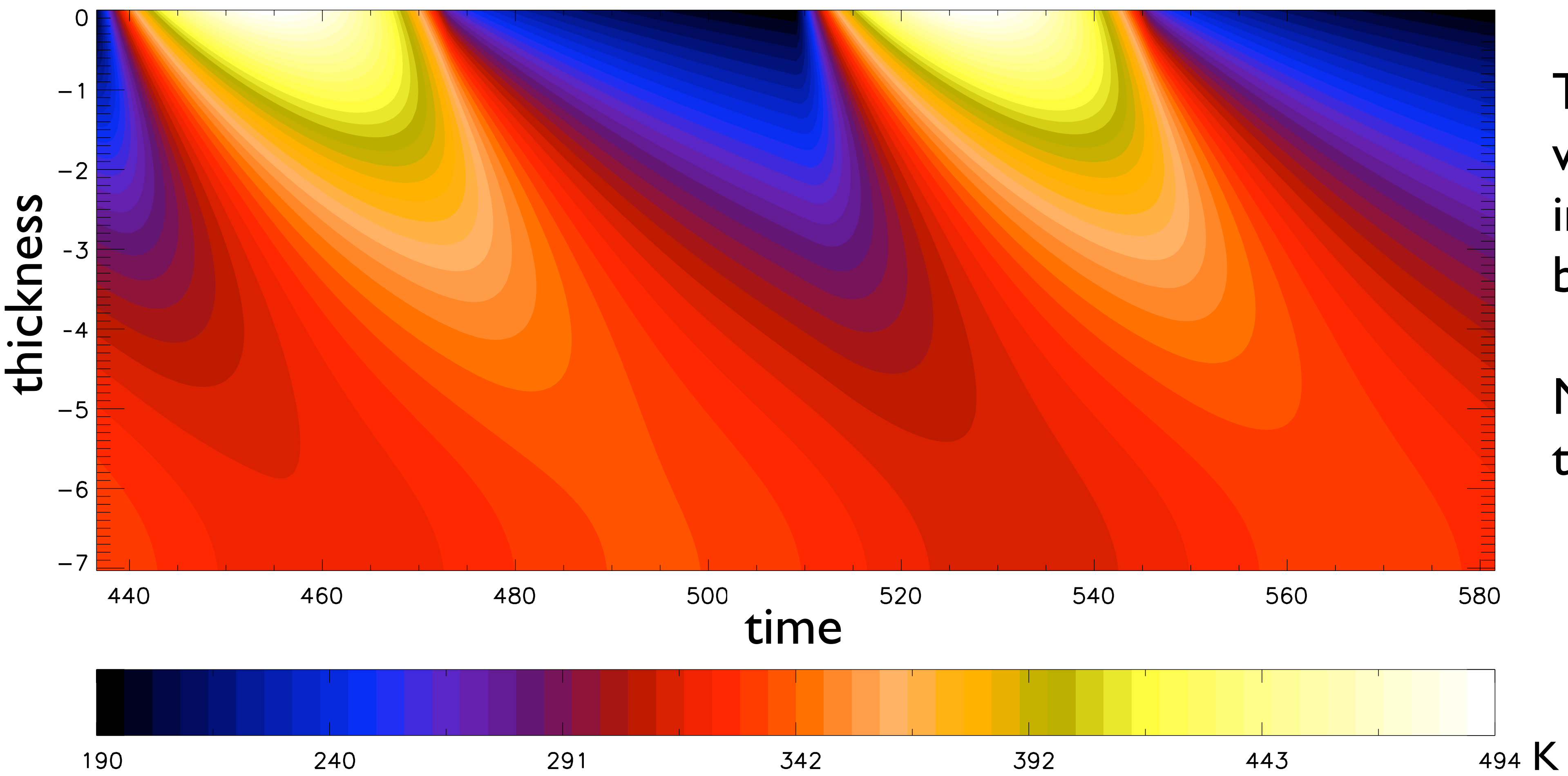
Dense atmospheres

planets with no atmosphere : the effect of surface thermal inertia





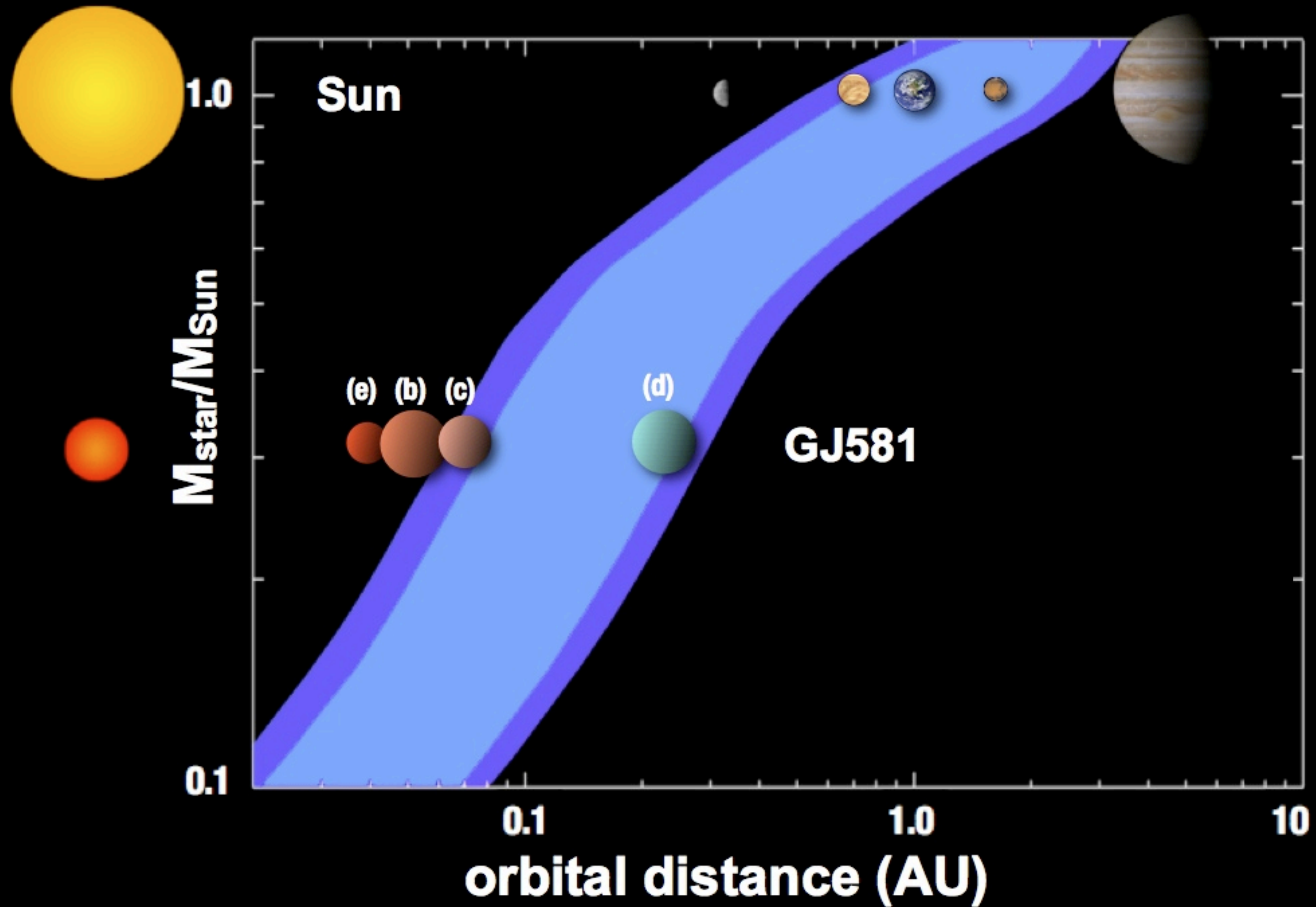
subsurface temperature



To get a significant effect with realistic thermal inertias, the rotation has to be fast.

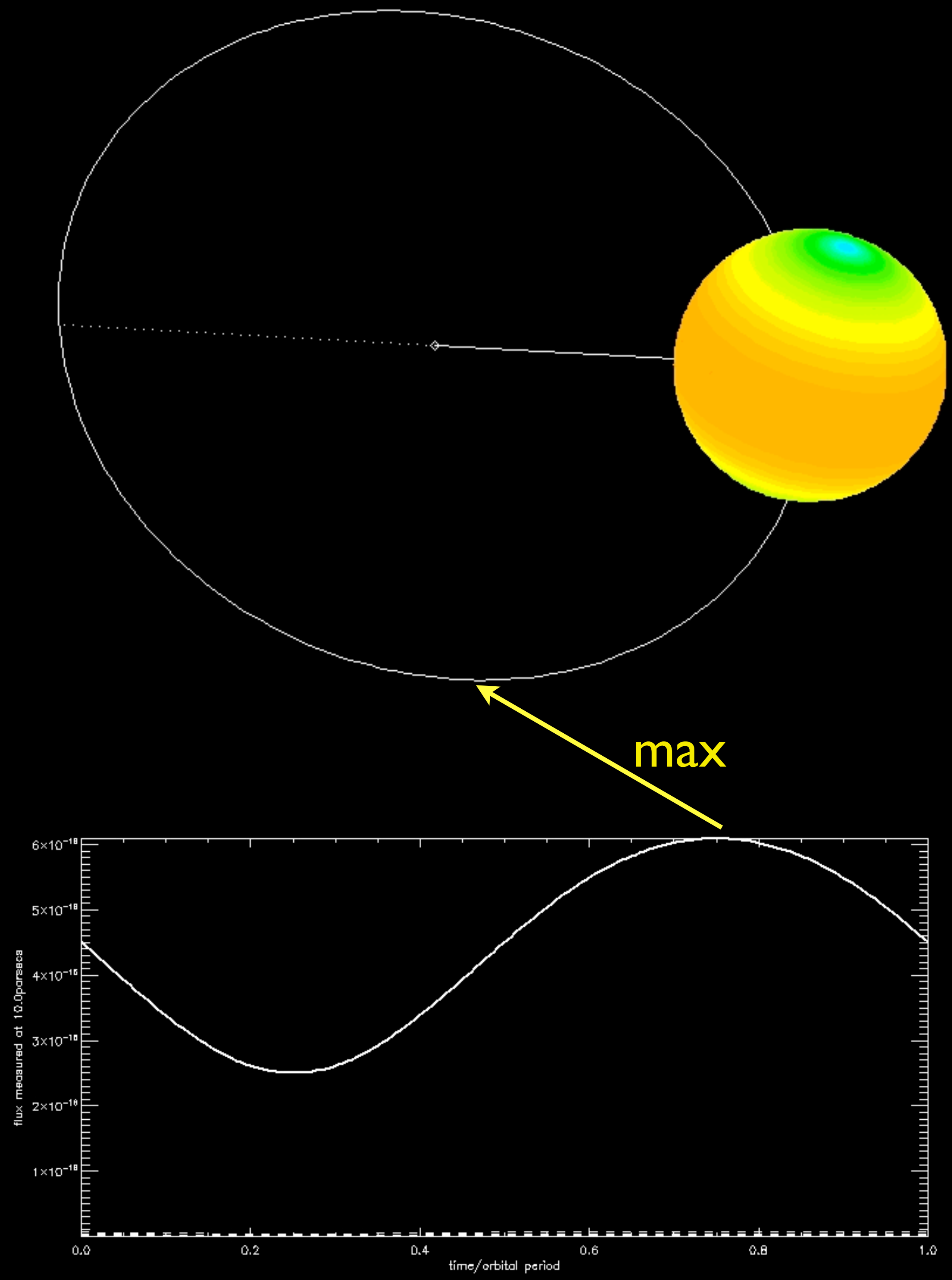
Not likely for short-period tidally-evolved objects

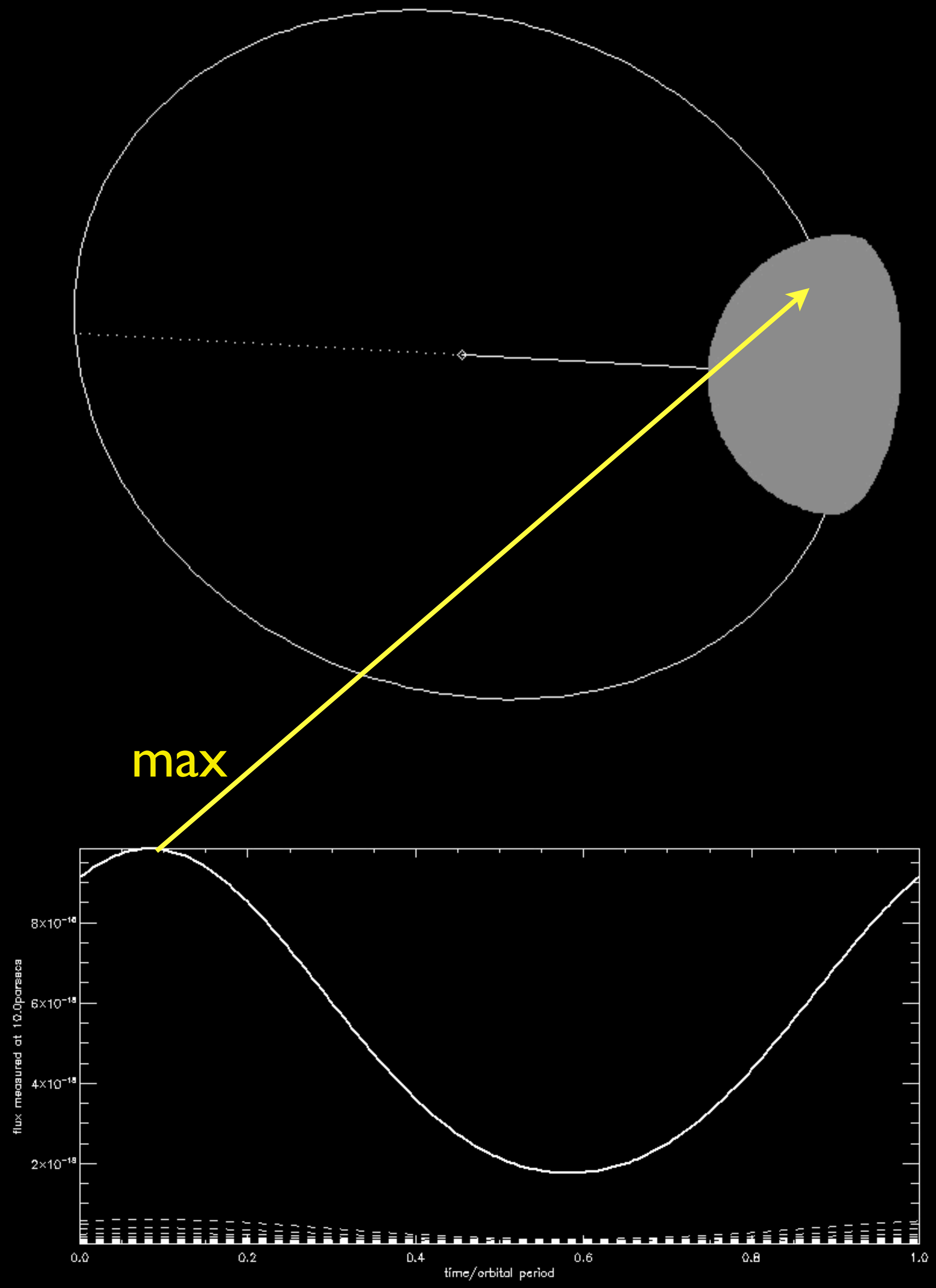
A.-S. Maurin (PhD)


1.0
Sun
0.1
Mstar/Msun
(e)
(b)
(c)
(d)
GJ581
0.1
1.0
10
orbital distance (AU)

Seasons

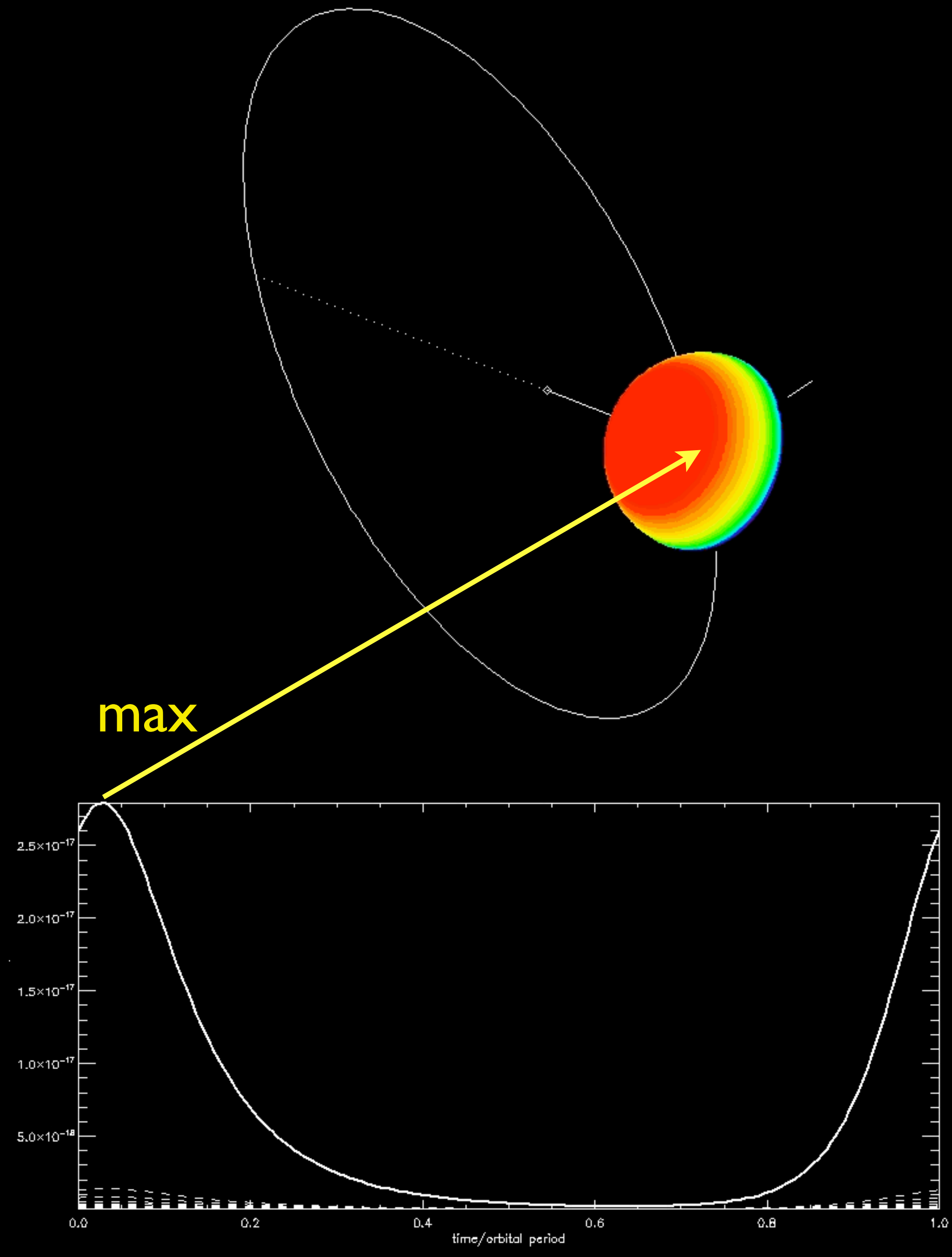
Obliquity= 45°
T=f(latitude, time,~~longitude~~)

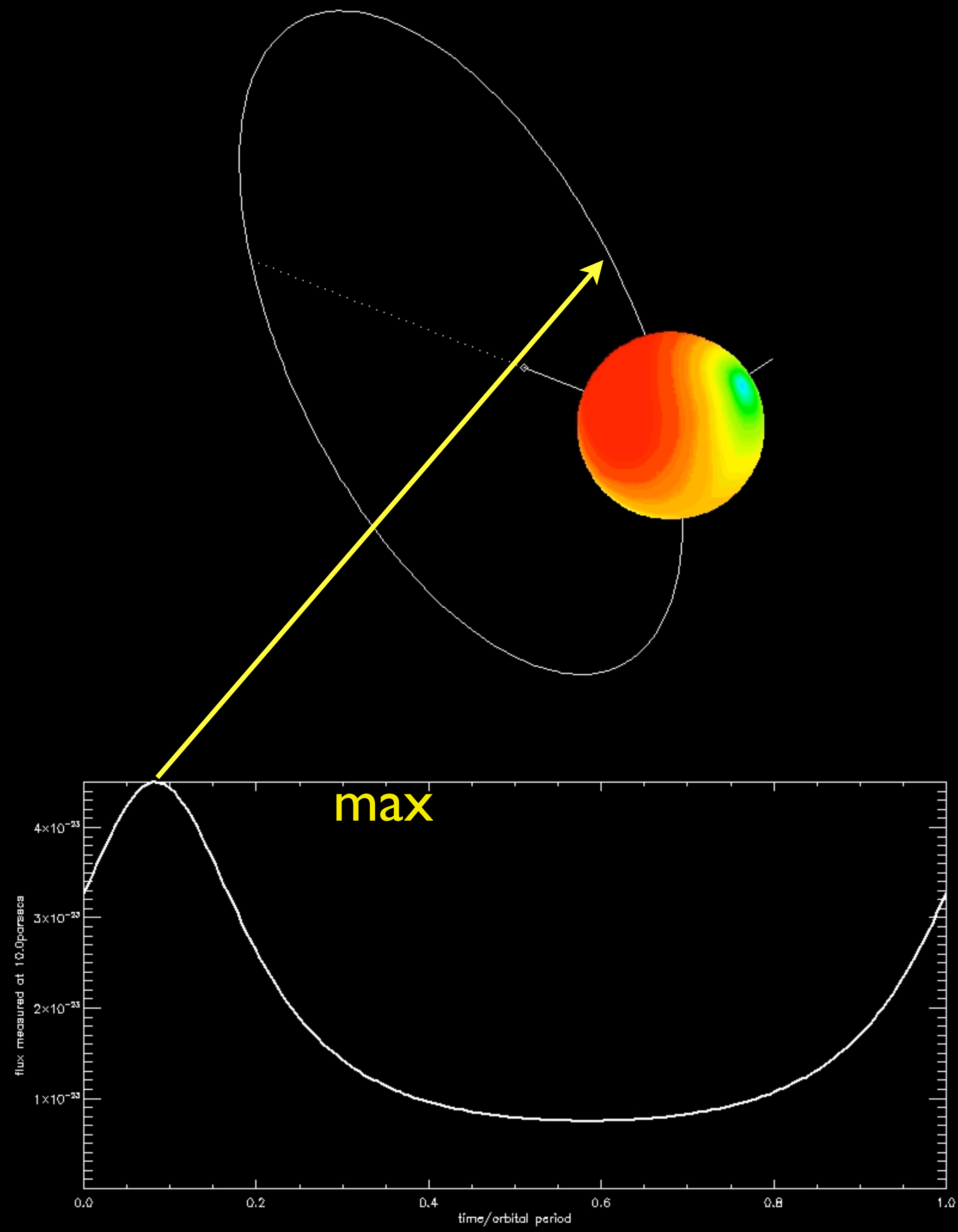




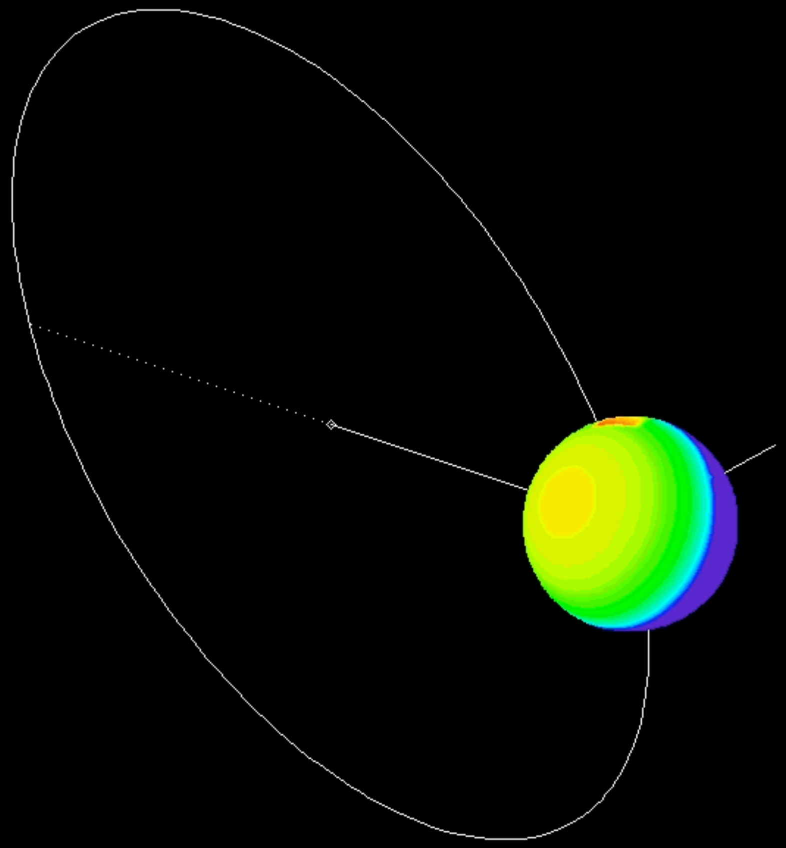
1 yr periodicity but phase-shift compared to the visible phase

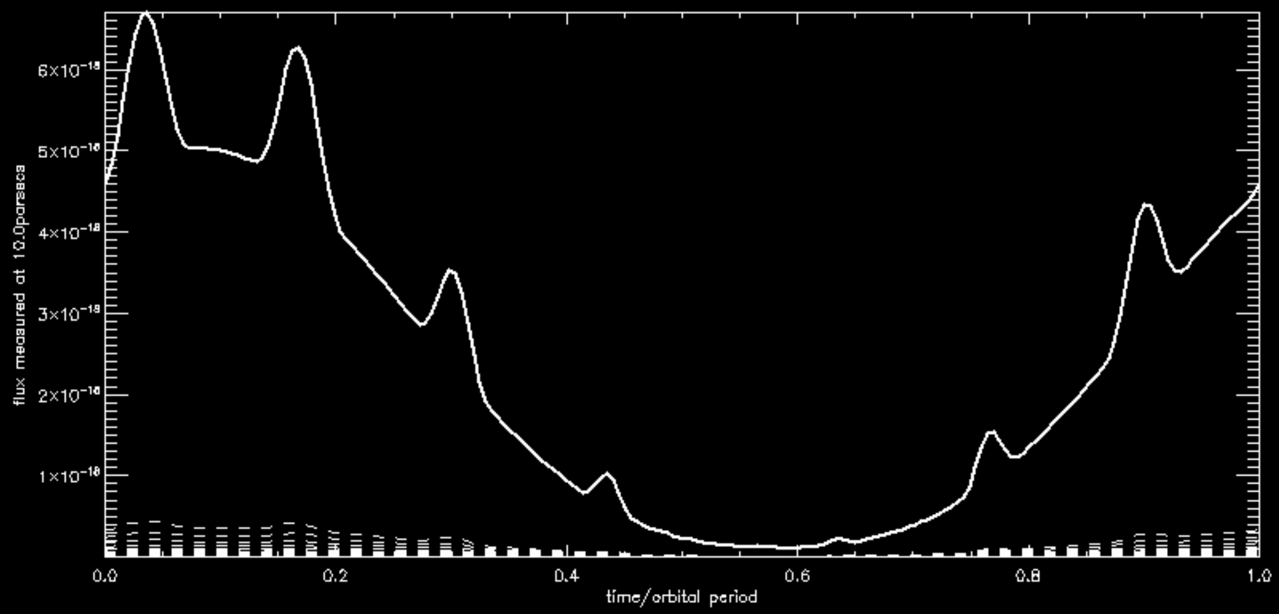
Eccentric planets



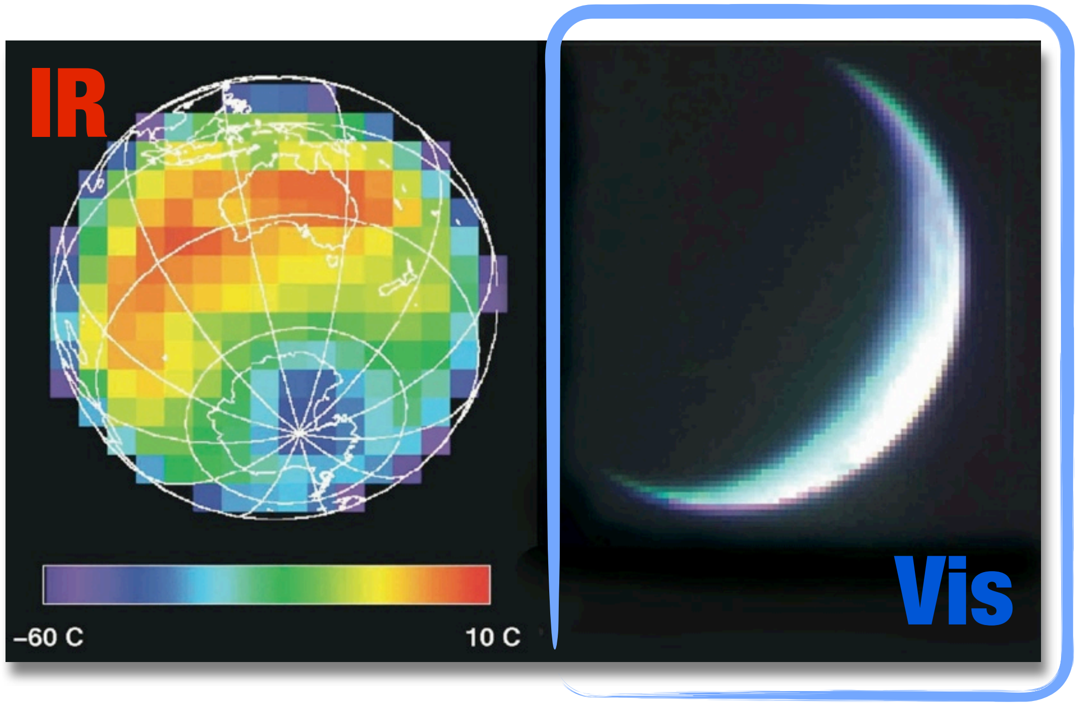


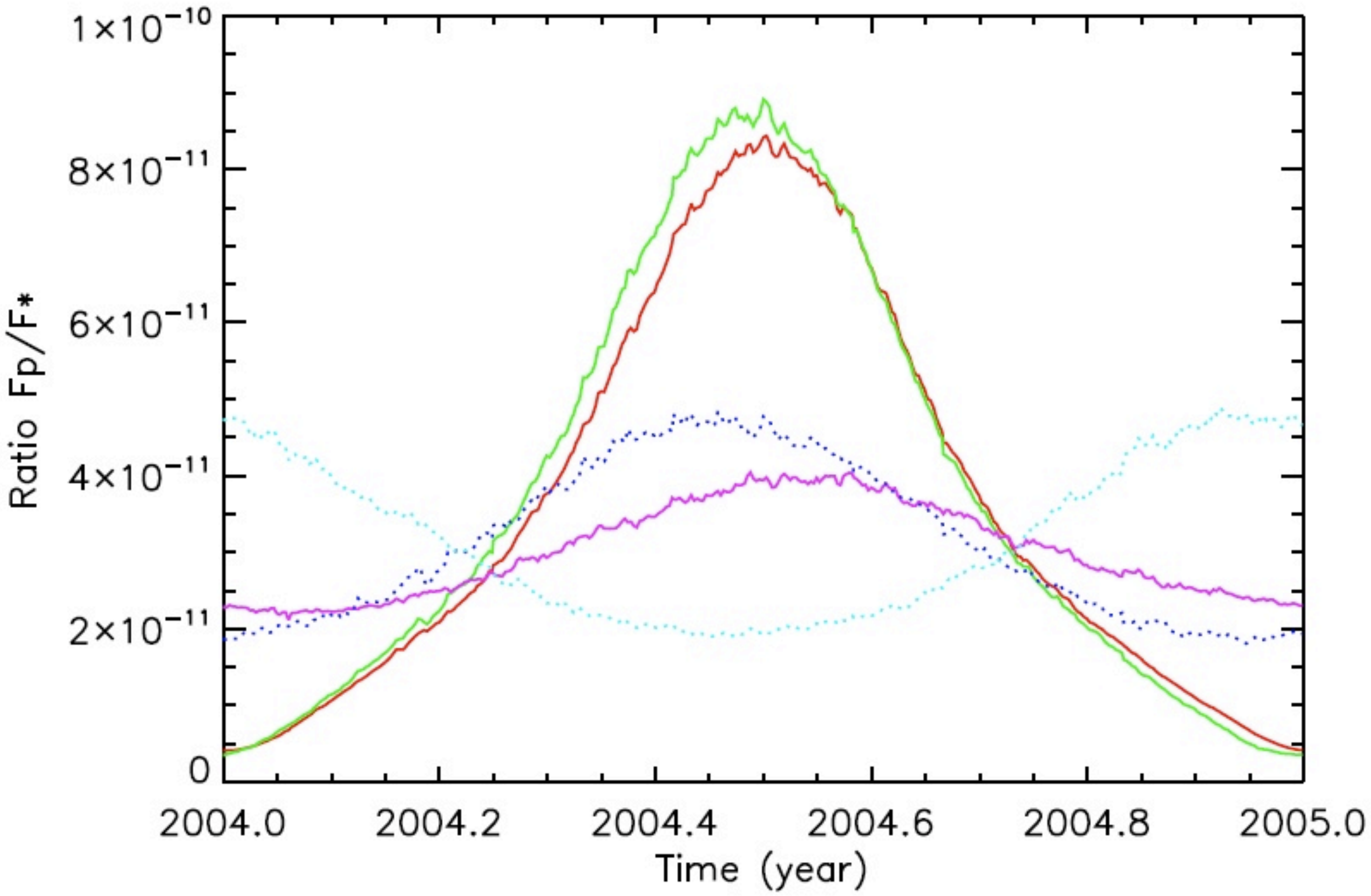
rotation modulation

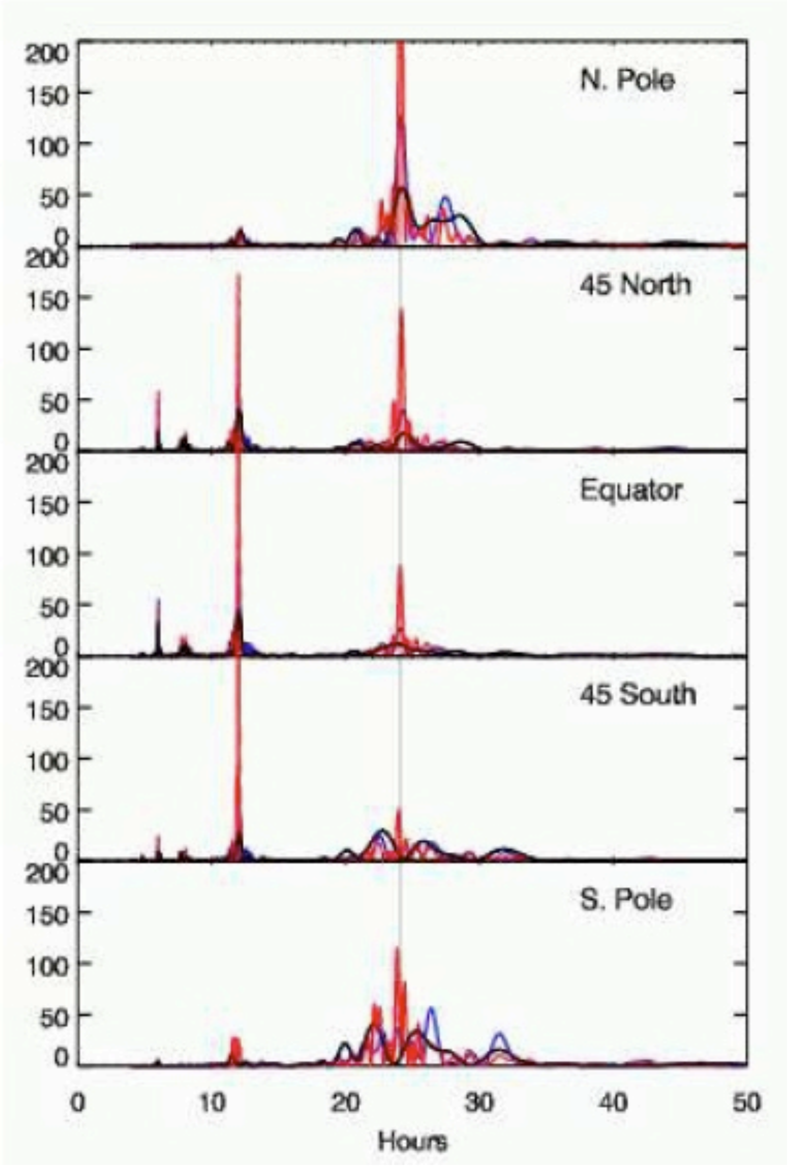




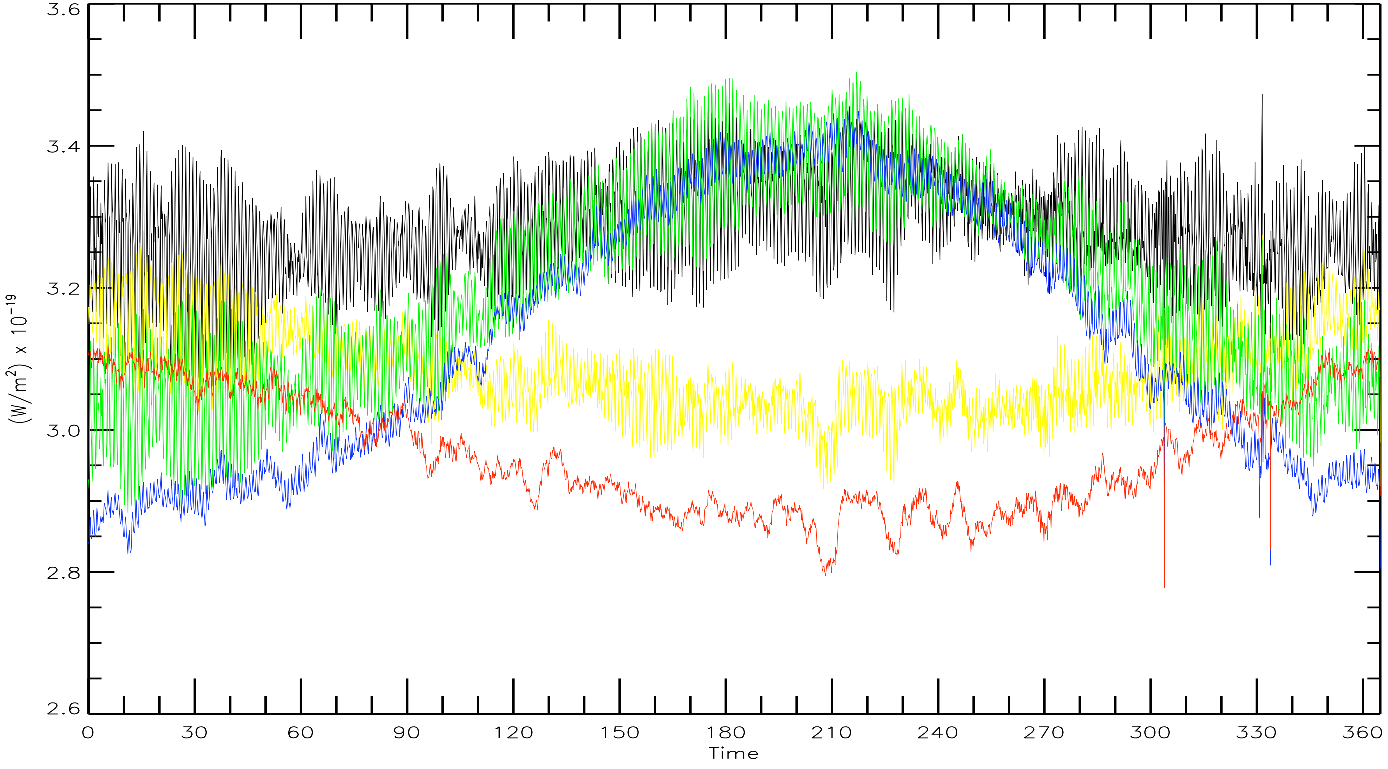
Earth

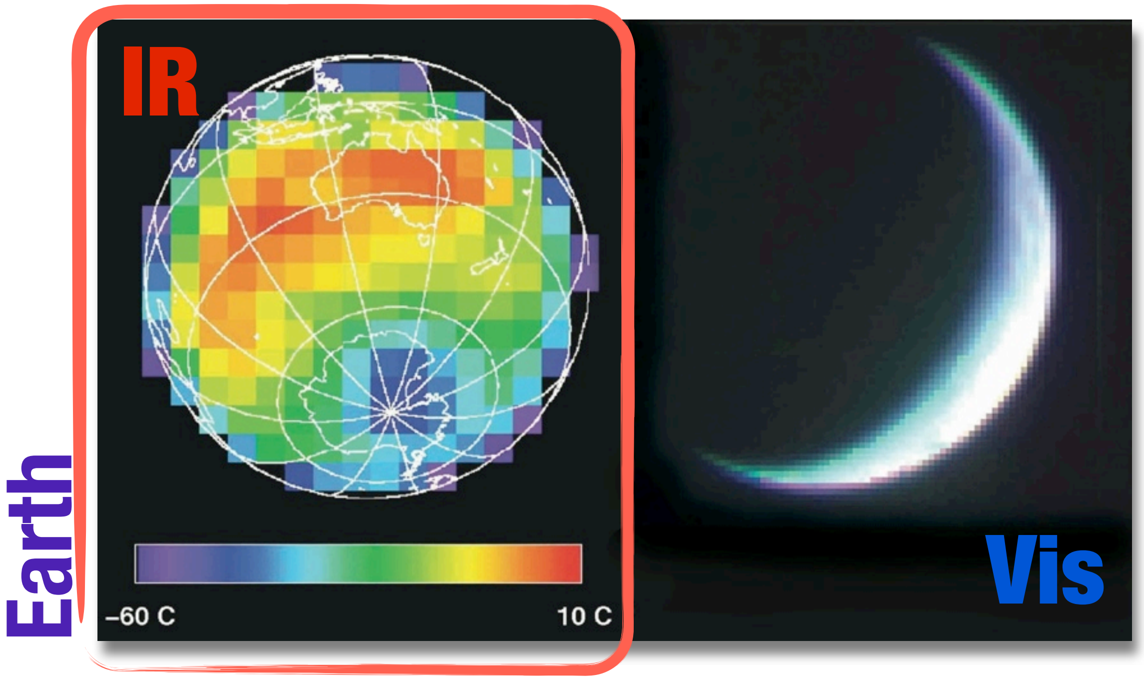

IR
−60 C
10 C
Vis


1×10⁻¹⁰
8×10⁻¹¹
6×10⁻¹¹
4×10⁻¹¹
2×10⁻¹¹
0
Ratio Fp/F*
2004.0
2004.2
2004.4
2004.6
2004.8
2005.0
Time (year)

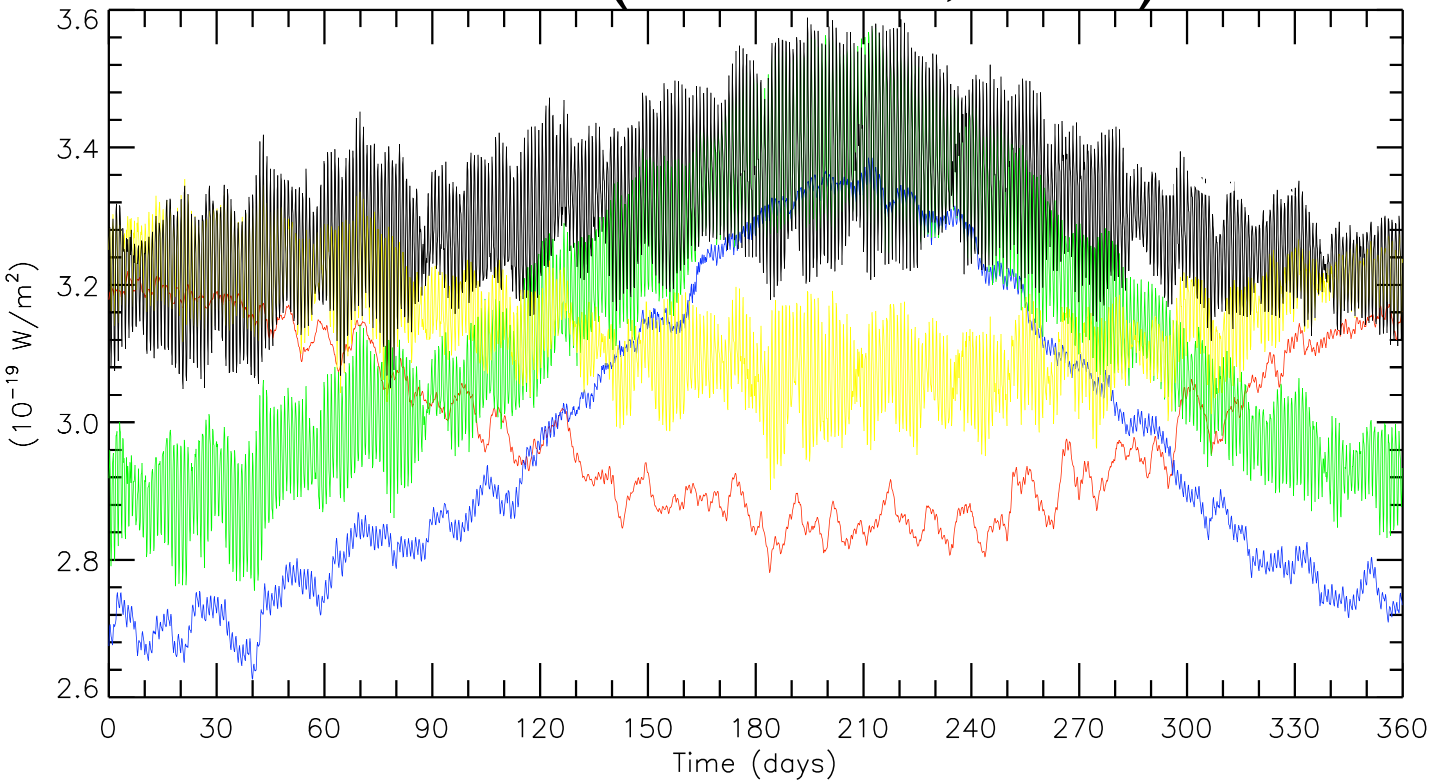

200
150
100
50
0
N. Pole
45 North
Equator
45 South
S. Pole
0
10
20
30
40
50
Hours

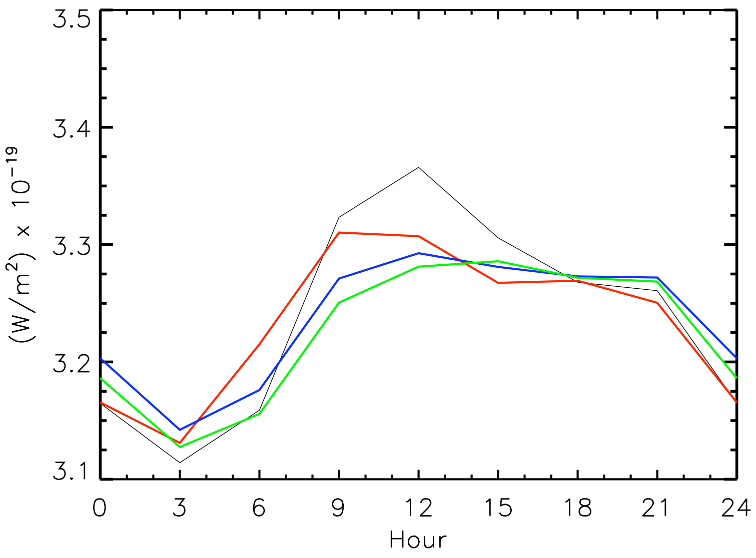
satellite observations (GEWEX)

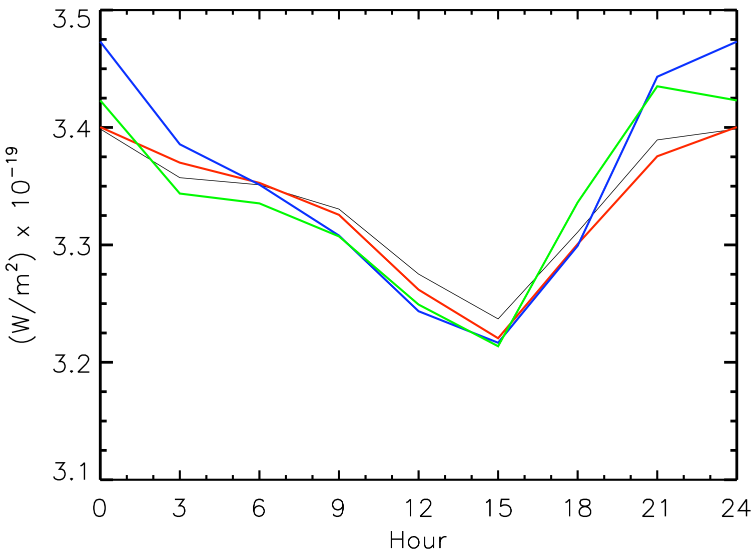




GCM (F. Codron, LMD)

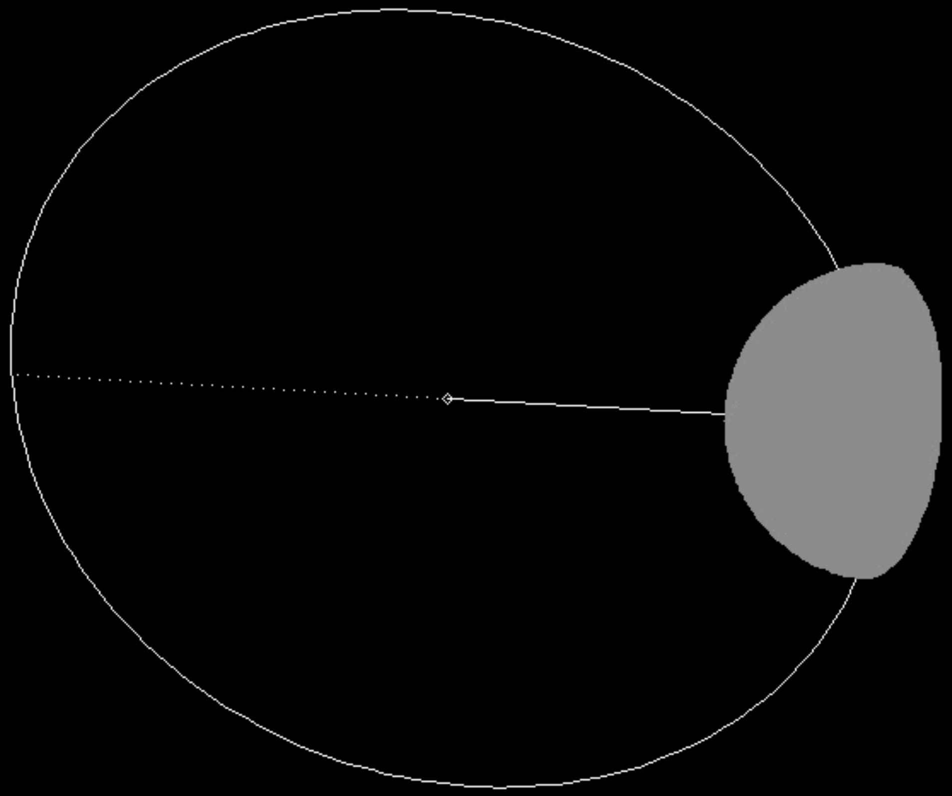






I. Gomez-Leal (PhD) - See her Poster

Test case for a non-transiting hot rocky planet



inclination = 60°

- a large rocky planet (1.8 R_{Earth}) around a low-mass star (0.3 MSun)

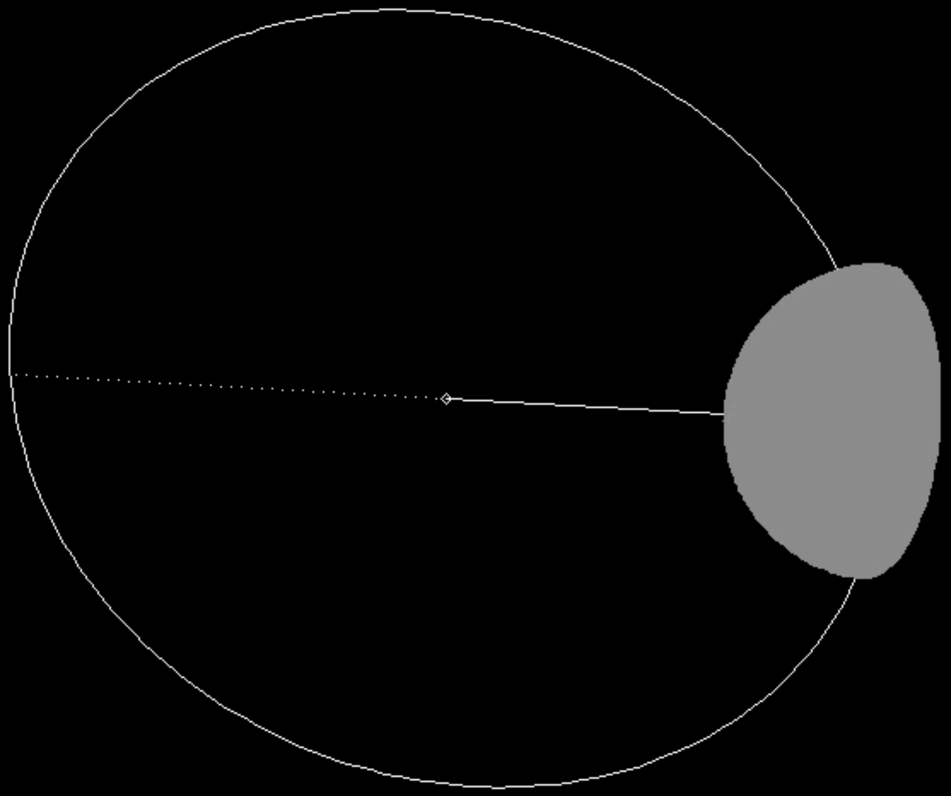
- hot planet (0.05 AU), with surface temperature reaching 500-600 K, but not too hot to keep an atmosphere

➔ about the highest planet/star contrast we can get for a terrestrial planet with an atmosphere

- 8-days period, 1 phase curve can be obtained fast

- tidally locked. Maximizes the amplitude of the phase curve. Consistent with orbit, unless the atmosphere prevents the synchronization (Correia et al. 2008).

- only one atmospheric constituant : CO_2
  + makes the identification of features much easier
  + atmospheric windows (e.g. 3.5 and 6 microns) probing the near-surface atmosphere,
  + no cloud (too hot for CO_2 condensation, no H_2O, no dust/aerosols)

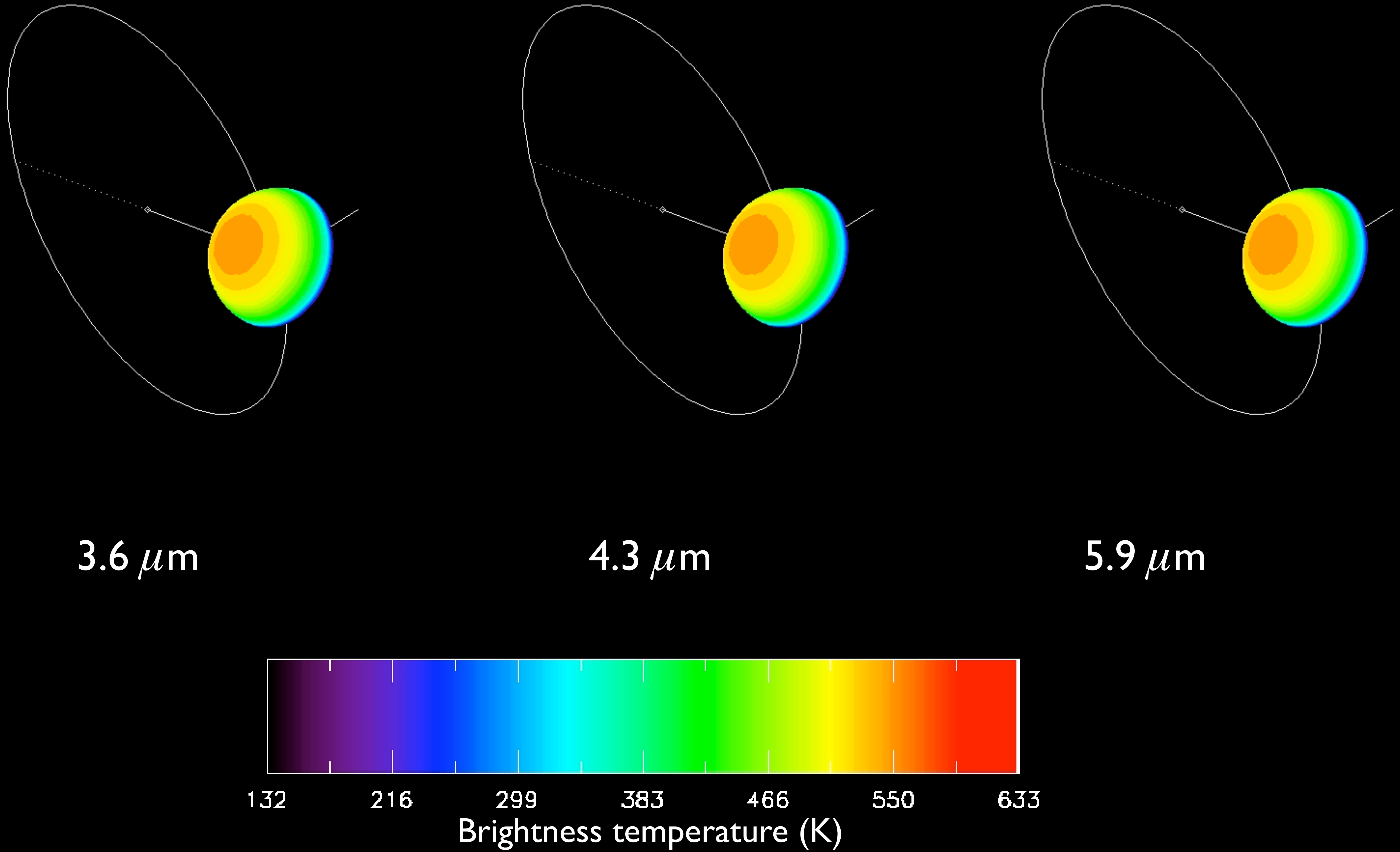


1.8 R_{Earth} planet
M star (0.3 M_{Sun})
synchronized, ecc=0, obl= 0
a ~ 0.05 au
P = 8 days

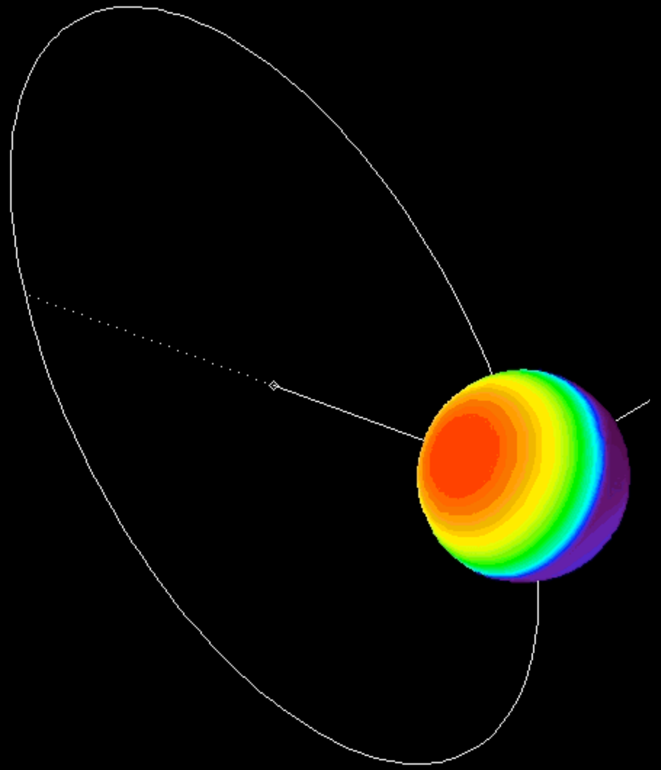
0.1 bar CO_2
1 bar CO_2
10 bar CO_2

3D climate model
developped by F. Forget and R. Wordsworth
(see F. Forget's talk this afternoon)

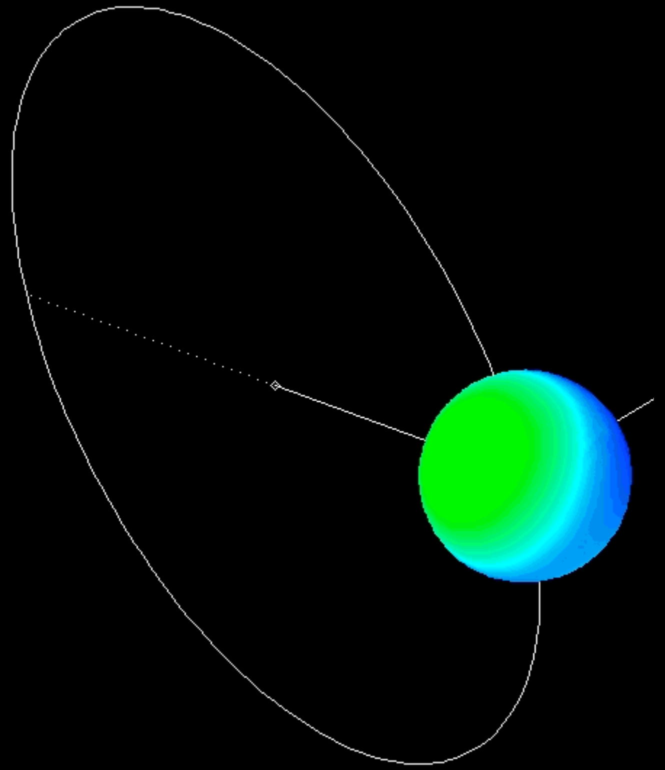
no atmosphere



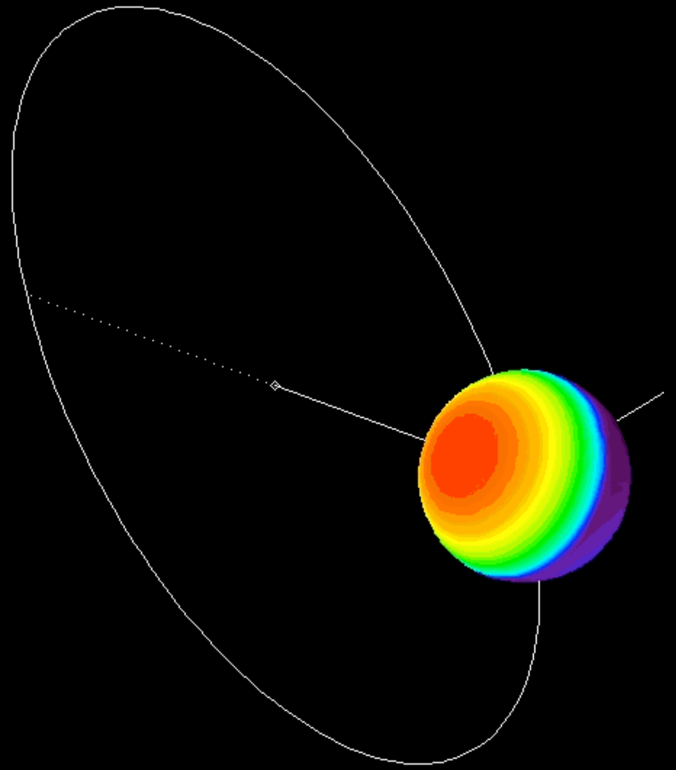
0.1 bar (CO_2)



3.6 μm

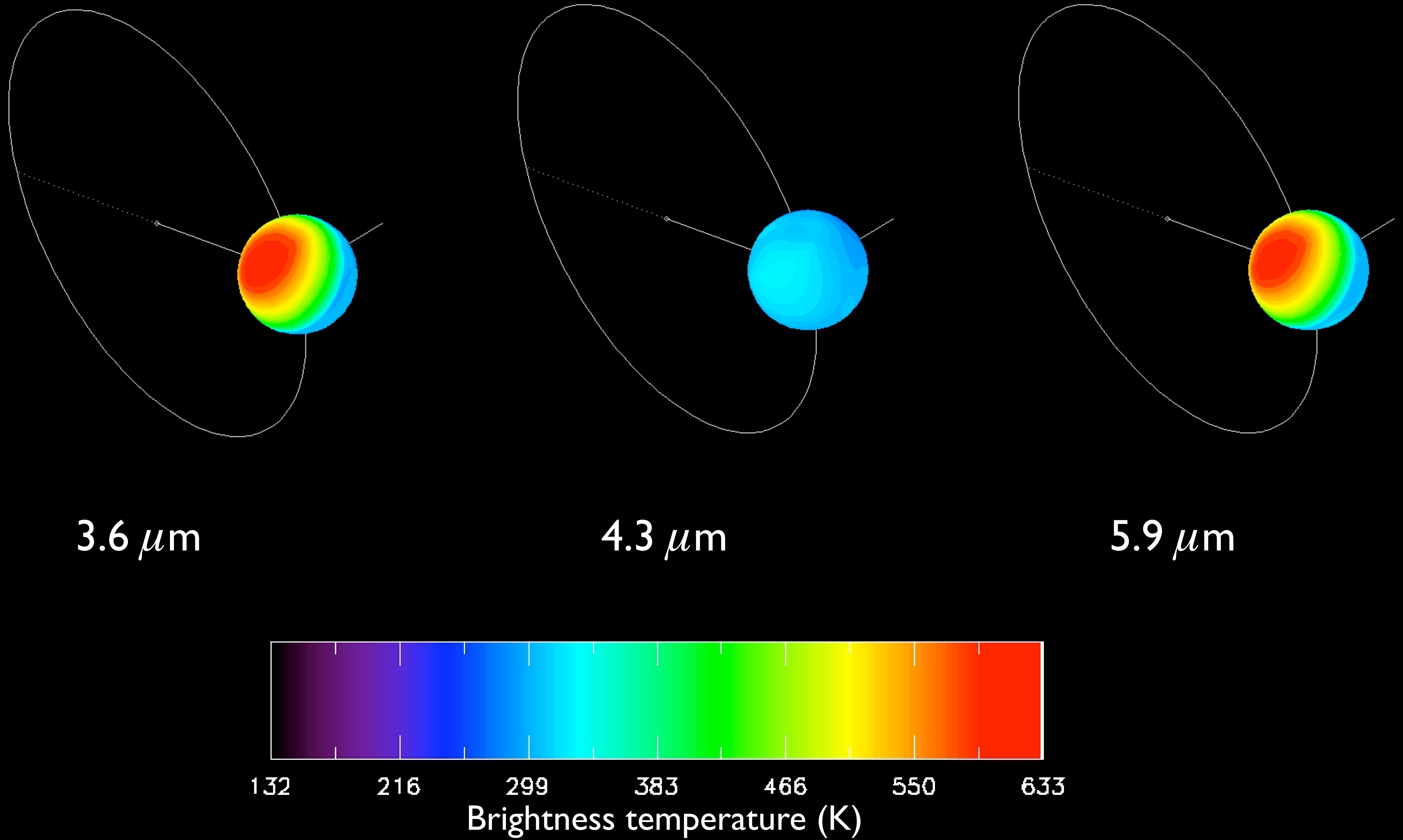


4.3 μm



5.9 μm

1 bar (CO_2)

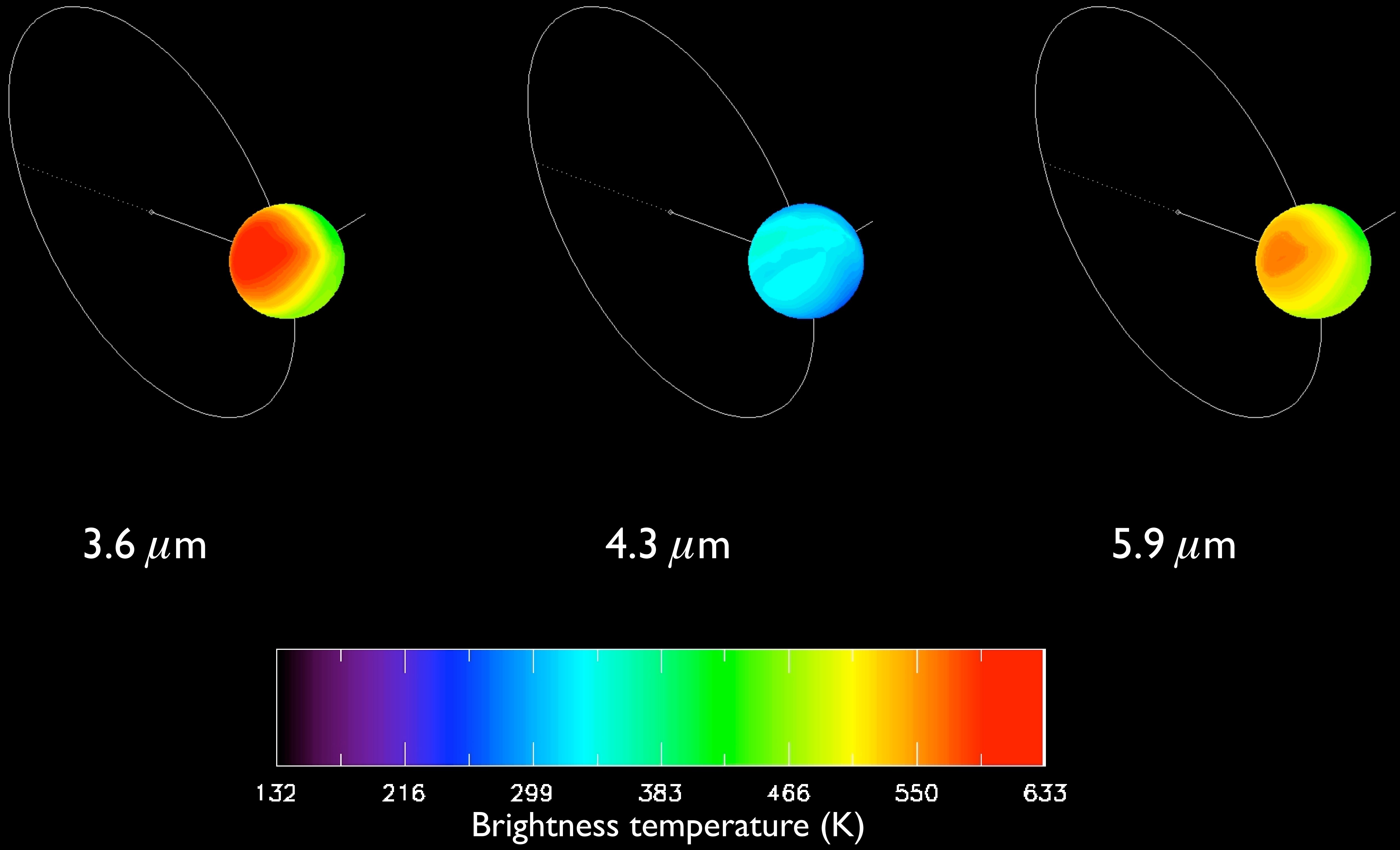


3.6 μm

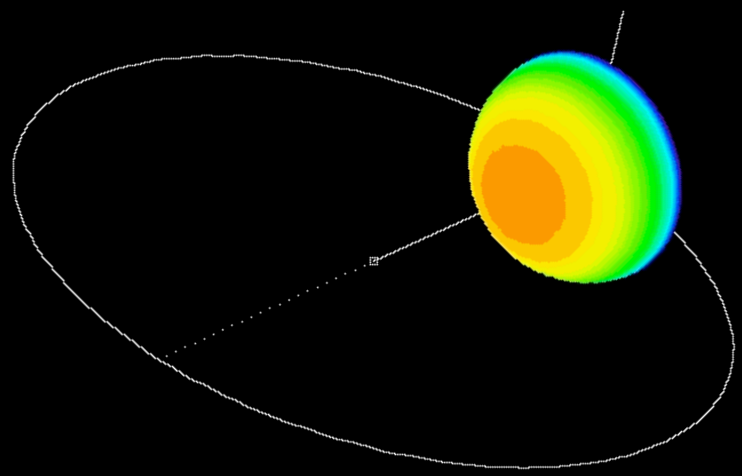
4.3 μm

5.9 μm

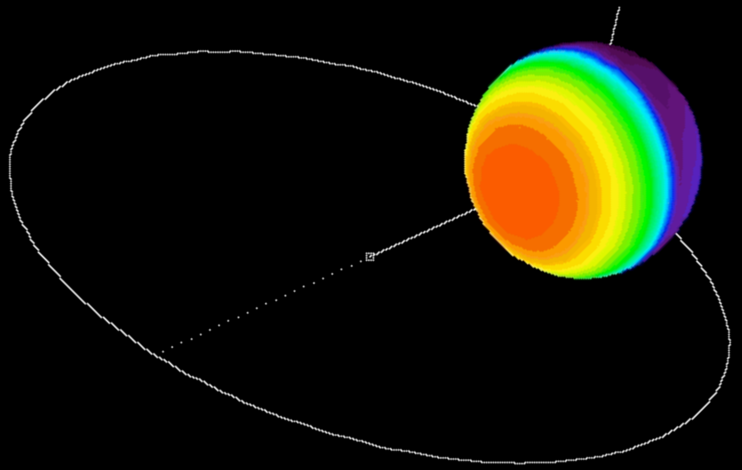
10 bar (CO_2)


3.6 μm
4.3 μm
5.9 μm
132
216
299
383
466
550
633
Brightness temperature (K)

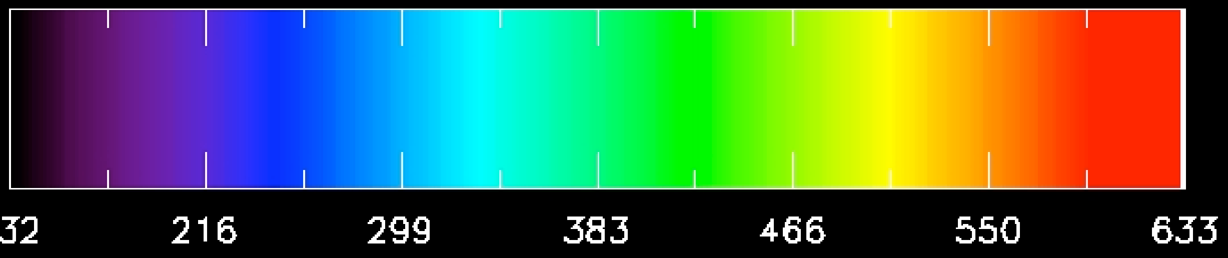
8.7 μm



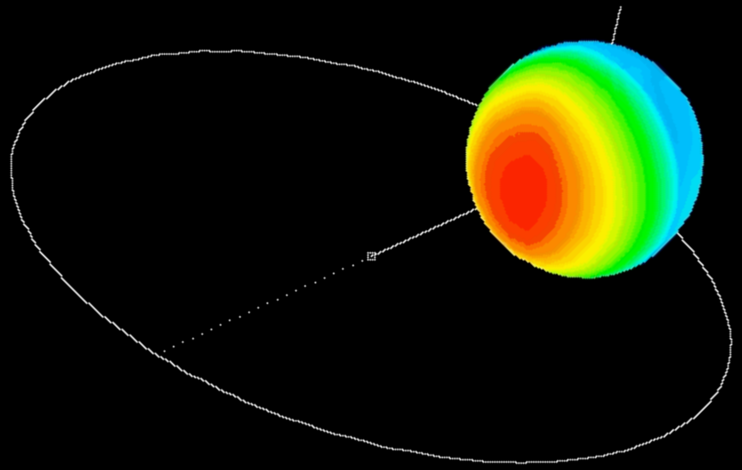
no atmosphere



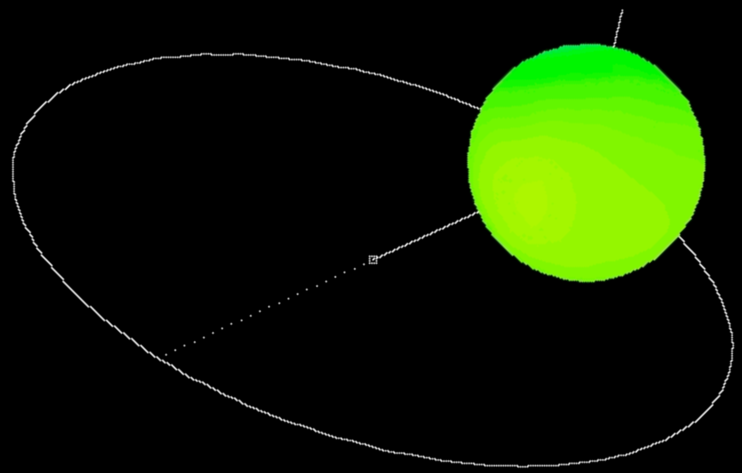
0.1 bar (CO_2)



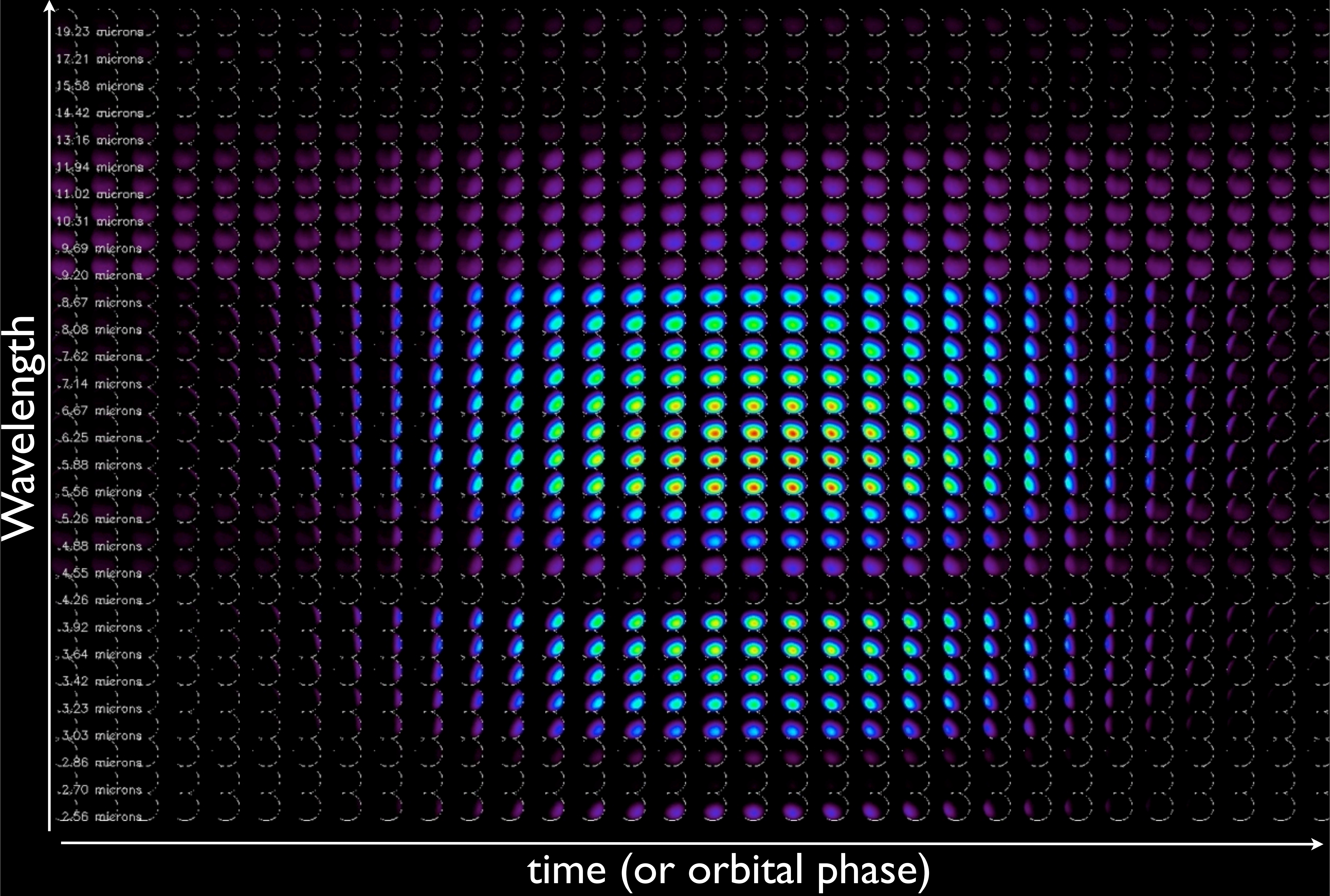
Brightness temperature (K)

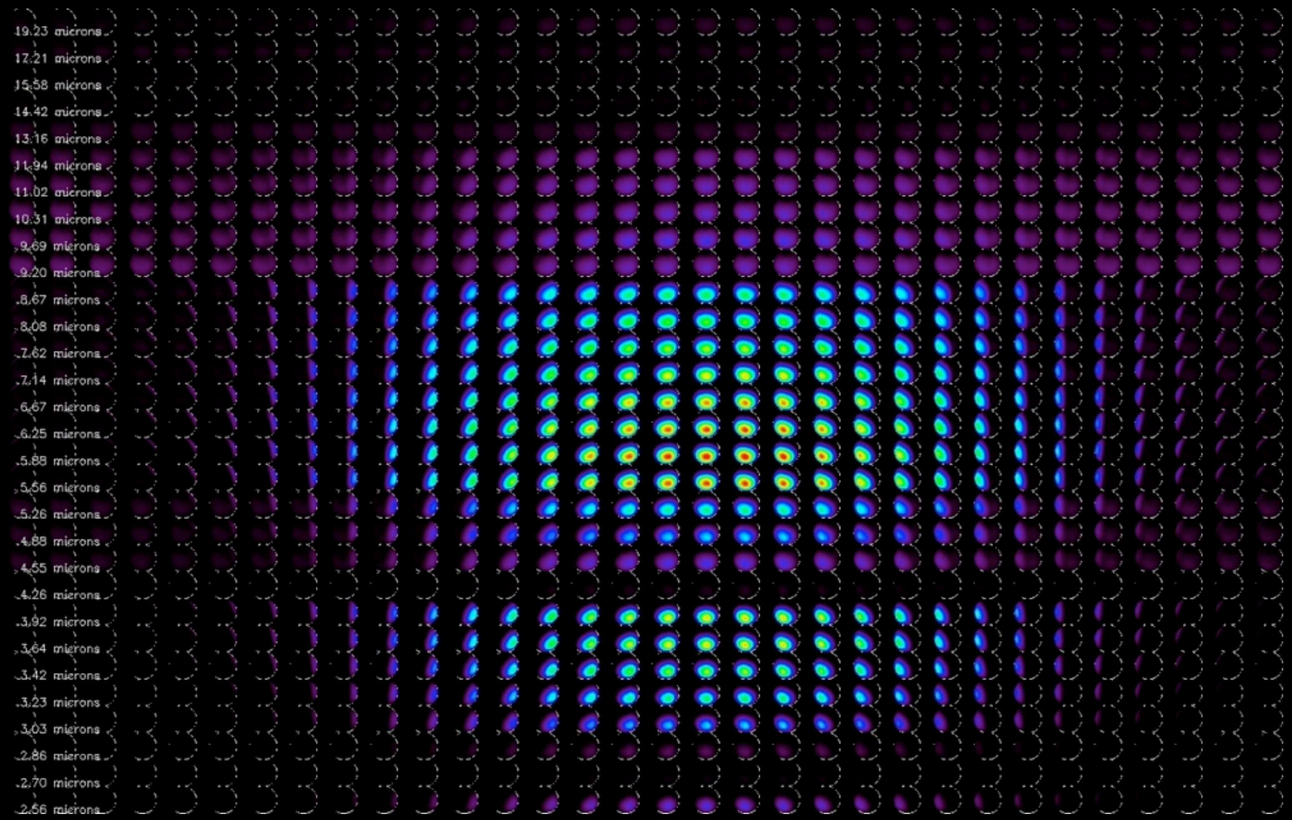


1 bar (CO_2)

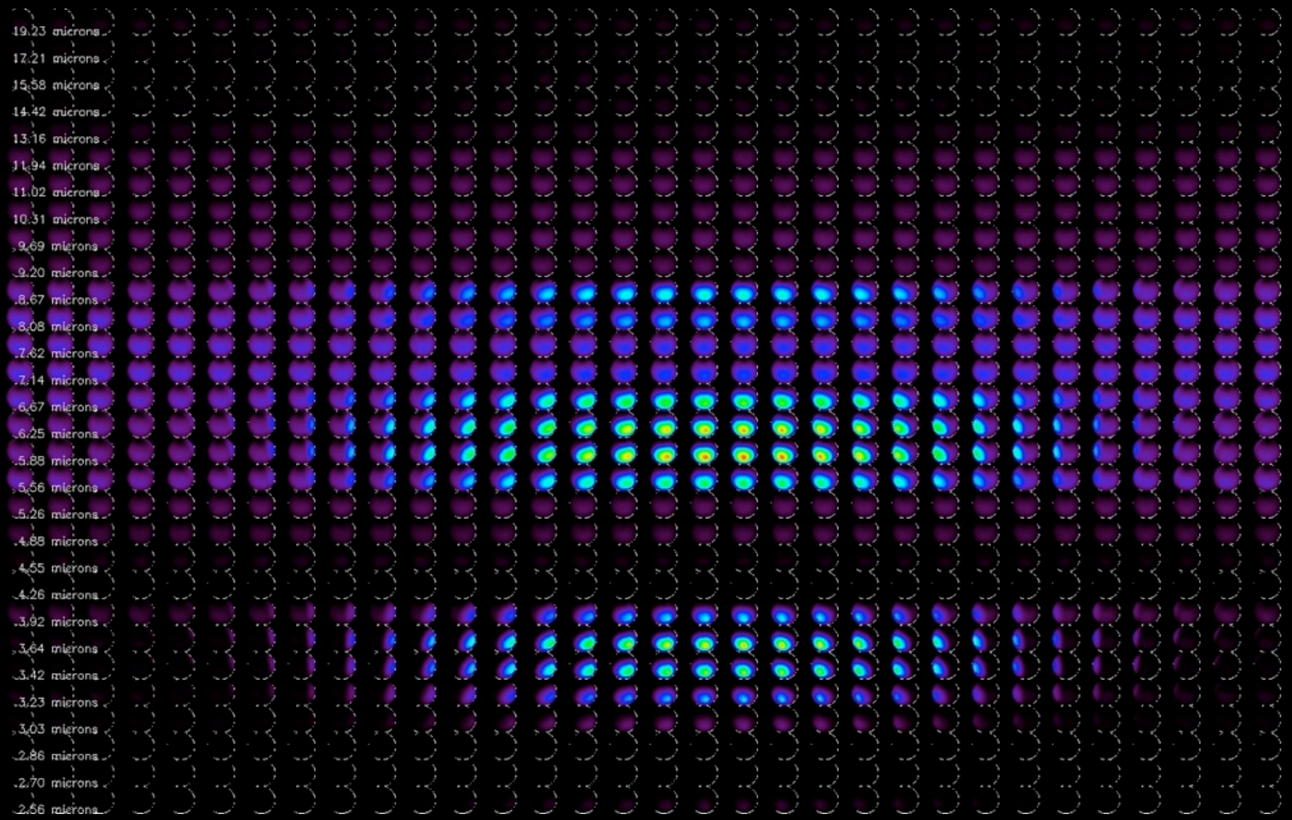


10 bar (CO_2)

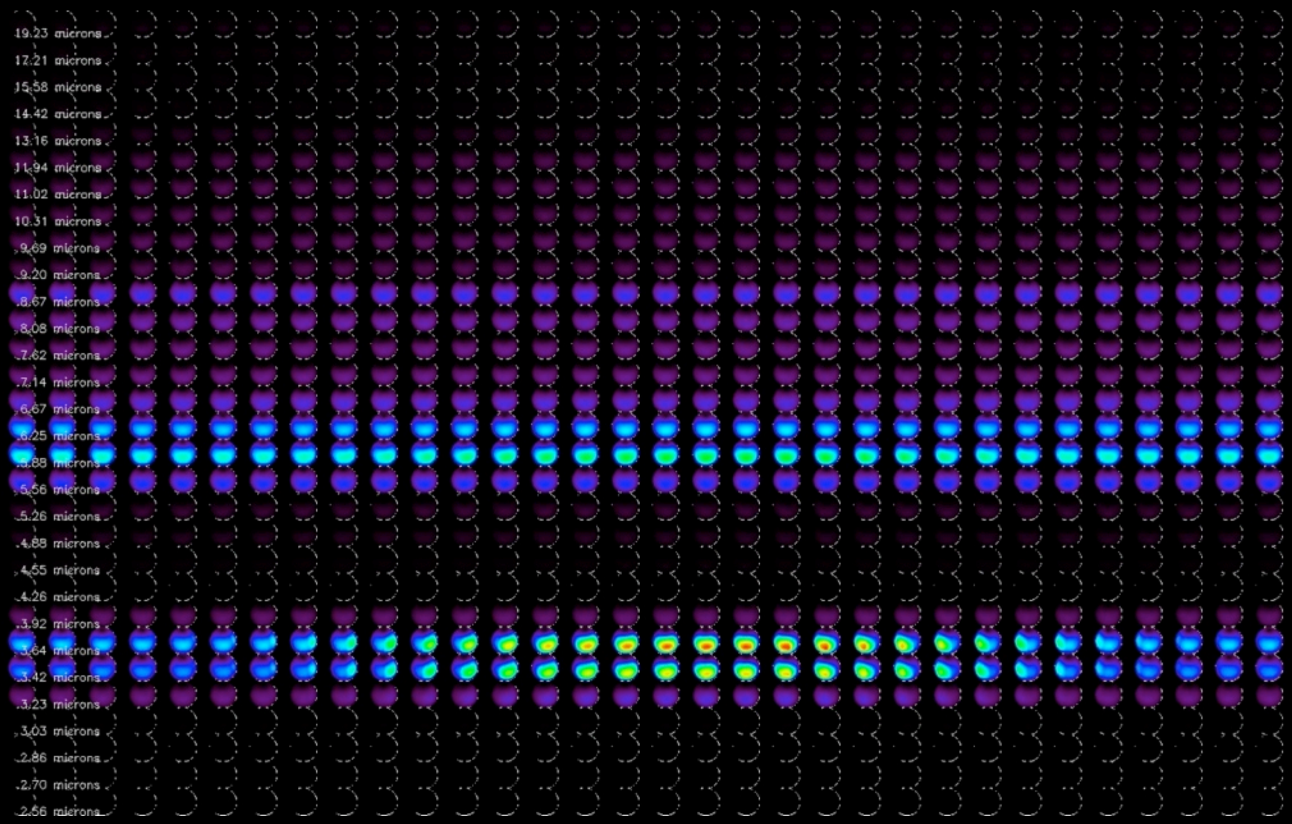

19.23 microns
17.21 microns
15.58 microns
14.42 microns
13.16 microns
11.94 microns
11.02 microns
10.31 microns
9.69 microns
9.20 microns
8.67 microns
8.08 microns
7.62 microns
7.14 microns
6.67 microns
6.25 microns
5.88 microns
5.56 microns
5.26 microns
4.88 microns
4.55 microns
4.26 microns
3.92 microns
3.64 microns
3.42 microns
3.23 microns
3.03 microns
2.86 microns
2.70 microns
2.56 microns
Wavelength
time (or orbital phase)



0.1 bar CO_2

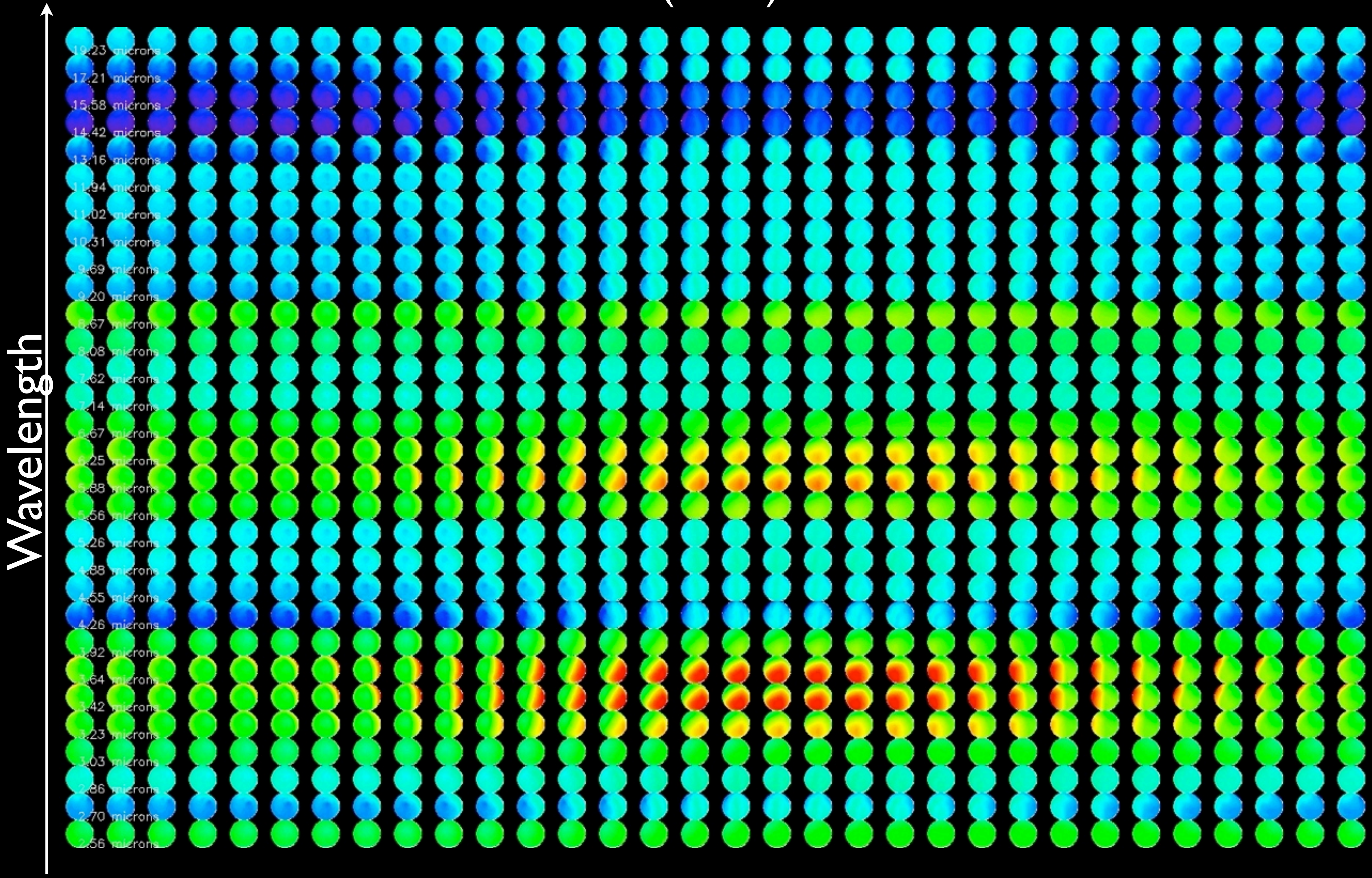


1 bar CO_2



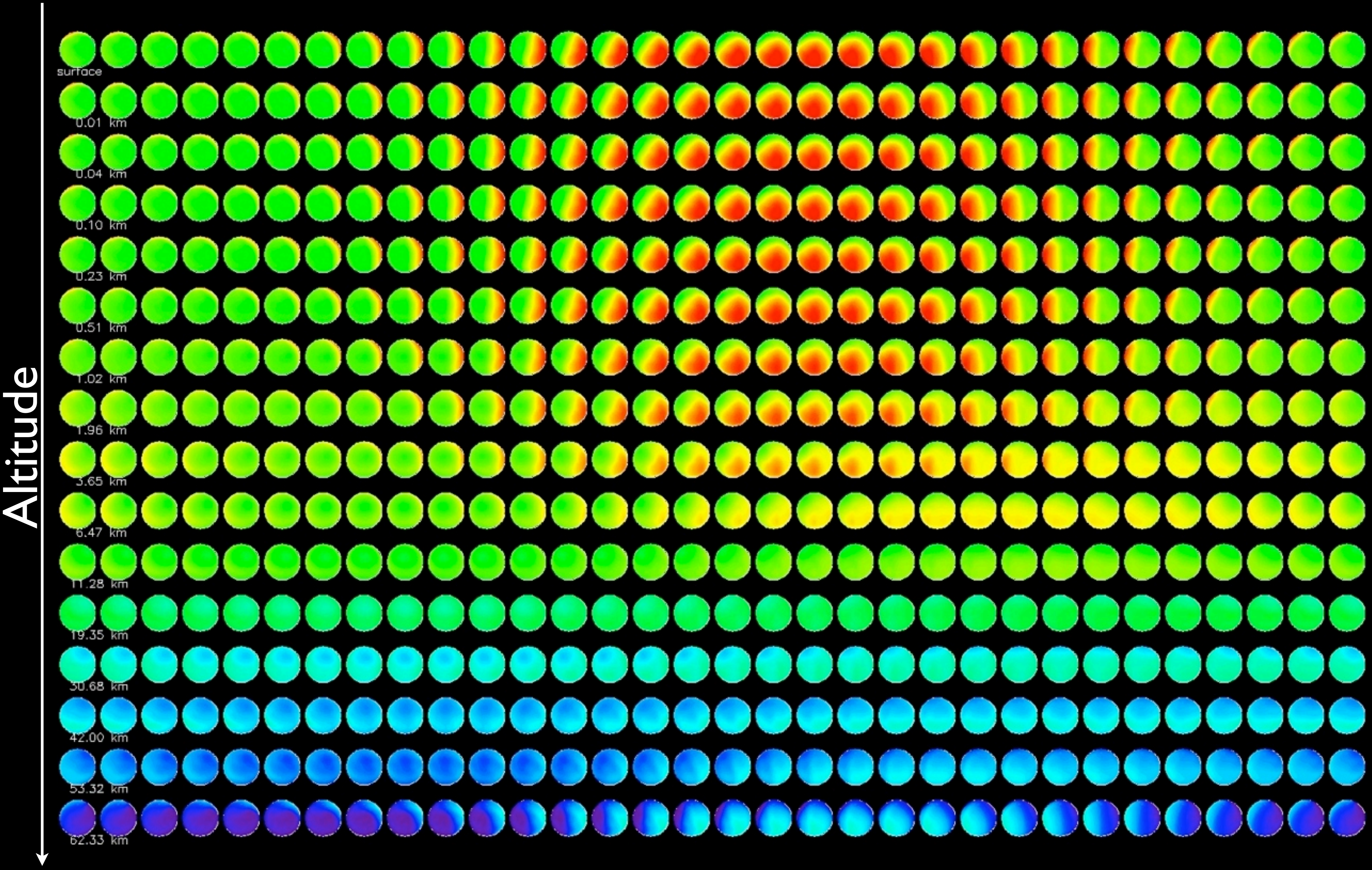
10 bar CO_2

10 bar (CO_2)

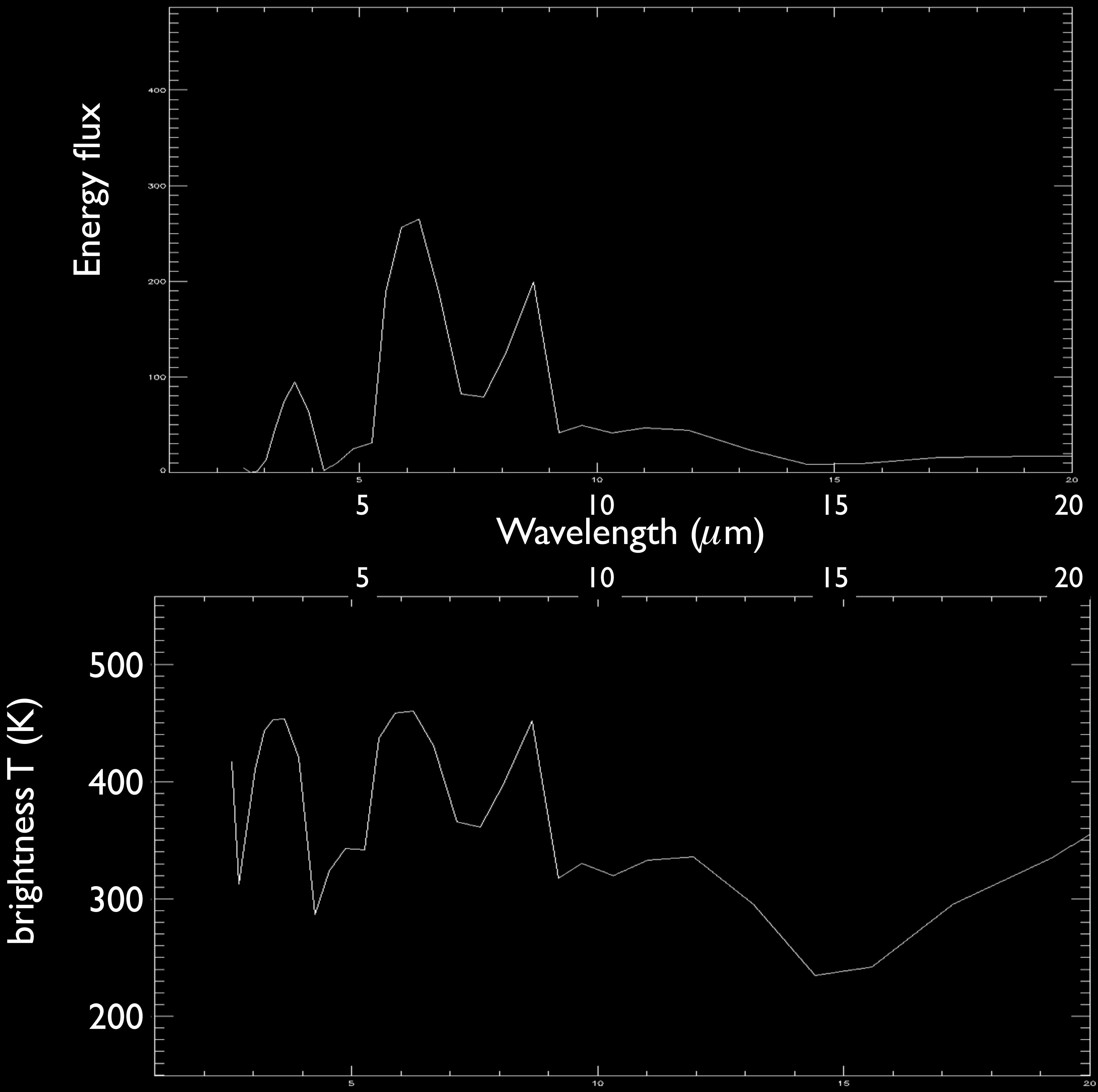


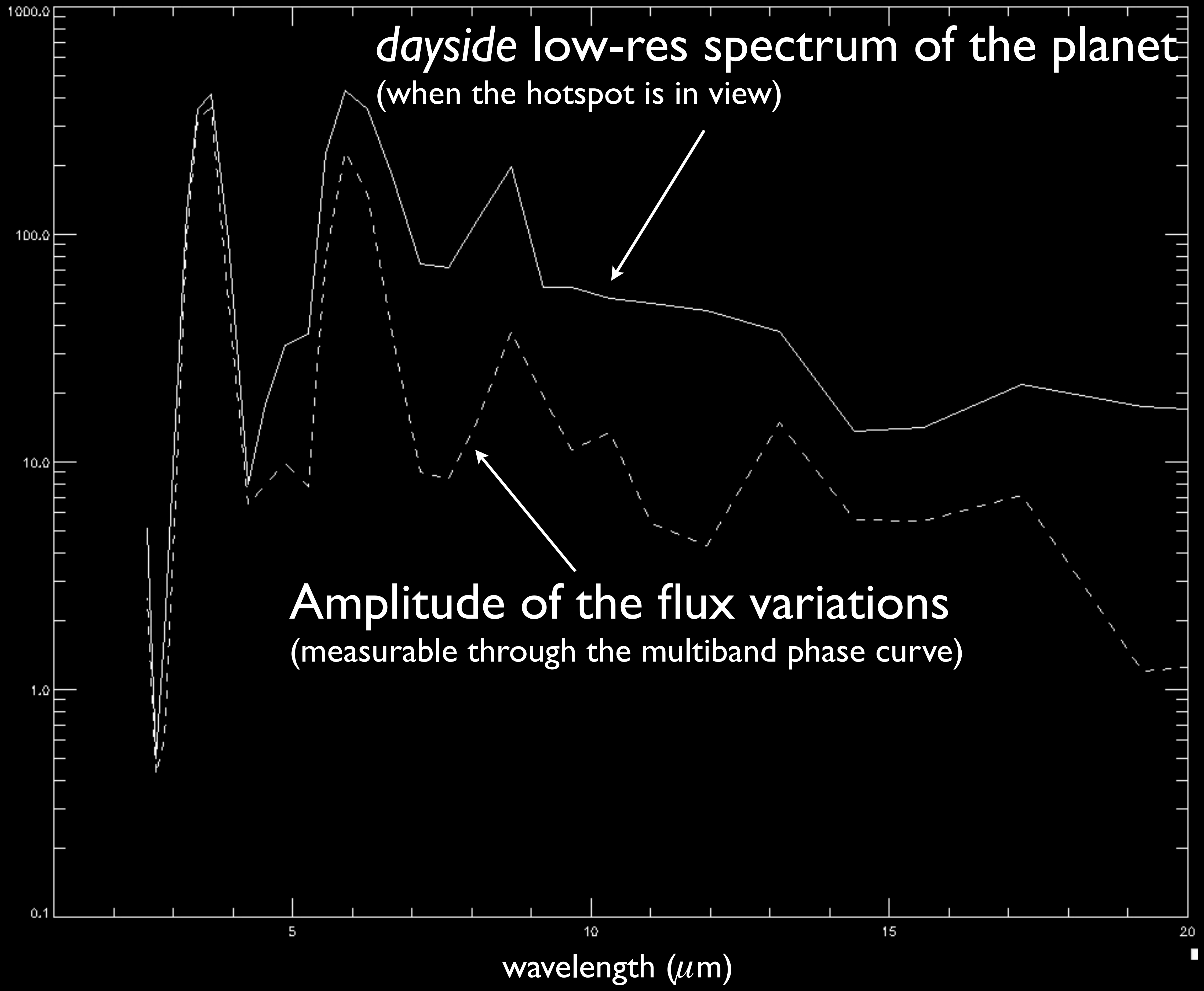
color=brightness temperature (red = 600 K, purple=180 K)

10 bar (CO_2)



color = gas temperature (red = 600 K, purple=180 K)


Energy flux
400
300
200
100
0
5
10
15
20
Wavelength (μm)
5
10
15
20
brightness T (K)
500
400
300
200
5
10
15
20



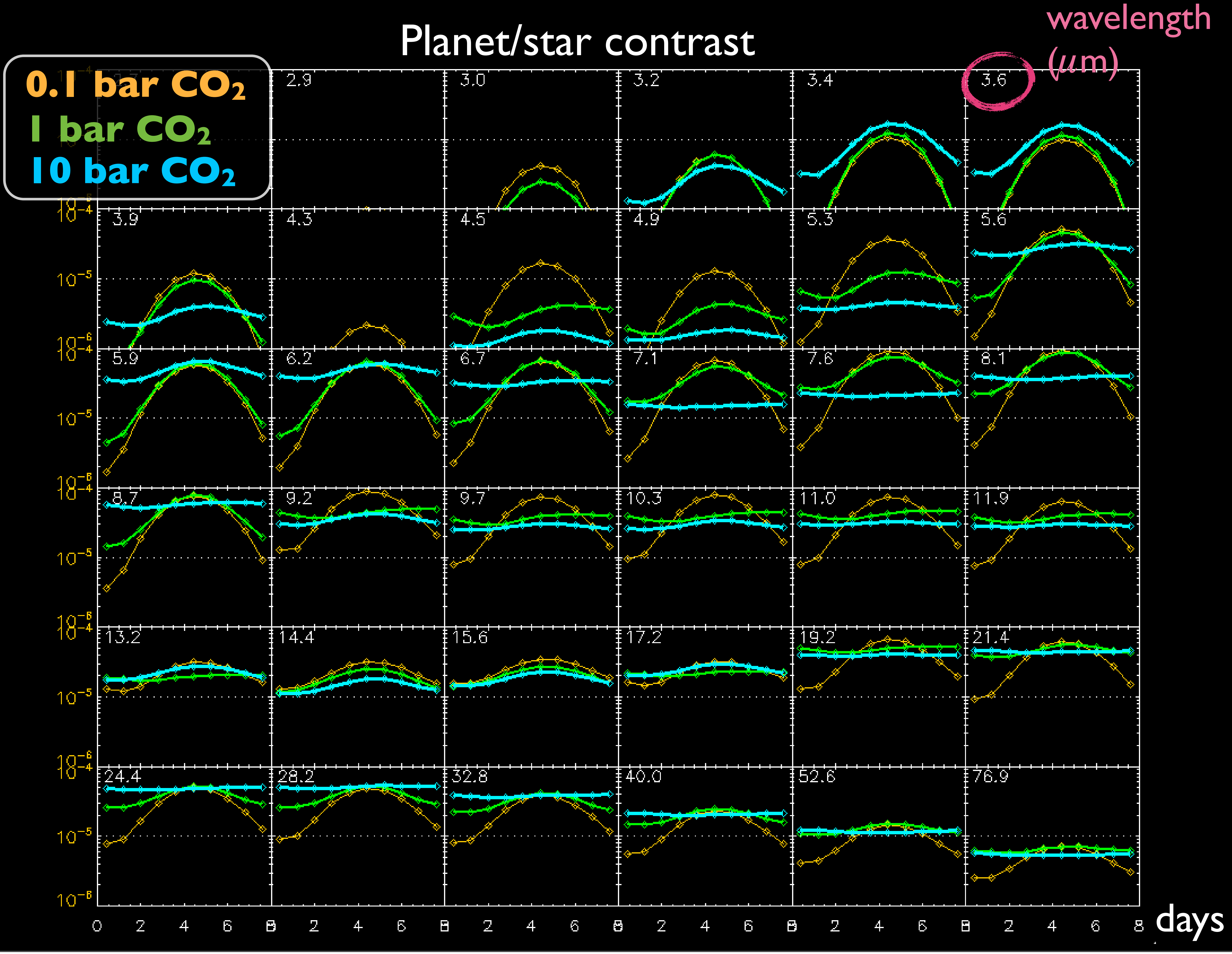
dayside low-res spectrum of the planet

(when the hotspot is in view)

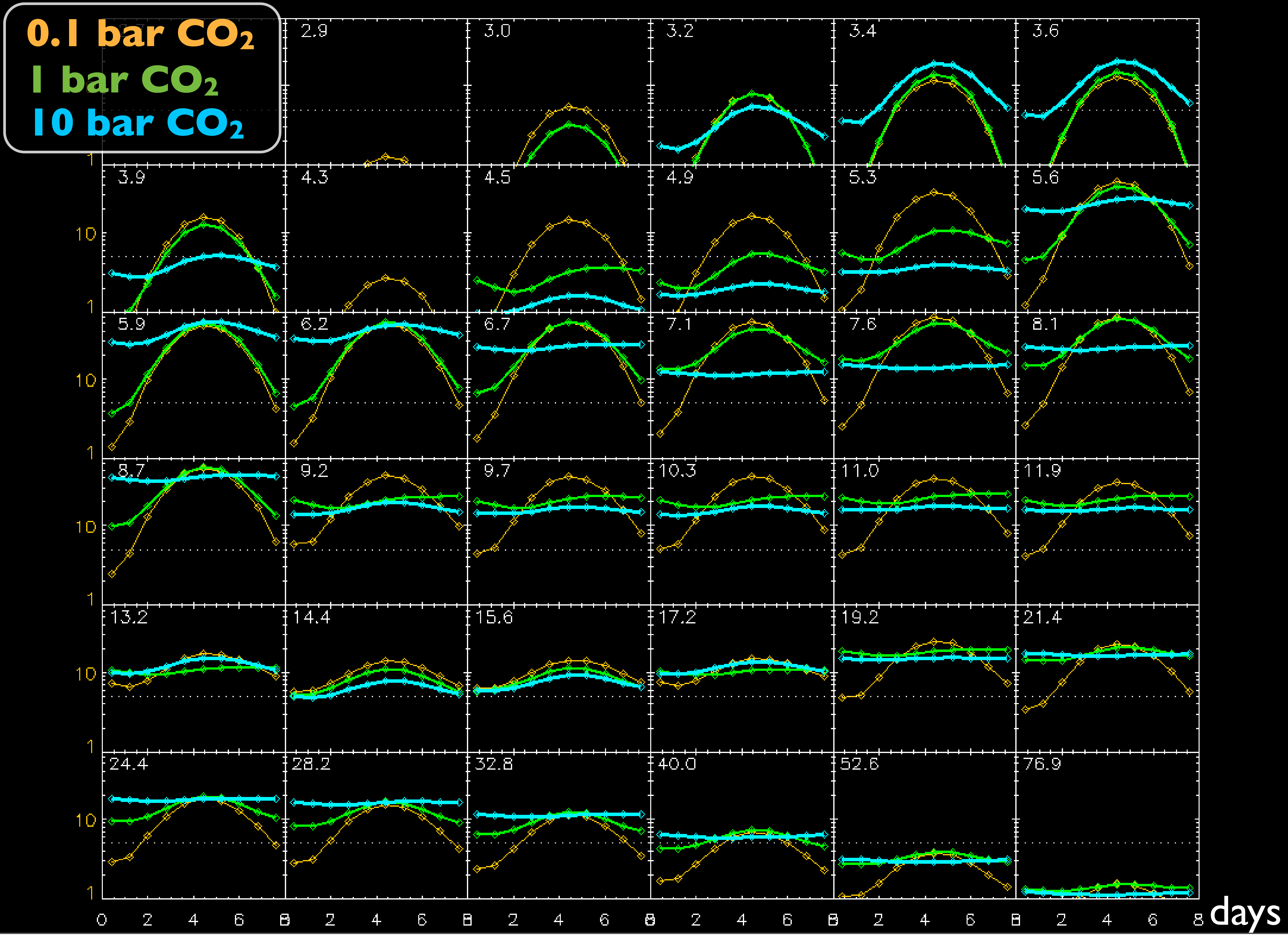
Amplitude of the flux variations

(measurable through the multiband phase curve)

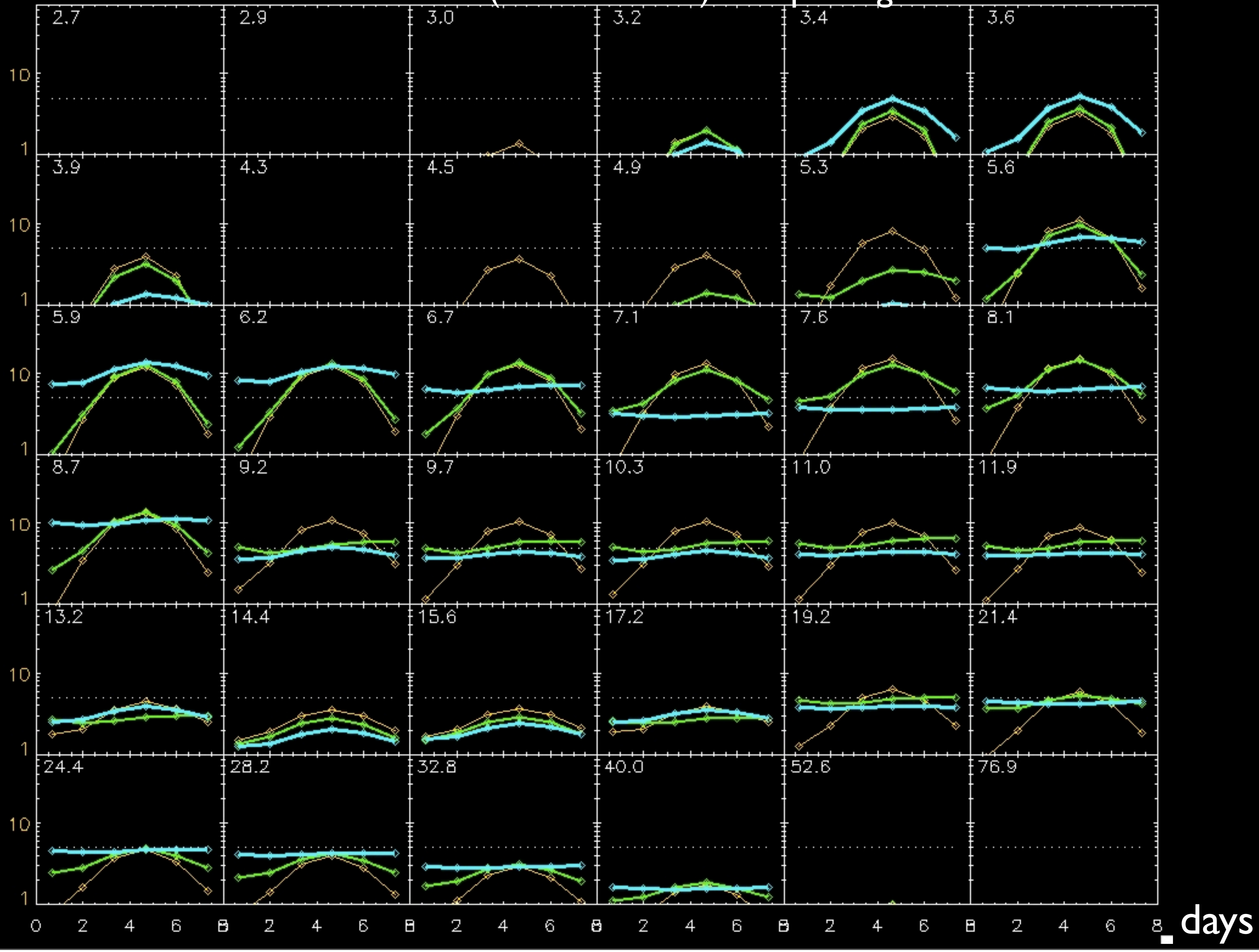
Planet/star contrast

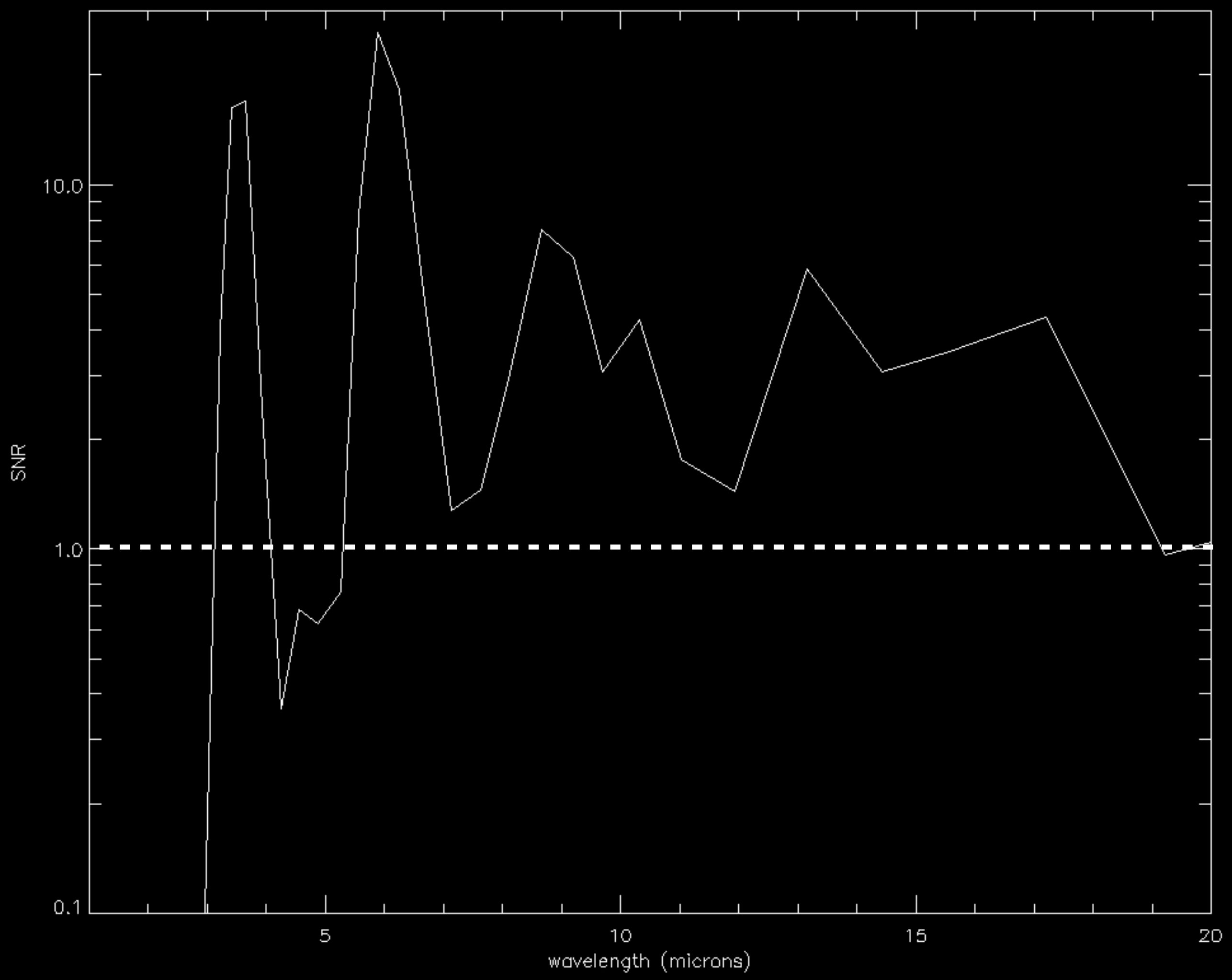


SNR with an ideal 6m telescope (1/10th of orbit) - 10 pc target

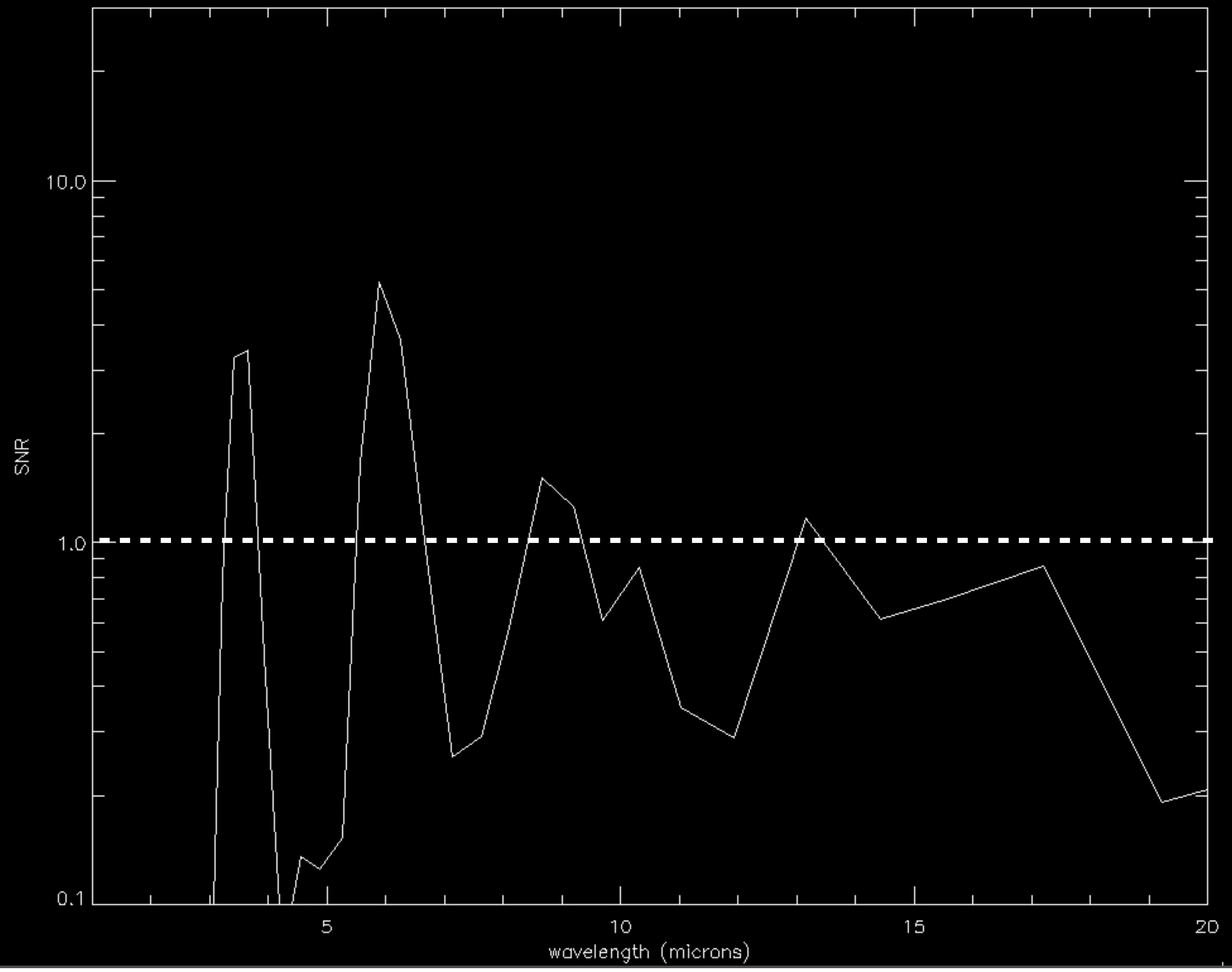

0.1 bar CO_2
1 bar CO_2
10 bar CO_2

SNR with 1.2m (1/6th of orbit) - 10 pc target



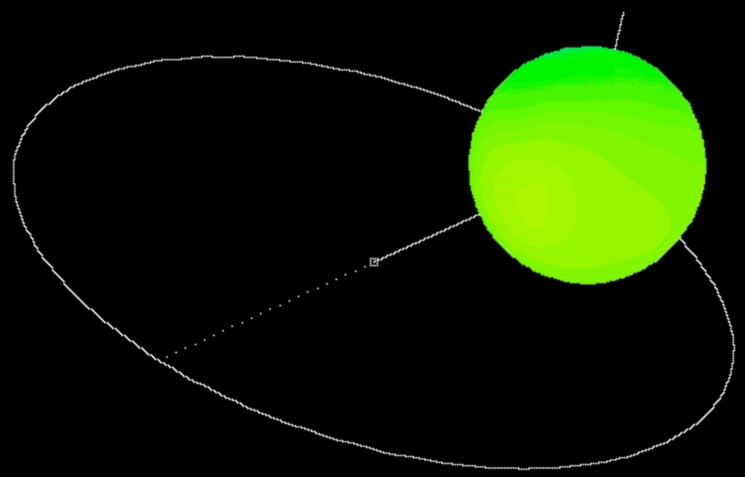


ideal SNR with a 6m telescope
integration time =1/6th of orbit (32h)
signal = amplitude of variations
1 single orbit - 10 pc target

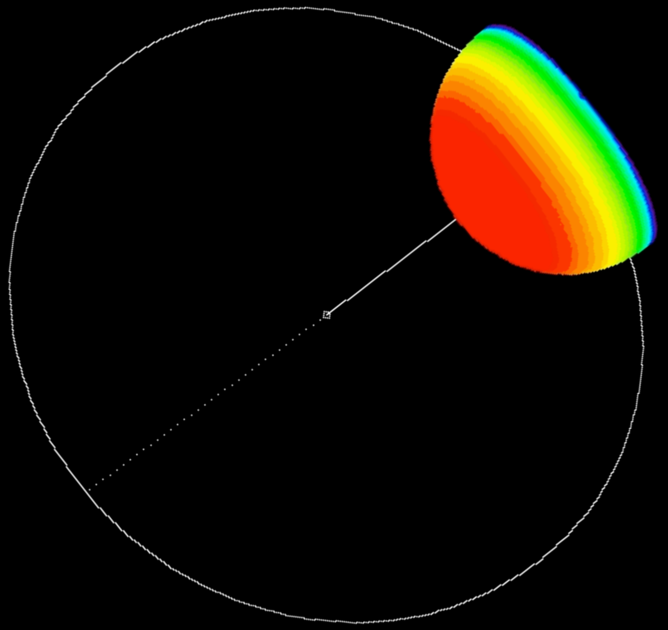


ideal SNR with a 1.2m telescope
integration time =1/6th of orbit (32h)
signal = amplitude of variations
1 single orbit - 10 pc target

Degenerecies
atm vs inclination



dense atmosphere
30°



no atmosphere
70°

- SNR calculations for phasecurve detection based on stellar photon noise only.
Main limitations will be stellar variability and instrument stability

- the theoretical phase curves are available to anyone who wants to test their observability with a more realistic instrument simulator

- if non-transiting planets are observable this way, it increases the number of targets by ~10

- new models will include a mixture of species (CO_2, H_2O, CH_4,...) and clouds