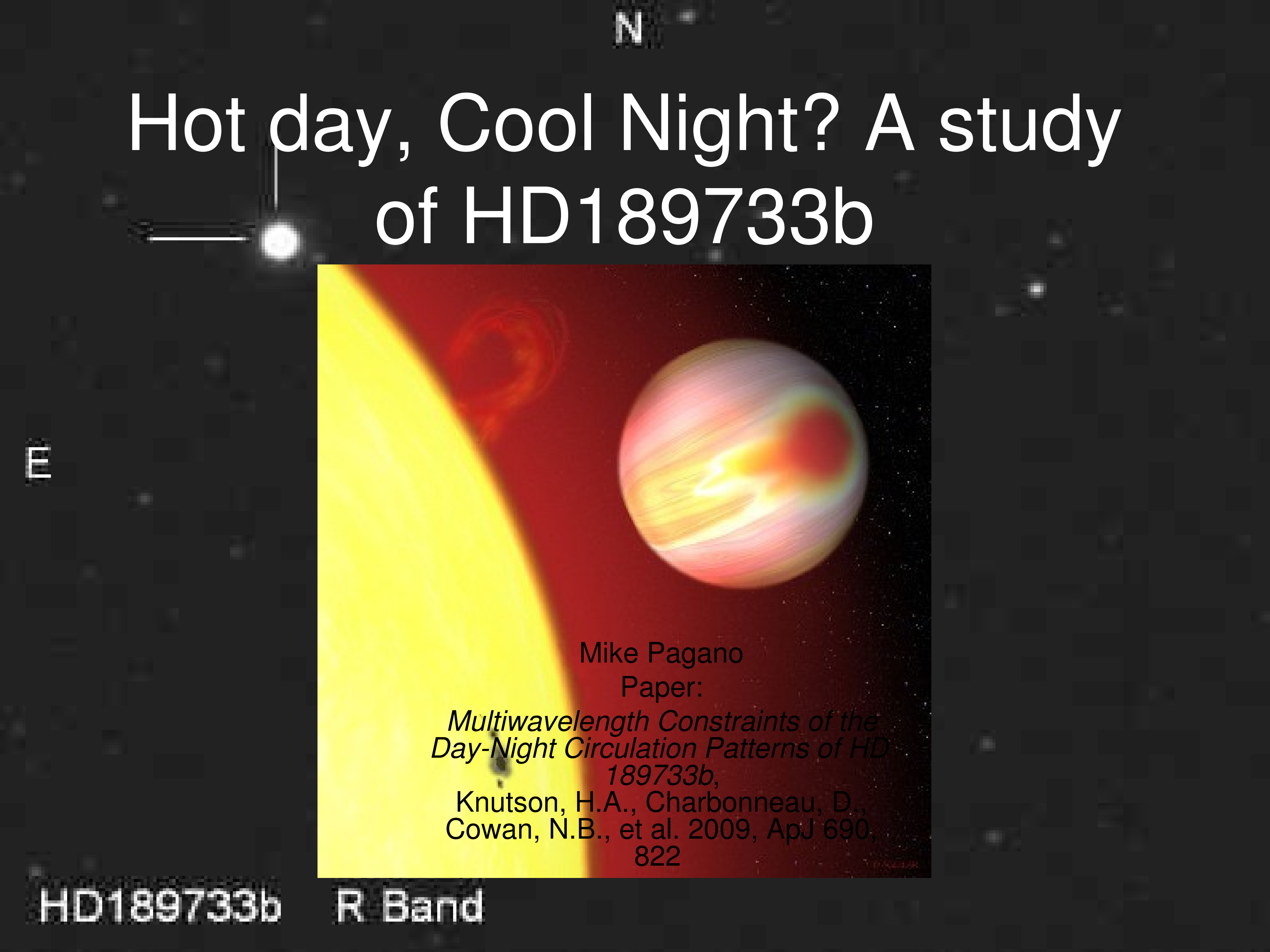
Hot day, Cool Night? A study of HD189733b



Mike Pagano

Paper:

Multiwavelength Constraints of the Day-Night Circulation Patterns of HD 189733b,
Knutson, H.A., Charbonneau, D., Cowan, N.B., et al. 2009, ApJ 690, 822

Hot Jupiters

- Important facts about hot Jupiters:
  - – Exosolar planets, close to their parent stars
    - Usually closer than 0.05 AU
    - This means that they are usually tidally locked
    - This creates permanent night and day sides

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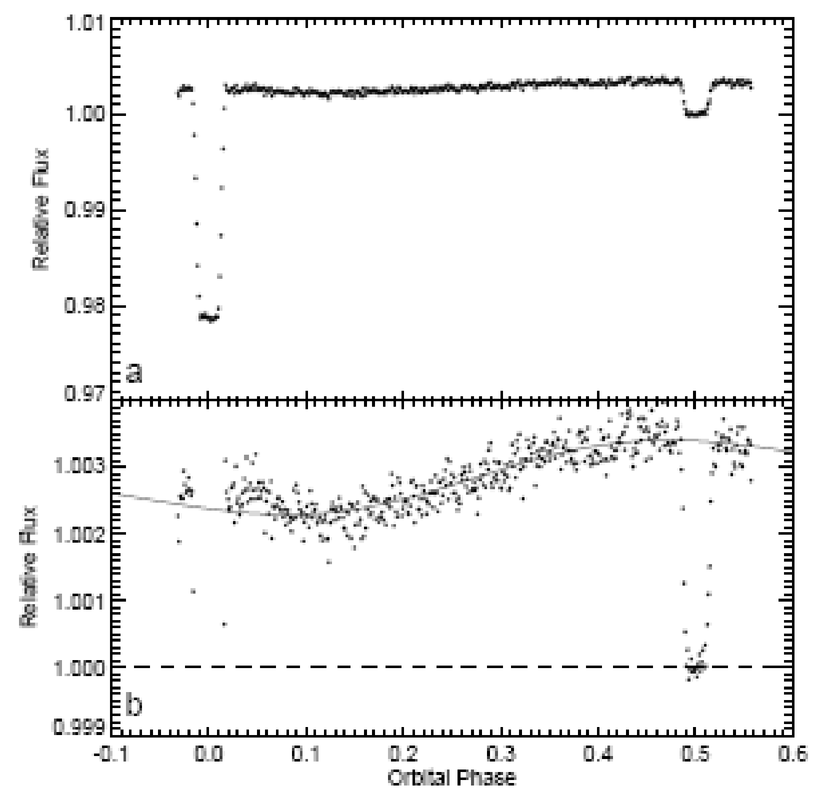
Detecting flux – Transiting Planets



- Transit – Planet in front of star
- Secondary Eclipse– Planet behind star
- First transit Hot Jupiter detected : Charbonneau 2000: HD 2094588b

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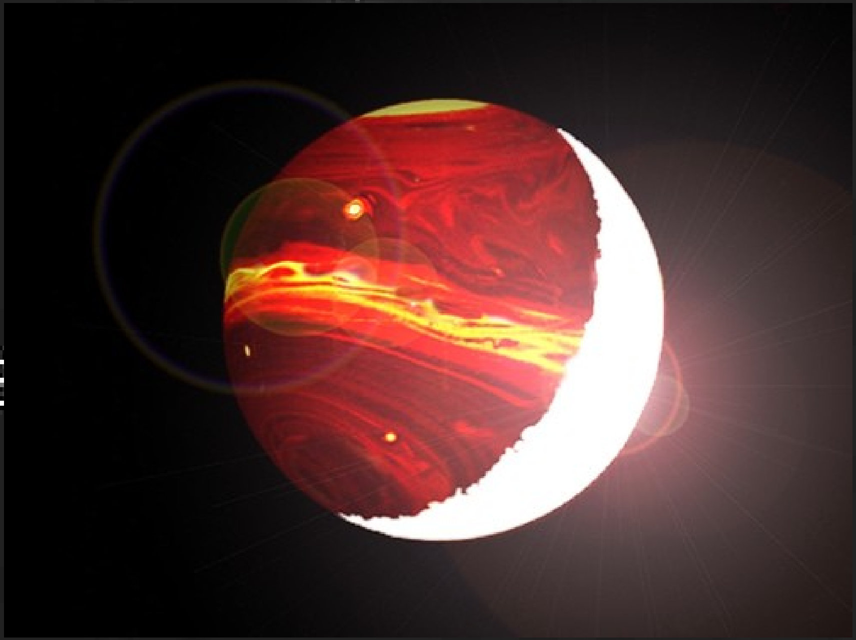
Why we care

- Hot Jupiters represent planets entirely unknown just a few years. Break our tradition conventions of what planets really are
- Tidally locked system are known to us, however none at such extreme temperatures, and possible temperature differences
  - Our only good example of this difference is Mercury (whose 3:2 resonance makes it close to tidally locked) where Dark/Light variations can be up to 640 K

Day side vs. Night side



$$T_{\rm day}^4 = (1 - A_B)(1 - P_n)\left(\frac{R_*^2}{2a^2}\right) T_{\rm eff}^4,$$

and

$$T_{\rm night}^4 = (1 - A_B)P_n\left(\frac{R_*^2}{2a^2}\right) T_{\rm eff}^4,$$

- Depth of secondary eclipse helps constrain day-side brightness/temperature

$$\frac{F_{\rm day}}{F_*} = A_g\left(\frac{R_p}{a}\right)^2 + \frac{B_\lambda(T_{\rm day})}{B_\lambda(T_{\rm bright})}\left(\frac{R_p}{R_*}\right)^2,$$

- Look at changes in thermal emission as function of orbital phase

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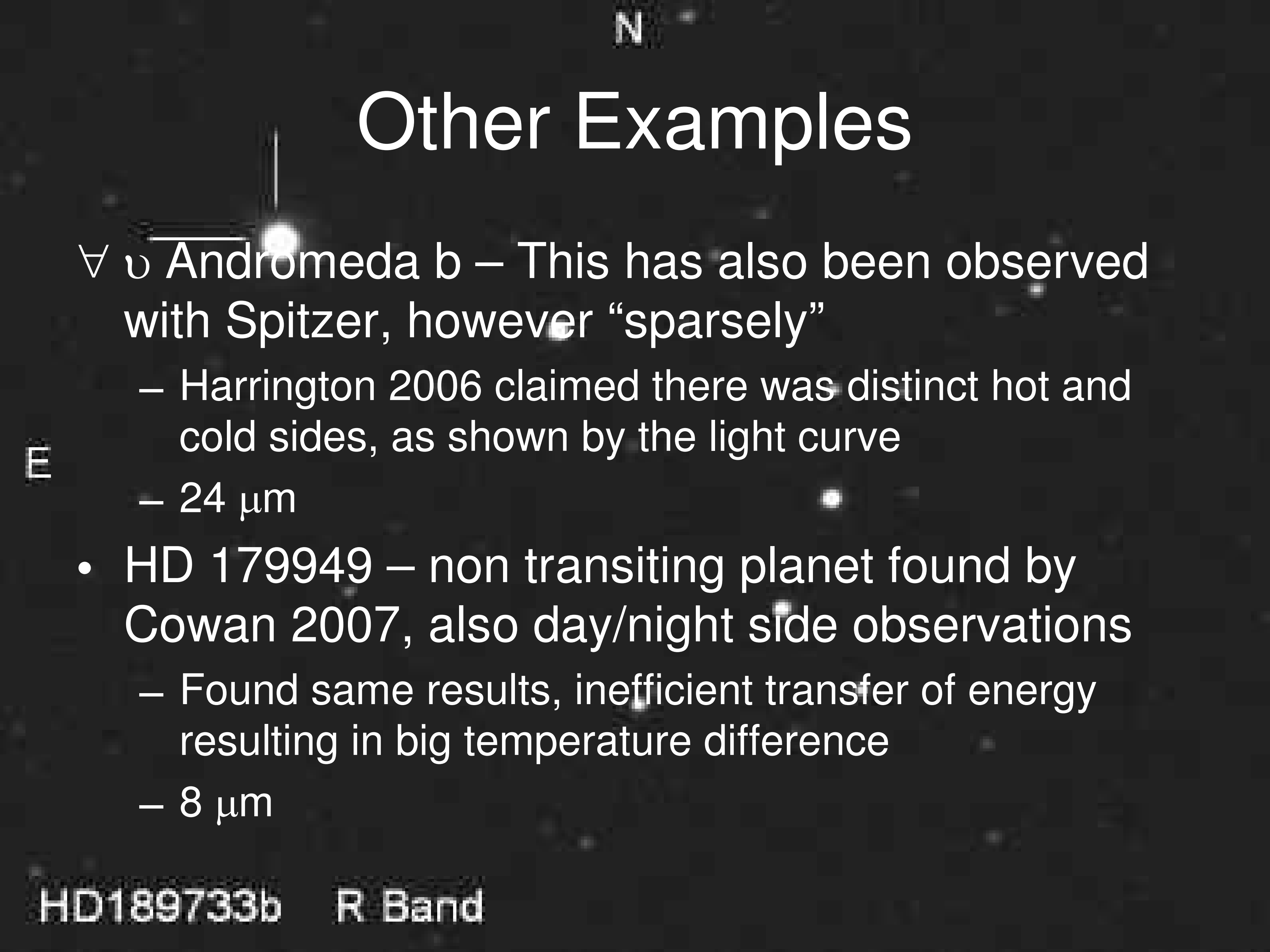
Other Examples



∀ υ Andromeda b – This has also been observed with Spitzer, however “sparsely”

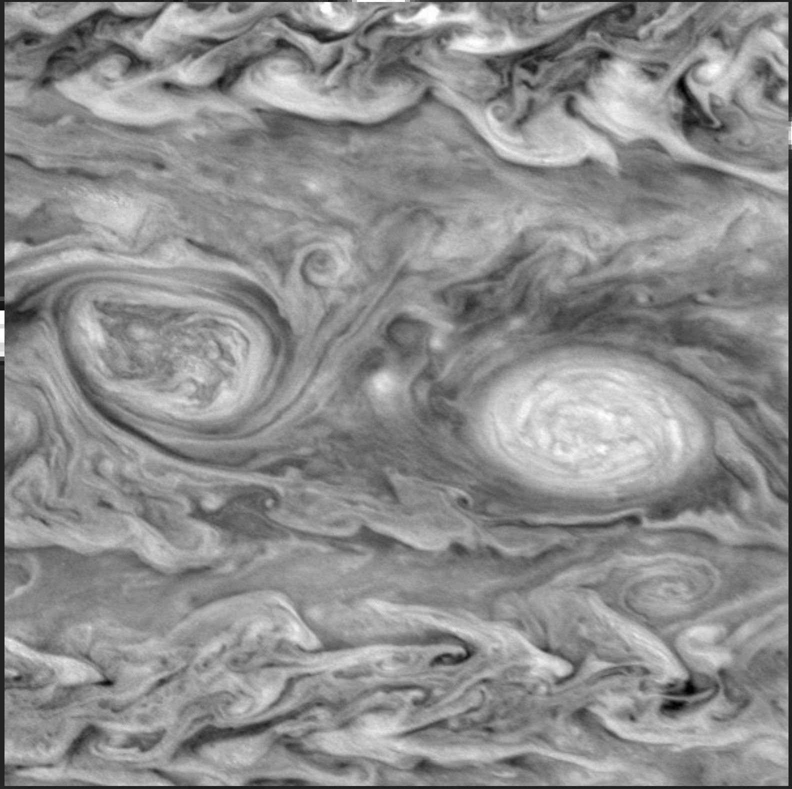
- Harrington 2006 claimed there was distinct hot and cold sides, as shown by the light curve
- 24 μm

- HD 179949 – non transiting planet found by Cowan 2007, also day/night side observations
  - Found same results, inefficient transfer of energy resulting in big temperature difference
  - 8 μm

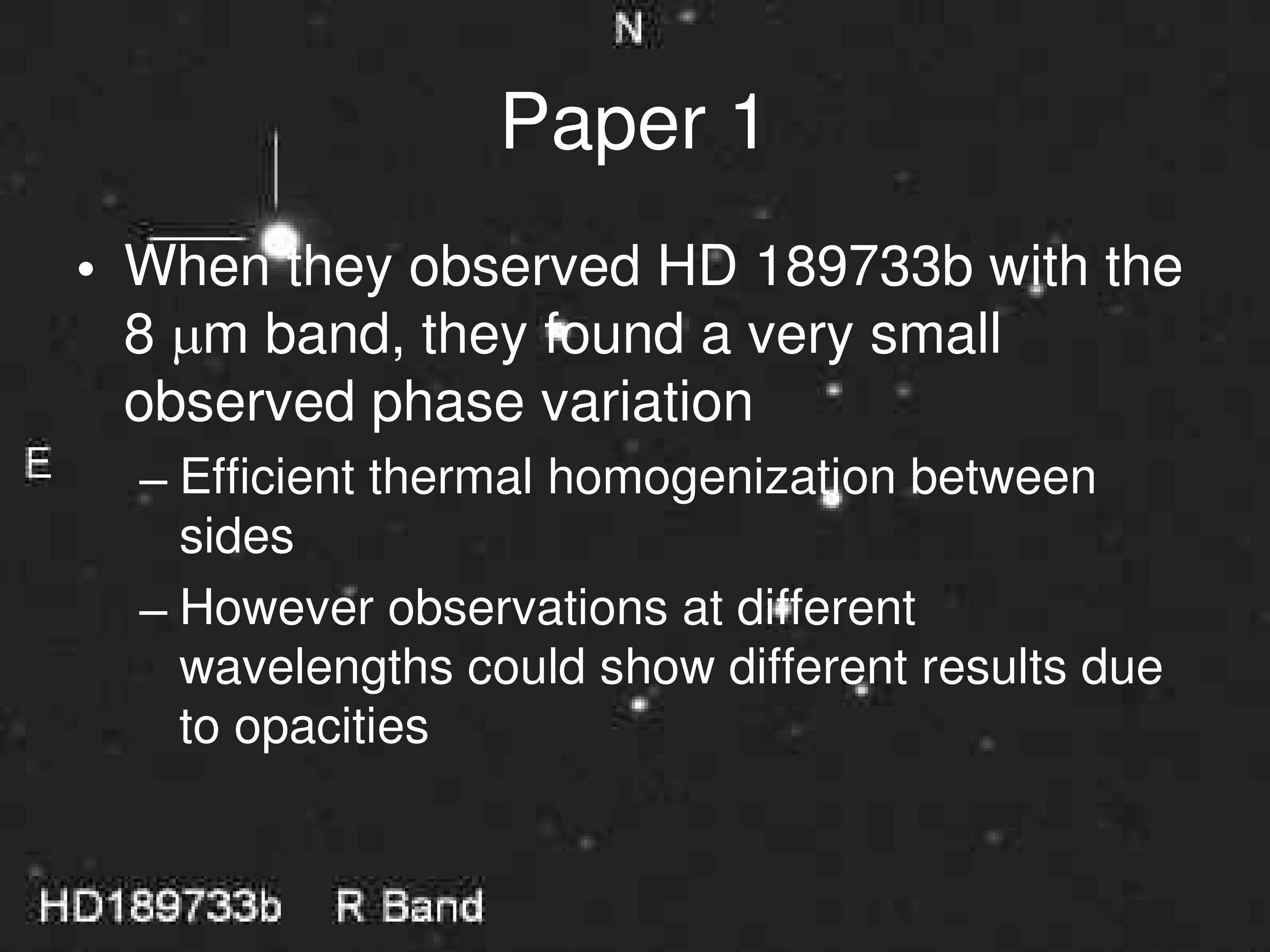
HD 189733b

- 63 Light years away
- K0V star
- 0.03099 ± 0.0006 AU orbit
- 2.218 day period
- ~ 1.14 M Jupiter
- Brightest known star with transiting planet(IR)

Predictions



- Circulation models predict that the day side would be 500-1000 K hotter than the permanent dark side
- Many circulation/wind models give similar results
- More complicated structures such as vortices possible

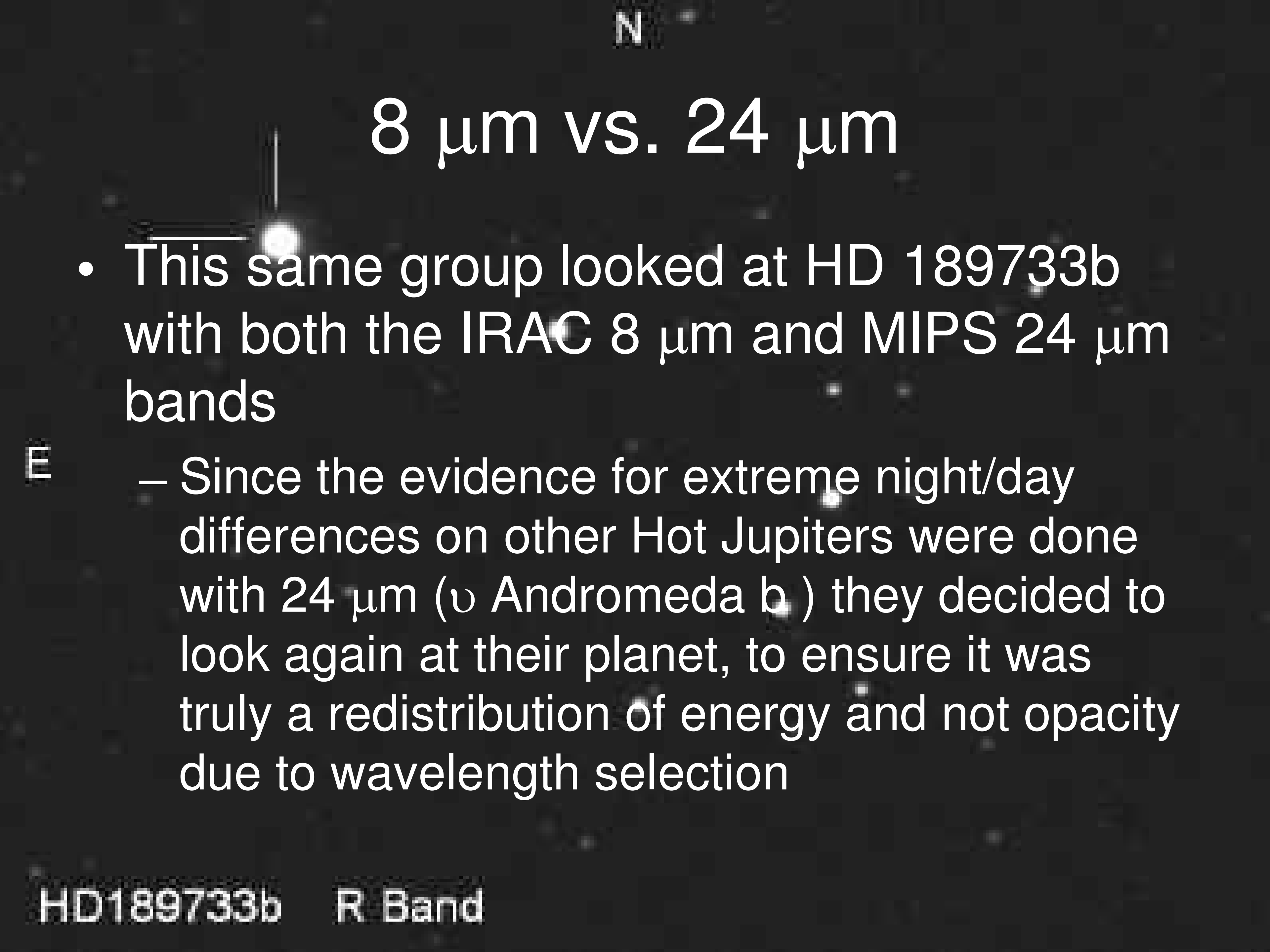


Paper 1

- When they observed HD 189733b with the 8 μm band, they found a very small observed phase variation
  - Efficient thermal homogenization between sides
  - However observations at different wavelengths could show different results due to opacities

8 μm vs. 24 μm

- This same group looked at HD 189733b with both the IRAC 8 μm and MIPS 24 μm bands
  - Since the evidence for extreme night/day differences on other Hot Jupiters were done with 24 μm (υ Andromeda b) they decided to look again at their planet, to ensure it was truly a redistribution of energy and not opacity due to wavelength selection



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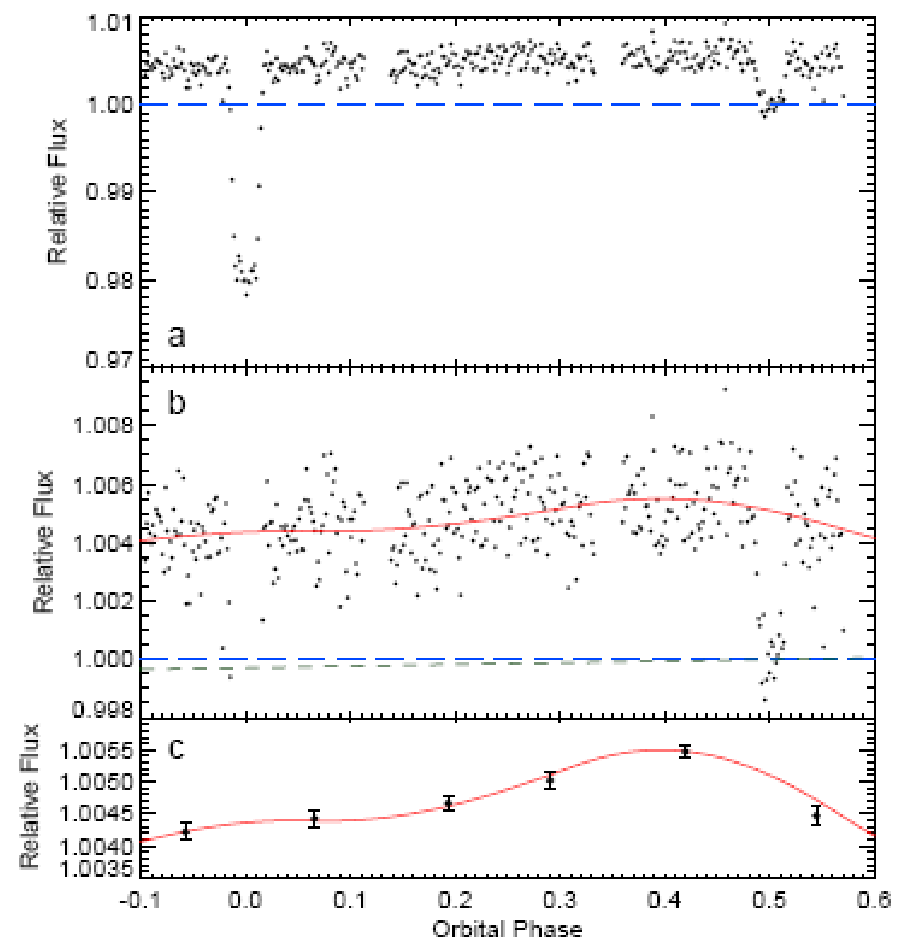
Methodology

- 10,104 images from Spitzer on UT 2007 Oct. 25/26 with 10 s integration time
- There is an Mdwarf companion that they trim off



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Eclipses

- Finding the depth of the transit
  - Proportional to the square of the ratio of the planetary and stellar radii and the transit time

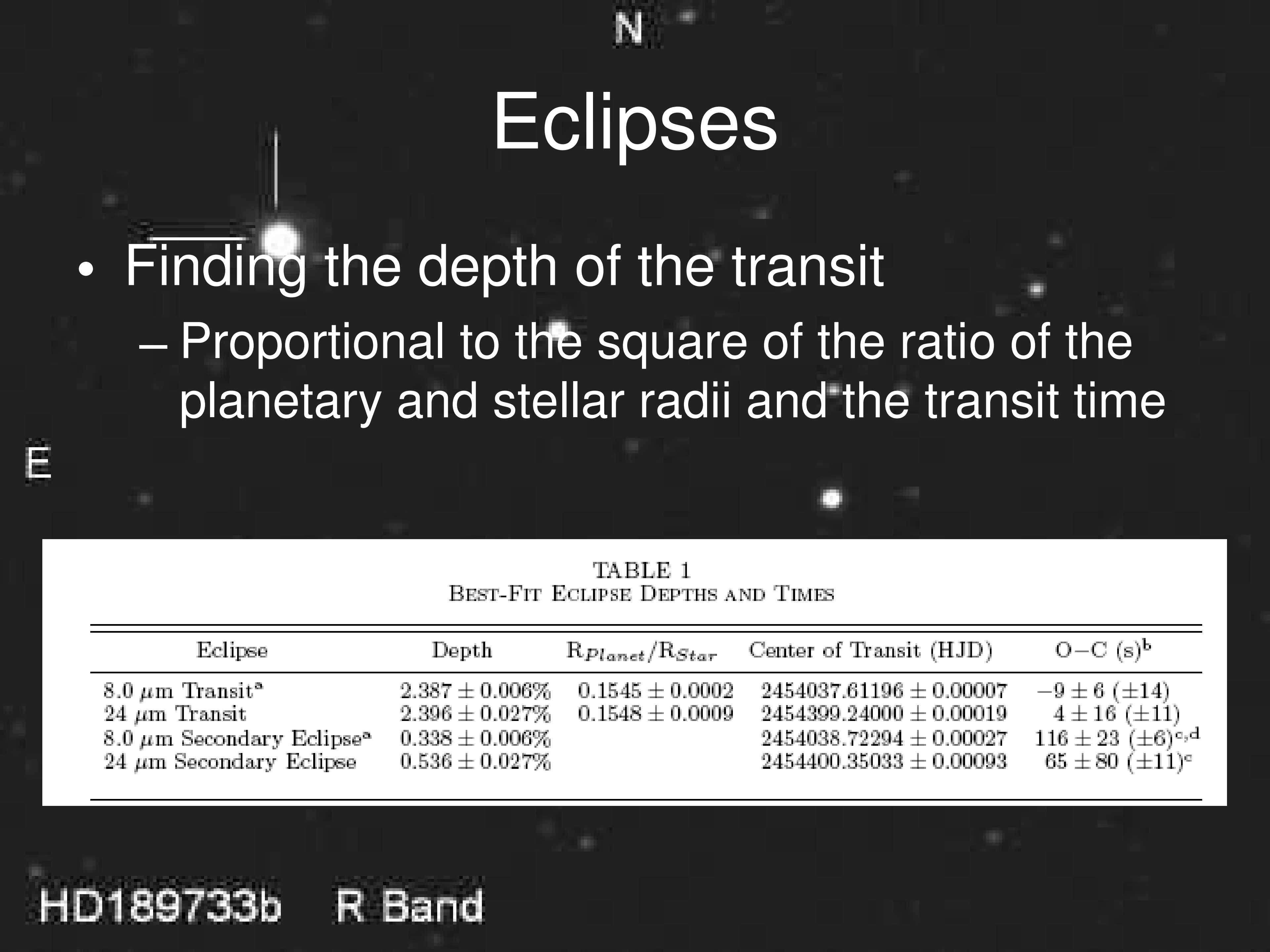

TABLE 1
Best-Fit Eclipse Depths and Times

Eclipse	Depth	R_{Planet}/R_{Star}	Center of Transit (HJD)	O−C (s)[b]
8.0 μm Transit[a]	$2.387 \pm 0.006\%$	0.1545 ± 0.0002	$2454037.61196 \pm 0.00007$	-9 ± 6 (± 14)
24 μm Transit	$2.396 \pm 0.027\%$	0.1548 ± 0.0009	$2454399.24000 \pm 0.00019$	4 ± 16 (± 11)
8.0 μm Secondary Eclipse[a]	$0.338 \pm 0.006\%$		$2454038.72294 \pm 0.00027$	116 ± 23 (± 6)[c,d]
24 μm Secondary Eclipse	$0.536 \pm 0.027\%$		$2454400.35033 \pm 0.00093$	65 ± 80 (± 11)[c]

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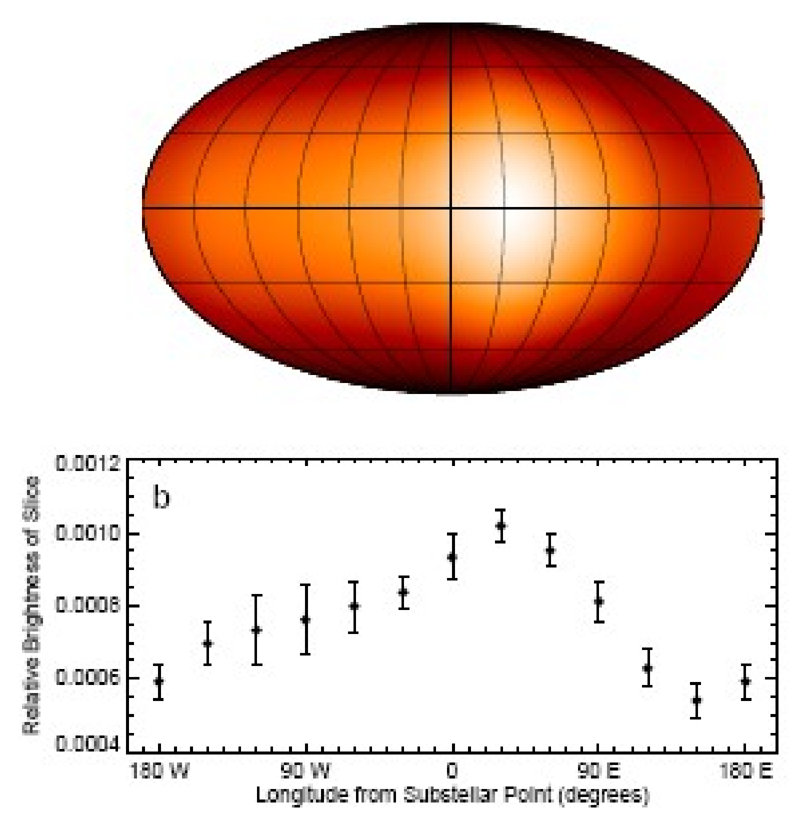
Fitting the Phase Curve



- Use an ‘orange slice’ model
- Find that the brightest region is actually on the east 20-30 degrees
- Both phase curves (8 and 24 μm) show this as an early peak of phase curve, right before secondary eclipse.

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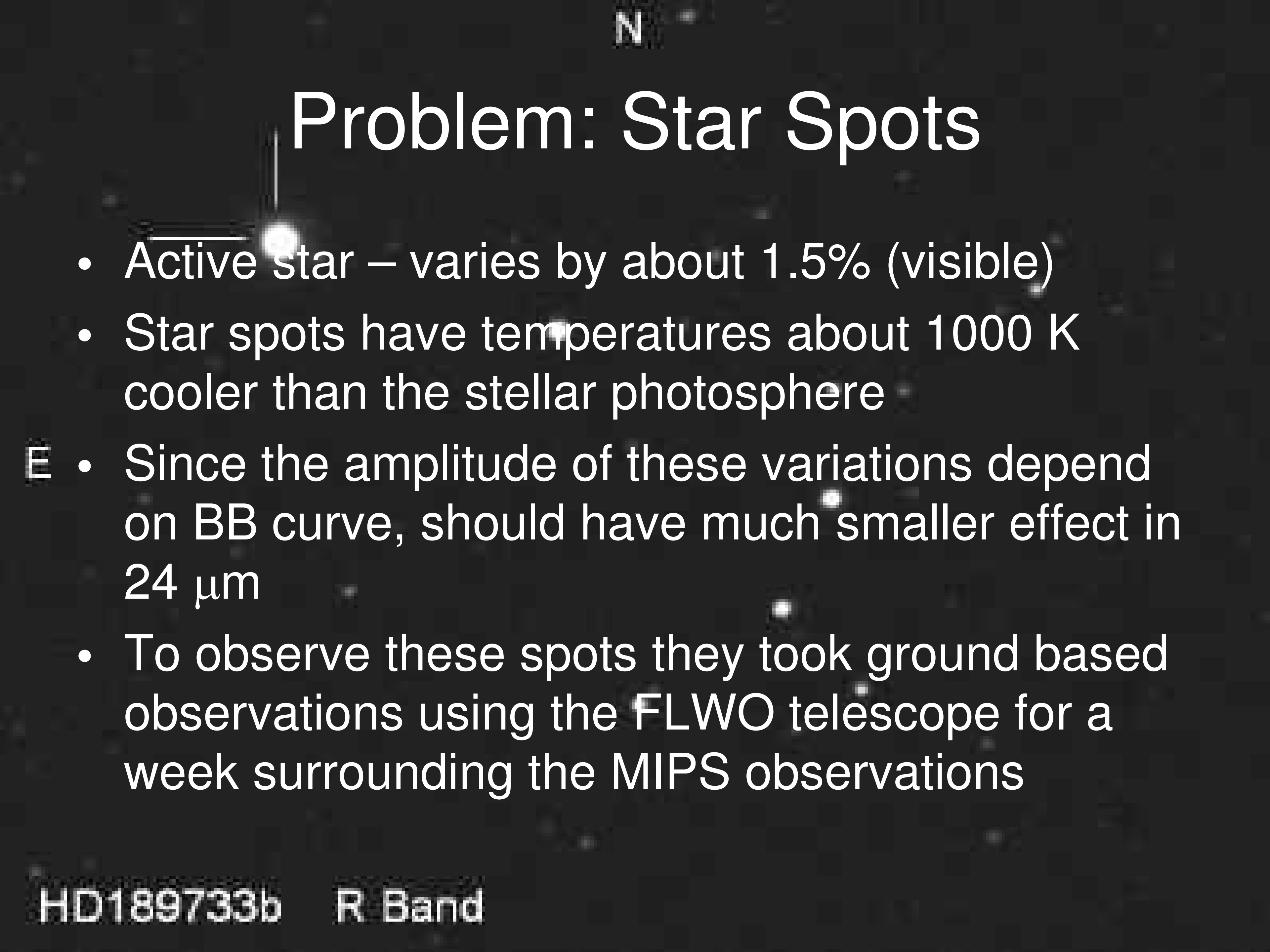
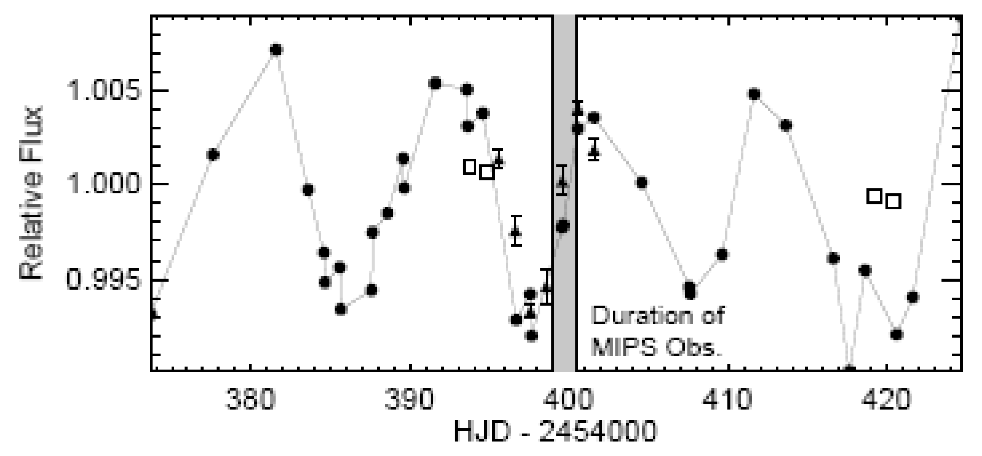
Problem: Star Spots



- Active star – varies by about 1.5% (visible)
- Star spots have temperatures about 1000 K cooler than the stellar photosphere
- Since the amplitude of these variations depend on BB curve, should have much smaller effect in 24 μm
- To observe these spots they took ground based observations using the FLWO telescope for a week surrounding the MIPS observations

Star spots

- Star rotates at 11.953 ±0.009 days



- Planetary weather can also effect the fluxes, but since the phase curves for both observations (1 year apart) are similar, this is probably minimal

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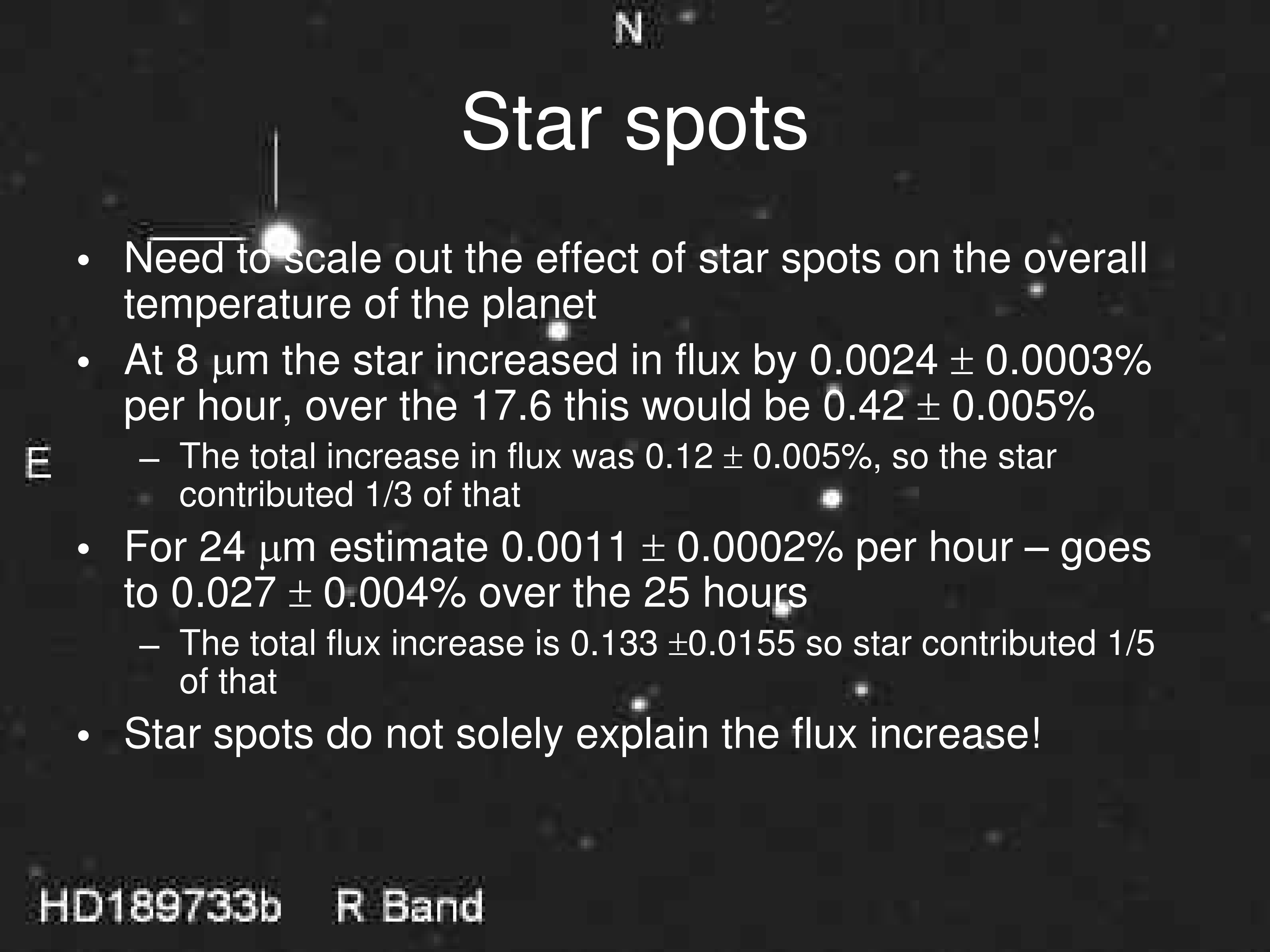
Star spots



- Need to scale out the effect of star spots on the overall temperature of the planet
- At 8 μm the star increased in flux by 0.0024 ± 0.0003% per hour, over the 17.6 this would be 0.42 ± 0.005%
  - The total increase in flux was 0.12 ± 0.005%, so the star contributed 1/3 of that
- For 24 μm estimate 0.0011 ± 0.0002% per hour – goes to 0.027 ± 0.004% over the 25 hours
  - The total flux increase is 0.133 ±0.0155 so star contributed 1/5 of that
- Star spots do not solely explain the flux increase!

Phase Curve/Flux max-min

- Using 4 slice model:
  - Phase curve max: 0.00010
  - Phase curve min: 0.00038

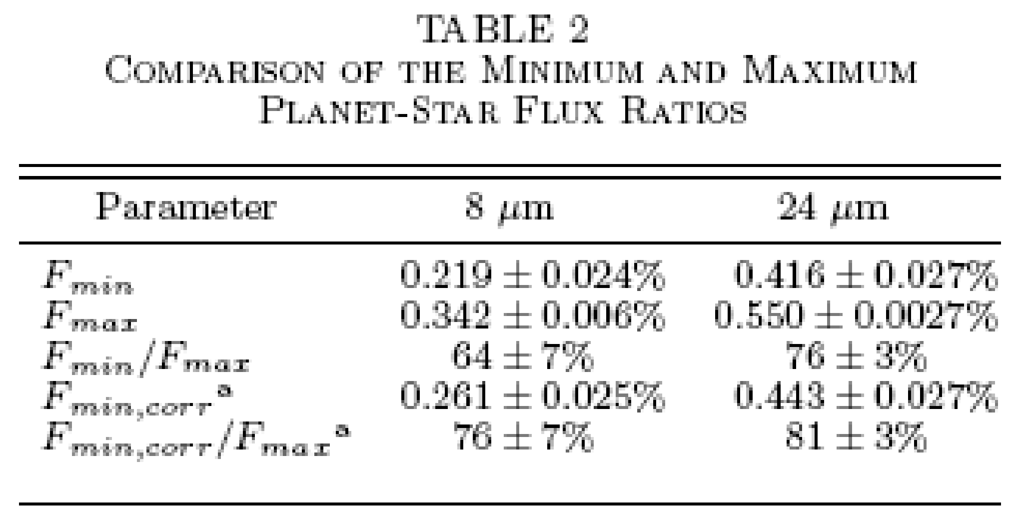


TABLE 2
COMPARISON OF THE MINIMUM AND MAXIMUM PLANET-STAR FLUX RATIOS

Parameter	8 μm	24 μm
F_{min}	$0.219 \pm 0.024\%$	$0.416 \pm 0.027\%$
F_{max}	$0.342 \pm 0.006\%$	$0.550 \pm 0.0027\%$
F_{min}/F_{max}	$64 \pm 7\%$	$76 \pm 3\%$
$F_{min,corr}$[a]	$0.261 \pm 0.025\%$	$0.443 \pm 0.027\%$
$F_{min,corr}/F_{max}$[a]	$76 \pm 7\%$	$81 \pm 3\%$

- Since maximum flux is measure by depth of secondary eclipse (short time scale) it is mostly uneffected by star spots
- Minimum flux is measure over longer times so is readjusted for star spots

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Temperature min-max

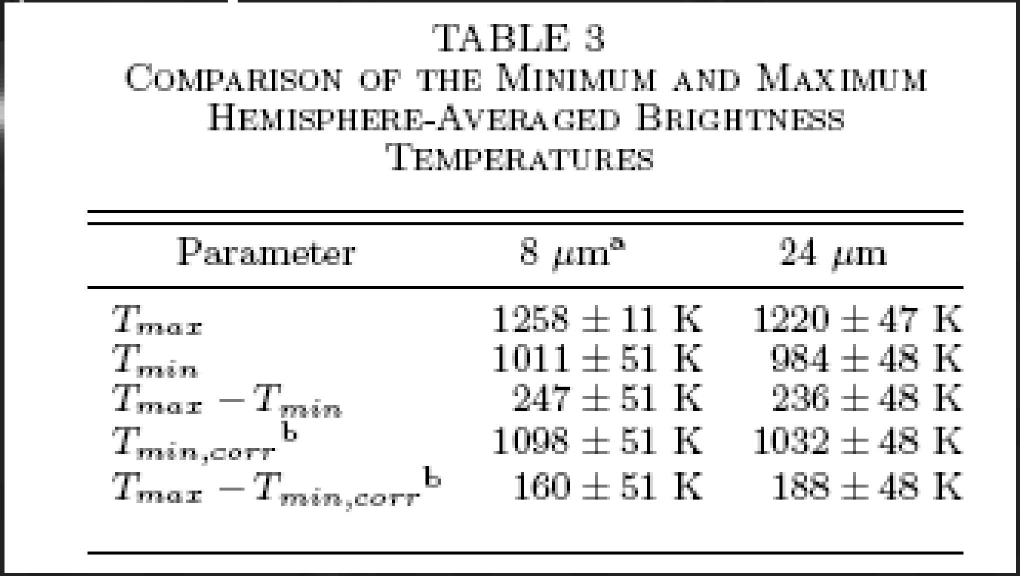

TABLE 3
COMPARISON OF THE MINIMUM AND MAXIMUM HEMISPHERE-AVERAGED BRIGHTNESS TEMPERATURES

Parameter	8 μm[a]	24 μm
T_{max}	1258 ± 11 K	1220 ± 47 K
T_{min}	1011 ± 51 K	984 ± 48 K
$T_{max} - T_{min}$	247 ± 51 K	236 ± 48 K
$T_{min,corr}$[b]	1098 ± 51 K	1032 ± 48 K
$T_{max} - T_{min,corr}$[b]	160 ± 51 K	188 ± 48 K

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- In radiative equilibrium (without transport between sides) day sides should have temperature > 1300 K and night sides around 200-300 K

- However in this case we do not observe this, but instead of a 1000 K difference, a mere ~250 K difference! For BOTH wavelengths

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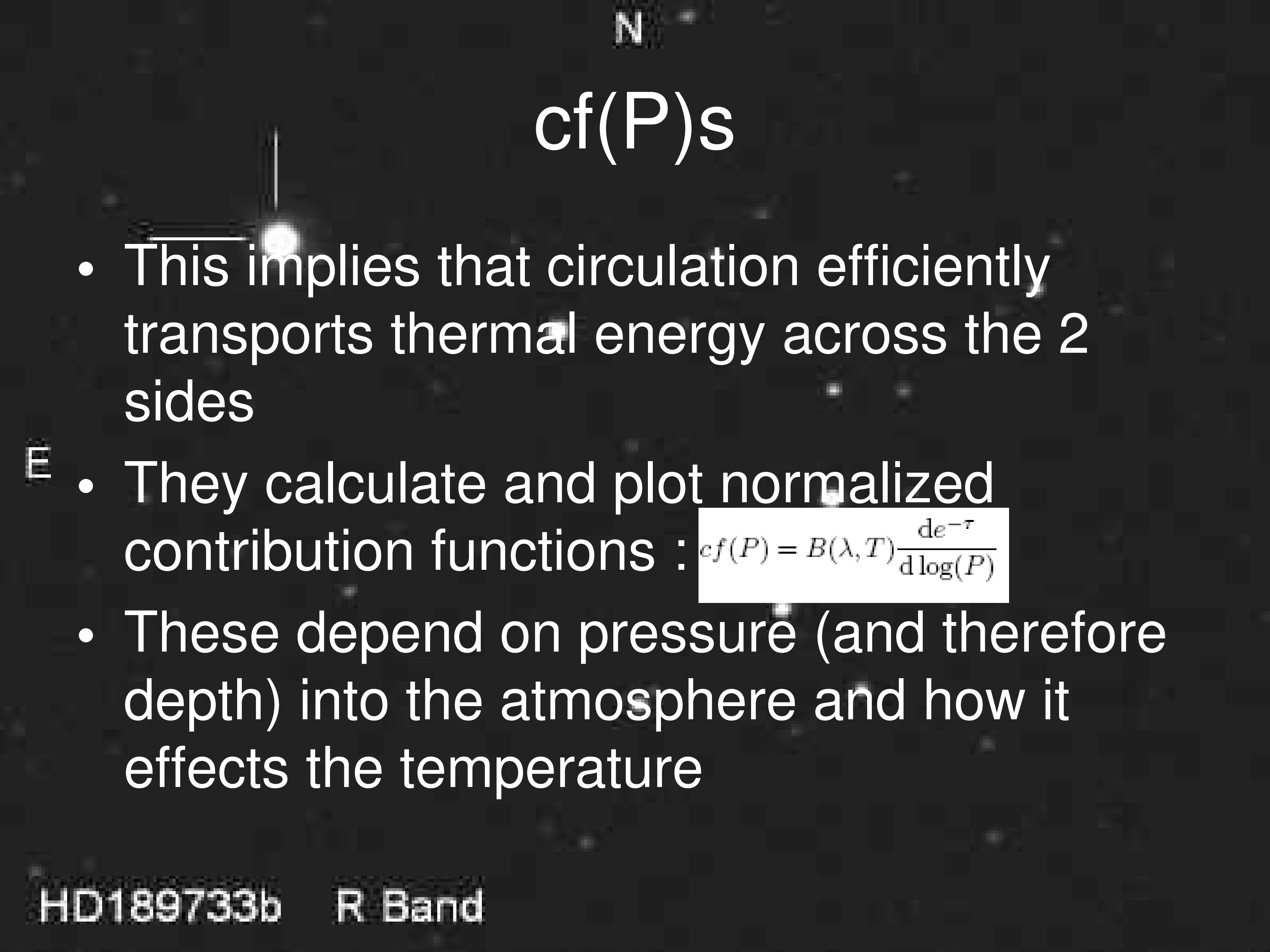
cf(P)s



- This implies that circulation efficiently transports thermal energy across the 2 sides
- They calculate and plot normalized contribution functions : $cf(P) = B(\lambda, T)\frac{\mathrm{d}e^{-\tau}}{\mathrm{d}\log(P)}$
- These depend on pressure (and therefore depth) into the atmosphere and how it effects the temperature

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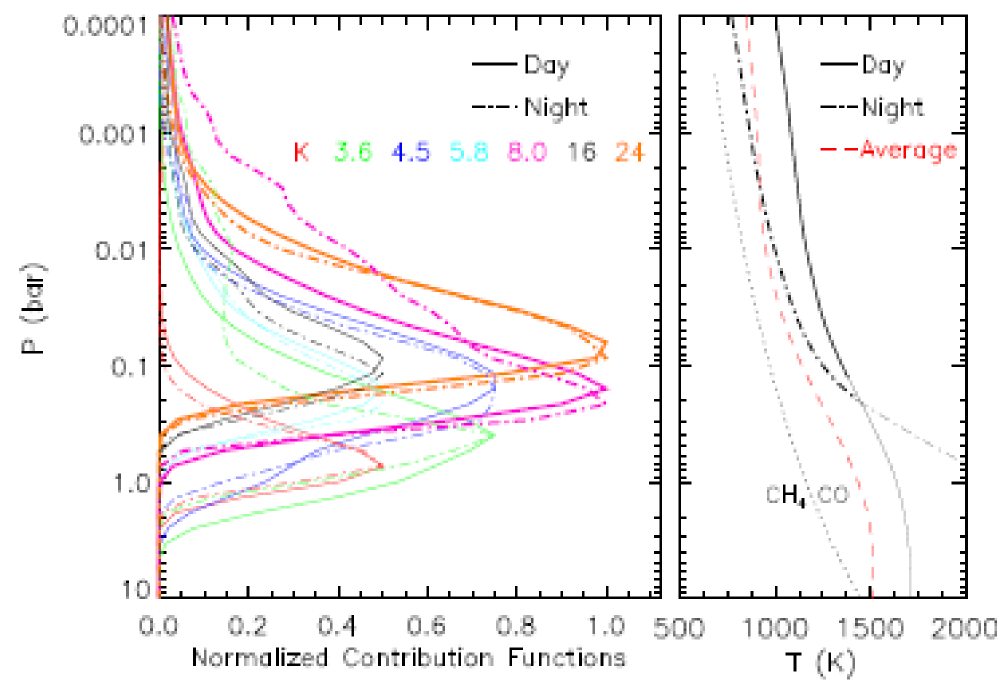
cfs and CO/CH_4

- The 24 μm peaks at lower pressures because of more water absorption at this longer wavelength
- Also you can see that CO dominates over CH_4 but both are important and can be seen in model spectra



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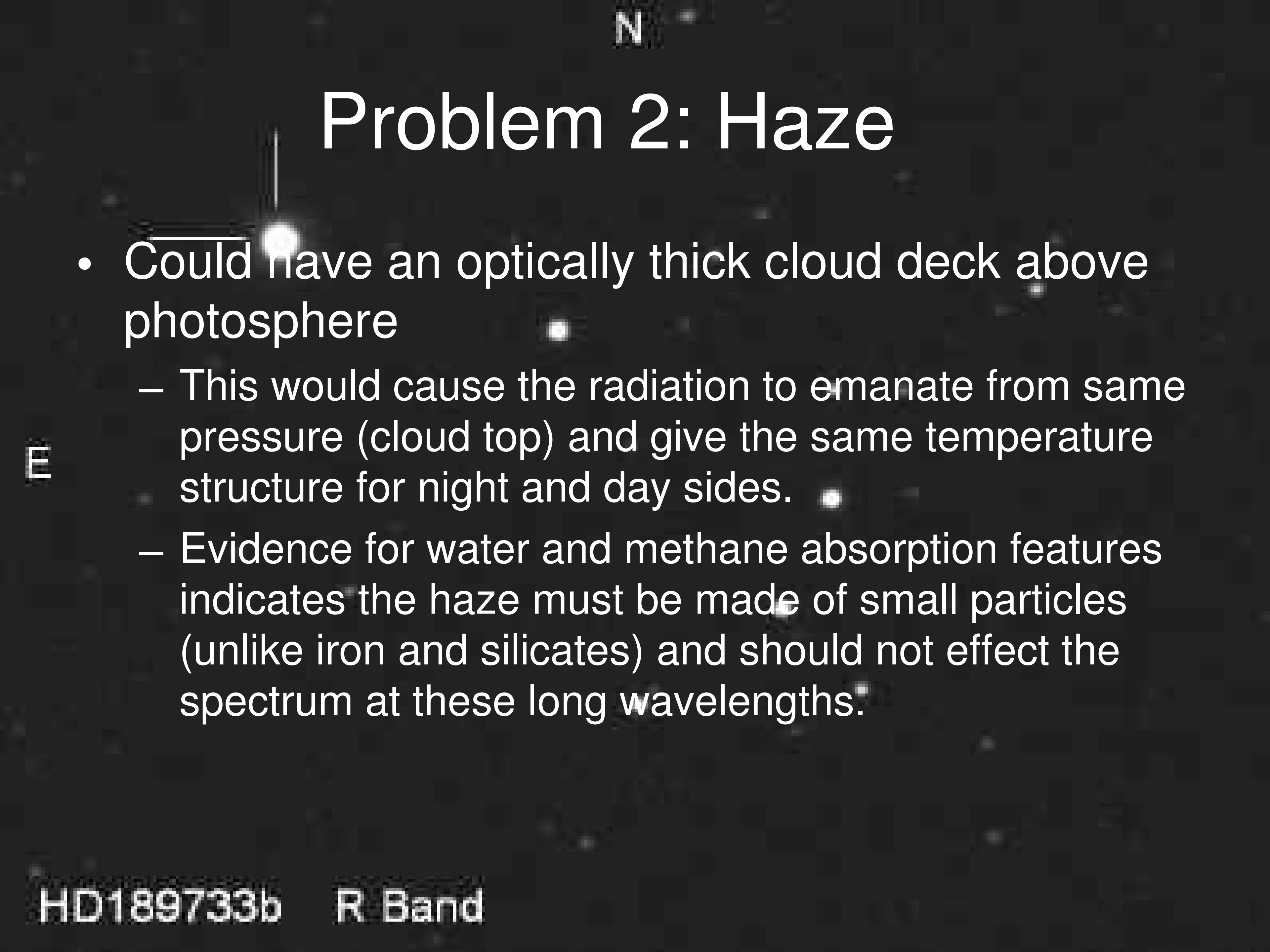
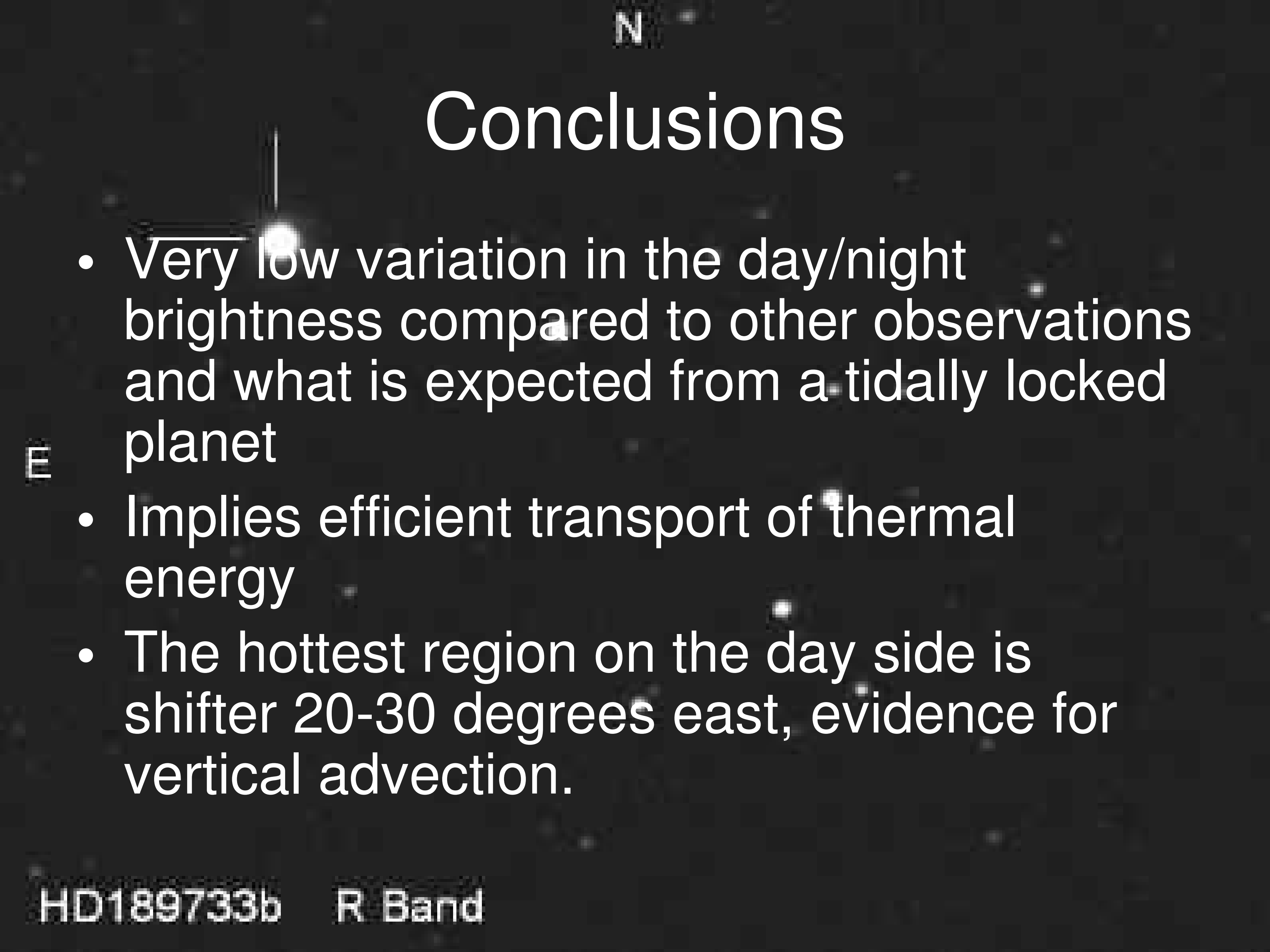
Problem 2: Haze



- Could have an optically thick cloud deck above photosphere
  - This would cause the radiation to emanate from same pressure (cloud top) and give the same temperature structure for night and day sides.
  - Evidence for water and methane absorption features indicates the haze must be made of small particles (unlike iron and silicates) and should not effect the spectrum at these long wavelengths.

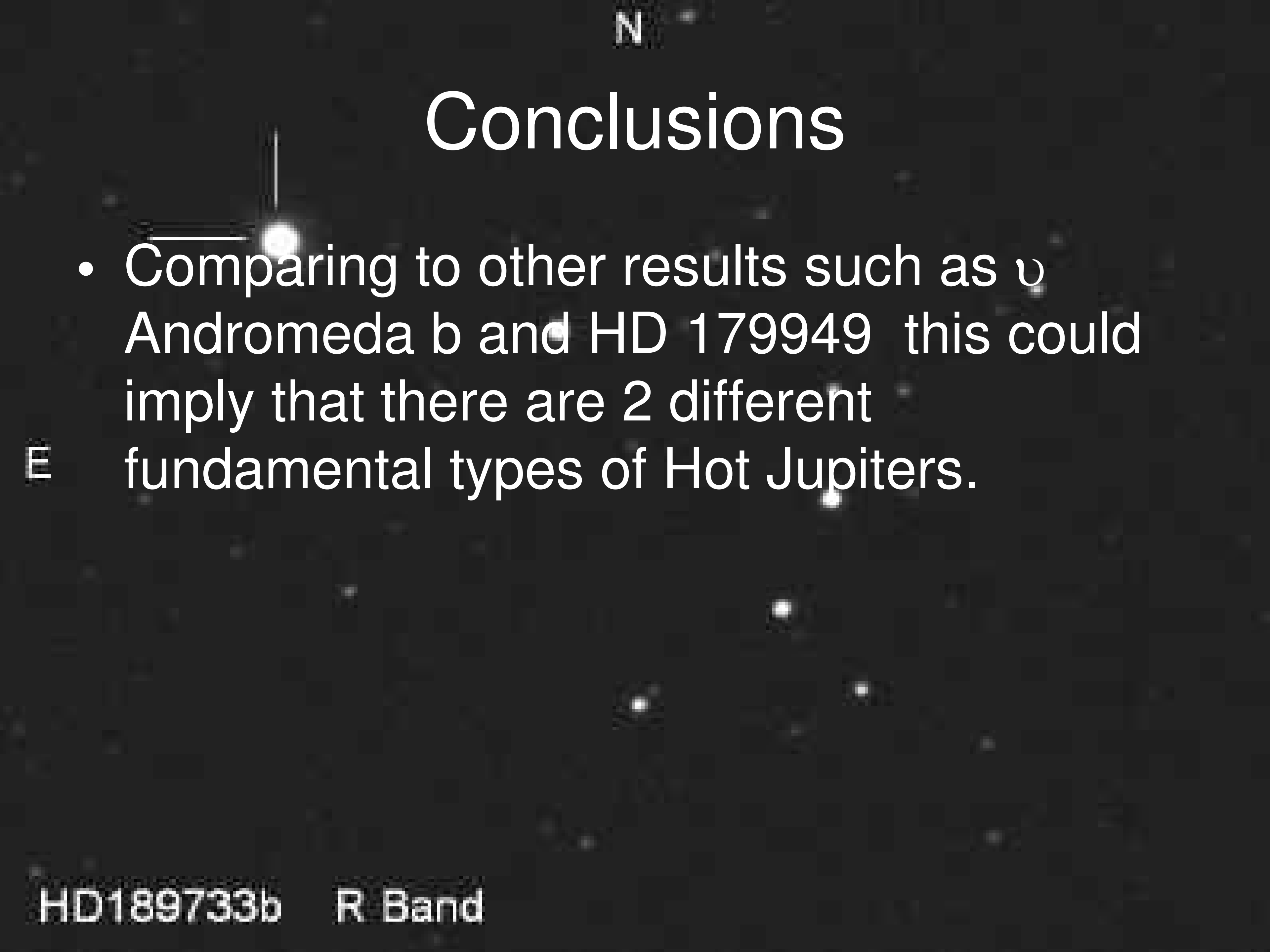
Conclusions

- Very low variation in the day/night brightness compared to other observations and what is expected from a tidally locked planet
- Implies efficient transport of thermal energy
- The hottest region on the day side is shifter 20-30 degrees east, evidence for vertical advection.

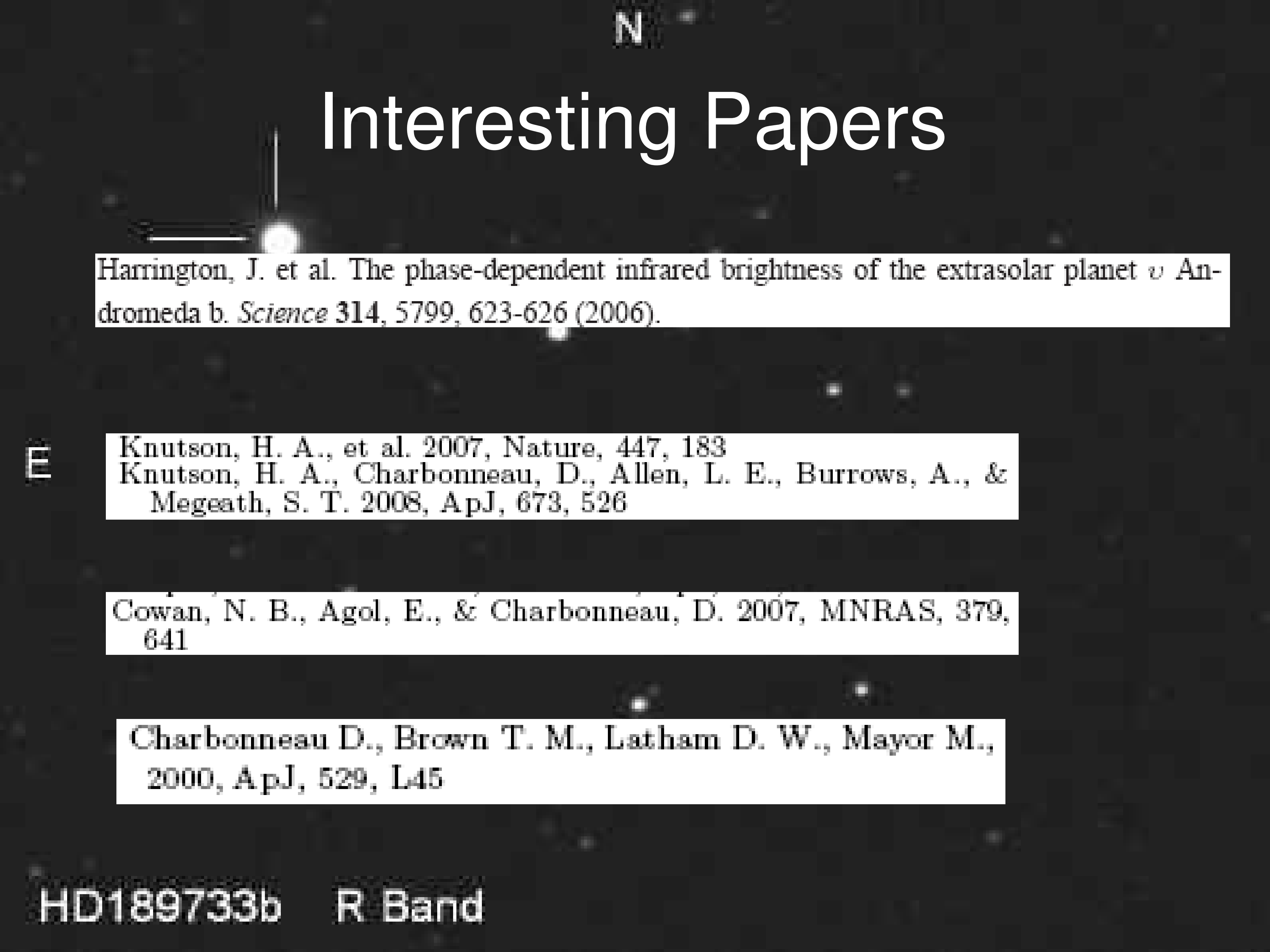


Conclusions

- Comparing to other results such as υ Andromeda b and HD 179949 this could imply that there are 2 different fundamental types of Hot Jupiters.



Interesting Papers



Harrington, J. et al. The phase-dependent infrared brightness of the extrasolar planet υ Andromeda b. *Science* **314**, 5799, 623-626 (2006).

Knutson, H. A., et al. 2007, Nature, 447, 183

Knutson, H. A., Charbonneau, D., Allen, L. E., Burrows, A., & Megeath, S. T. 2008, ApJ, 673, 526

Cowan, N. B., Agol, E., & Charbonneau, D. 2007, MNRAS, 379, 641

Charbonneau D., Brown T. M., Latham D. W., Mayor M., 2000, ApJ, 529, L45