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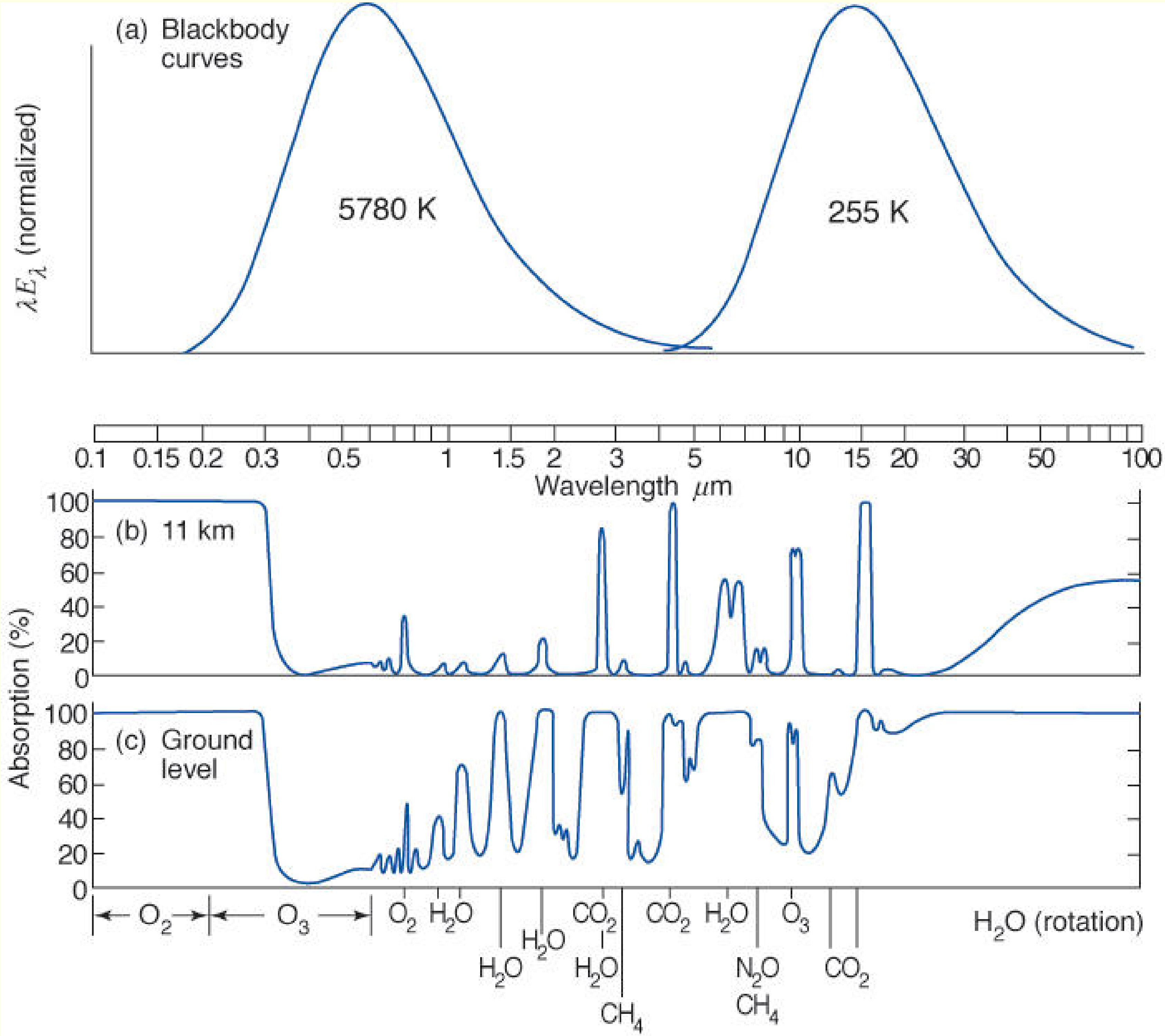
The distinction is quite striking, as shown in the following figure.



(a) Blackbody curves
λE_λ (normalized)
5780 K
255 K
0.1 0.15 0.2 0.3 0.5 1 1.5 2 3 5 10 15 20 30 50 100
Wavelength μm
(b) 11 km
Absorption (%)
100 80 60 40 20 0
(c) Ground level
O₂ O₃ O₂ H₂O H₂O H₂O CO₂ H₂O CH₄ CO₂ H₂O N₂O CH₄ O₃ CO₂ H₂O (rotation)

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Explain why the surface temperature computed above is considerably higher than the effective temperature in the absence of an atmosphere.

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This must equal the upward flux from the surface:

$$F_E = 0.9 \times F_S + F_L$$

The upward and downward fluxes at the top of the atmosphere must also be in balance, which gives us the relation

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To find F_E and F_L, we must solve the system of simultaneous equations

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This gives the values

$$F_E = \frac{1.9}{1.2} \times F_S = 380\,\mathrm{W\,m}^2 \qquad F_L = \frac{0.82}{1.2} \times F_S = 164\,\mathrm{W\,m}^2$$

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$$\sigma T^4_{\mathrm{surface}} = F_E = 380\,\mathrm{W\,m}^2$$

Therefore, since $\sigma = 5.67 \times 10^{-8}$ $\mathbf{W\,m^{-2}K^{-4}}$, we have

$$T_{\mathrm{surface}} = \sqrt[4]{\frac{380}{5.67 \times 10^{-8}}} = 286\,\mathrm{K} = +13^\circ\mathrm{C}$$

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Note that the surface temperature in this case is some 31°C higher than in the case of exercise 4.6 when there was no atmosphere:

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No atmosphere:

$$T_{\text{surface}} = -18^\circ\text{C}$$

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Show how the surface temperature of the planet is affected by the presence of this atmosphere and describe the radiative equilibrium temperature profile in the atmosphere of the planet.

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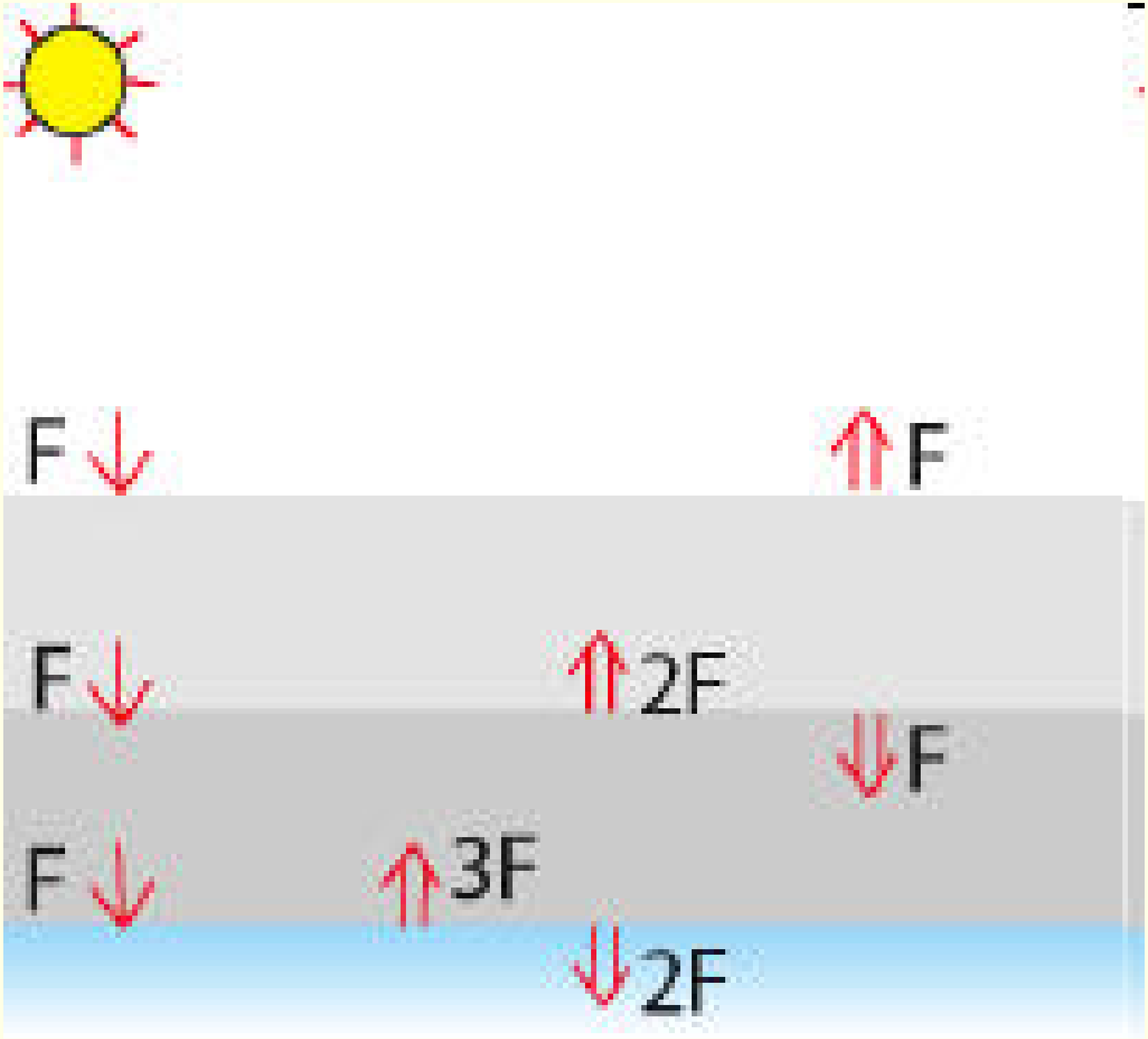
To balance the incident radiation, the lower layer must emit $2F$ units of longwave radiation. Since the layer is isothermal, it also emits $2F$ units of radiation in the downward radiation.

Hence, the downward radiation at the surface of the planet is F units of incident solar radiation plus $2F$ units of longwave radiation emitted from the atmosphere, a total of $3F$ units, which must be balanced by an upward emission of $3F$ units of longwave radiation from the surface.



Radiation balance for a planetary atmosphere that is transparent to solar radiation and consists of two isothermal layers that are opaque to planetary radiation.

By induction, the above reasoning can be extended to an N-layer atmosphere.

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The emissions from the atmospheric layers, working downward from the top, are F; $2F$; $3F$:::NF and the corresponding radiative equilibrium temperatures are 255, 303, 335.... $(F/N\sigma)^{1/4}$K.

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In effect, radiative transfer becomes less and less efficient at removing the energy absorbed at the surface of the planet due to the increasing blocking effect of the greenhouse gases.

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The bottom panel of Fig. 4.5 shows that the wavelength dependence is quite pronounced, with well defined *absorption bands* identified with specific gaseous constituents, interspersed with *windows* in which the atmosphere is relatively transparent.

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- **The water evaporated from the ocean is carried upward by convection.**
- **The moisture reaches levels above the main infra-red absorbers.**
- **The latent heat is then released by condensation, from where much of it radiates to space.**

End of §4.3