Non-LTE modeling of supernova-fallback disks

K. Werner

T. Nagel

T. Rauch

Institute for Astronomy and Astrophysics

University of Tübingen, Germany

Introduction

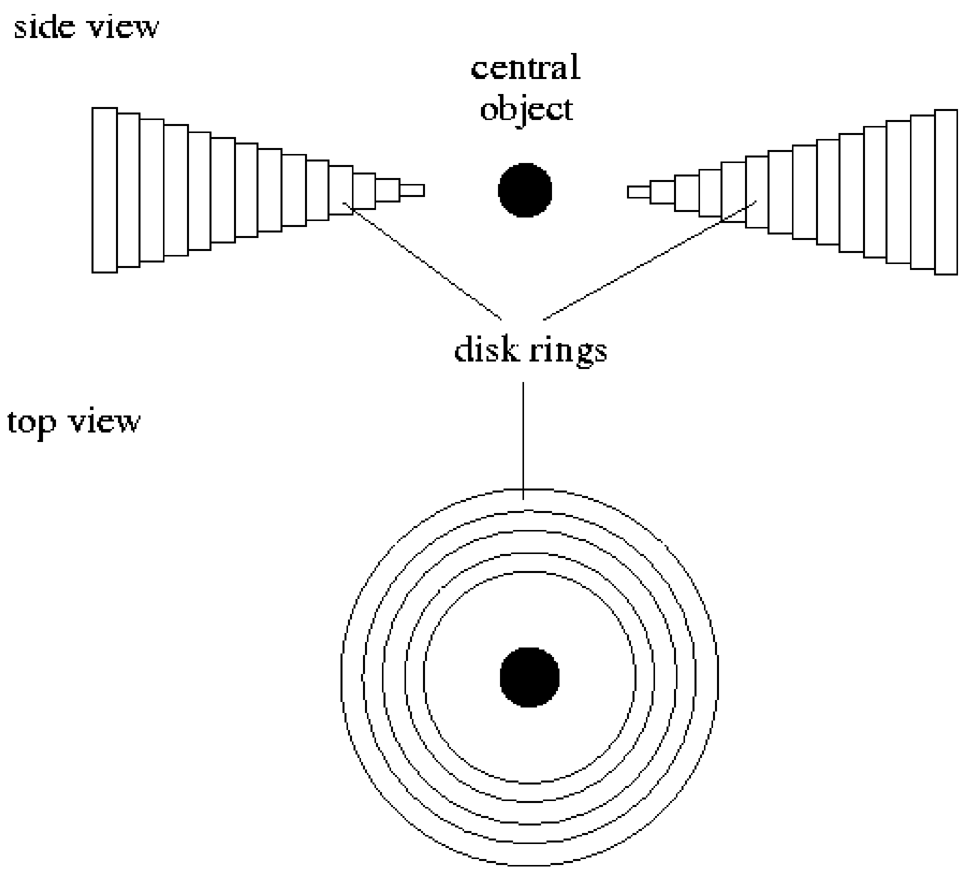
- Anomalous X-ray pulsars (AXPs) are slowly rotating (5-12 sec) young (< 100 000 yr) isolated neutron stars
- X-ray luminosities ($\sim 10^{36}$ erg/s) greatly exceed rates of rotational kinetic energy loss ($\sim 10^{33}$ erg/s)
- AXPs are generally believed to be magnetars ($B > 10^{14}$ G), their X-ray luminosity being powered by magnetic energy

- Alternative explanation: X-ray emission attributed to accretion from disk of SN-fallback material (van Paradijs et al. 1995, Chatterjee et al. 2000, Alpar 2001)

- Fallback-disk idea has difficulties explaining some observations (e.g. Hulleman et al. 2004), but strong motivation for further study of disk characteristics, because optical/IR emission might stem from disk.
- Discovery of IR emission from the AXP 4U 0142+61 (Wang, Chakrabarty & Kaplan 2006), attributed to a cool, passive (X-ray irradiated) dust disk, however,
- Ertan et al. (yesterday's talk) show that IR emission stems from an active, dissipating gas disk. Allows, e.g., derivation of NS magnetic field strength from inner disk radius.
- But: disk-emission hitherto modeled exclusively with blackbody-rings. Our aim: Construct more realistic models by detailed radiation transfer calculations.

NLTE disk modeling

- Radial structure: α-disk (Shakura & Sunyaev 1973)
- Divide disk into concentric rings



NLTE disk modeling

- Radial structure: α-disk (Shakura & Sunyaev 1973)
- Divide disk into concentric rings
- Each ring: plane-parallel radiating slab, detailed vertical structure, computed by AcDc (Accretion Disk code):
  - **hydrostatic equilibrium** (gas and radiation pressure)
  - **radiative equilibrium** (full line blanketing, generalized Unsöld-Lucy scheme)
  - **NLTE rate equations** (pre-conditioned $\rightarrow$ linear)

Non-LTE rate equations

For each atomic level ***i*** of each ion, of each chemical element we have:

$$n_i \sum_{j \neq i} P_{ij} - \sum_{j \neq i} n_j P_{ji} = 0$$

In detail:

$$n_i \left[\sum_{j>i} \left(R_{ij} + C_{ij} \right) + \sum_{j<i} \left(\frac{n_j}{n_i} \right)^* \left(R_{ij} + C_{ji} \right) \right]$$

excitation and ionization

rates out of ***i***

de-excitation and recombination

$$- \sum_{j>i} n_j \left(\frac{n_i}{n_j} \right)^* \left(R_{ji} + C_{ij} \right)$$

de-excitation and recombination

rates into ***i***

$$- \sum_{j<i} n_j \left(R_{ji} + C_{ji} \right)$$

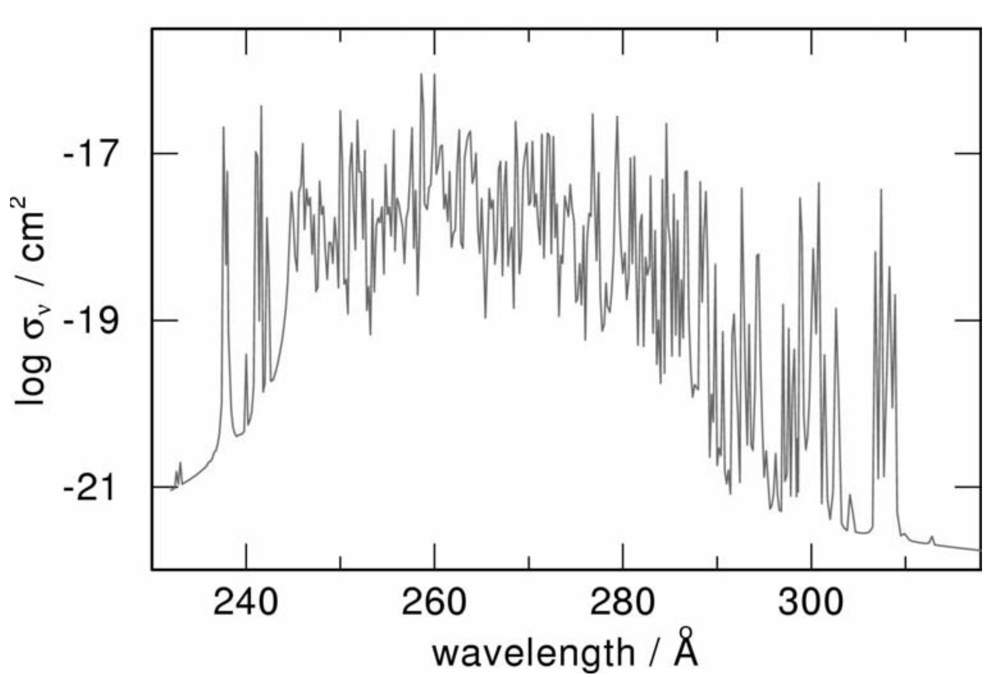
excitation and ionization

$$= 0$$

Non-LTE model atom for iron

- Ionisation stages Fe I – XI
- Number of line transitions: 3 001 235 (from Kurucz)
- Combined into „superlines“ between „superlevels“
- Opacity sampling with 30 700 frequency points

photon cross-section Fe IV superline 1 → 7



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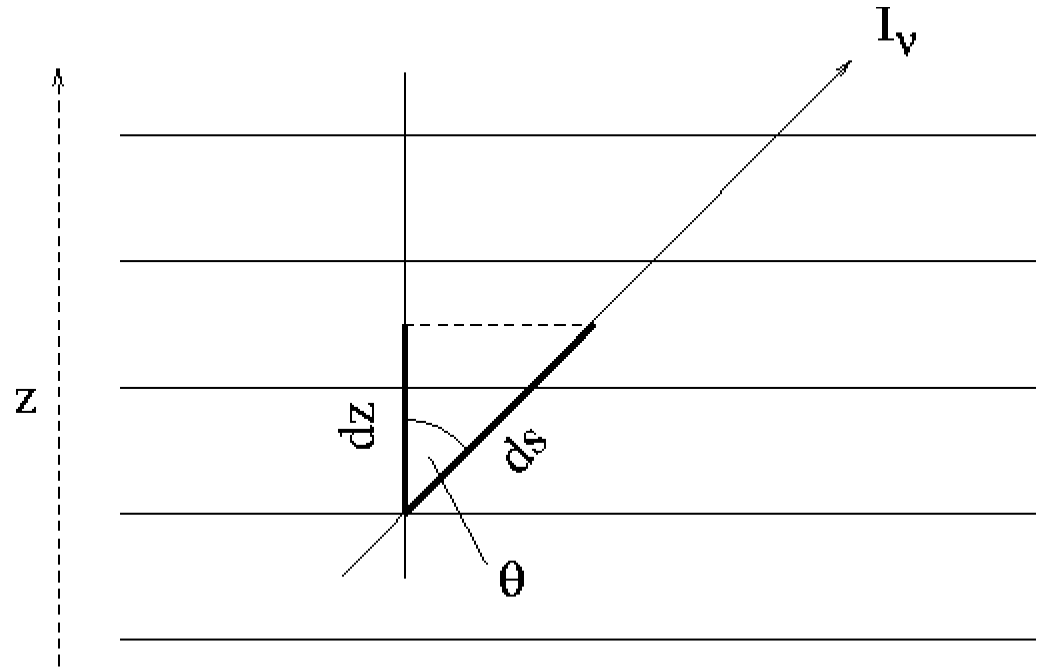
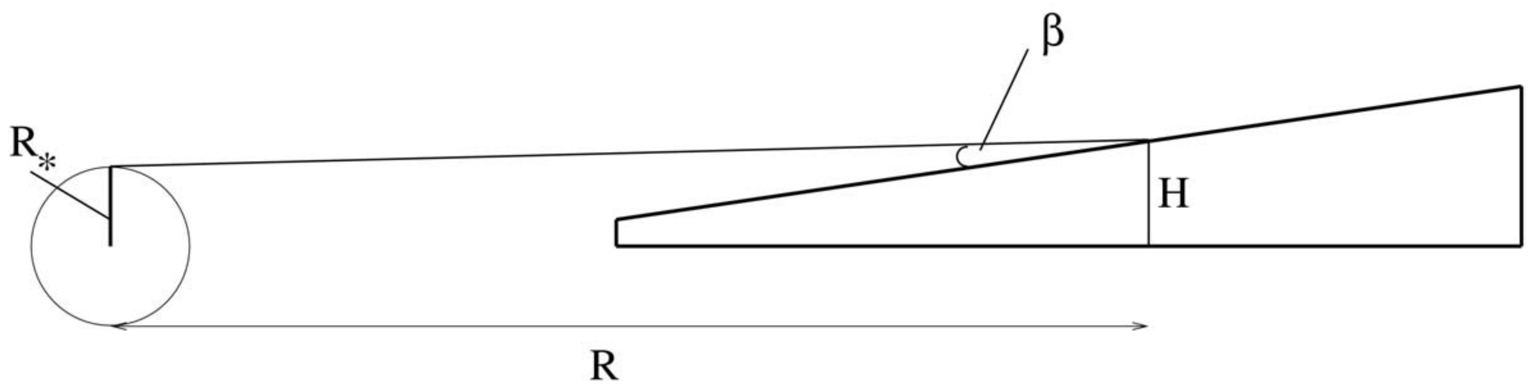
  - **radiation transfer eqs.** (short characteristics, allowing for irradiation)



$$\mu = \cos\theta$$

$$dz = \mu \, ds$$

$$\mu \frac{\partial I_\nu(\nu,\mu,z)}{\partial z} = -\chi_\nu(\nu,z)\, I_\nu(\nu,\mu,z) + \eta_\nu(\nu,z)$$



NLTE disk modeling

- Computational method: **A**ccelerated **L**ambda **I**teration (ALI) for simultaneous solution of all equations
  - **kinematic viscosity** parameterized by Reynolds number (Re=15 000 $\rightarrow$ α≈0.01)
  - **vertical run of viscosity** according to Hubeny & Hubeny (1997)

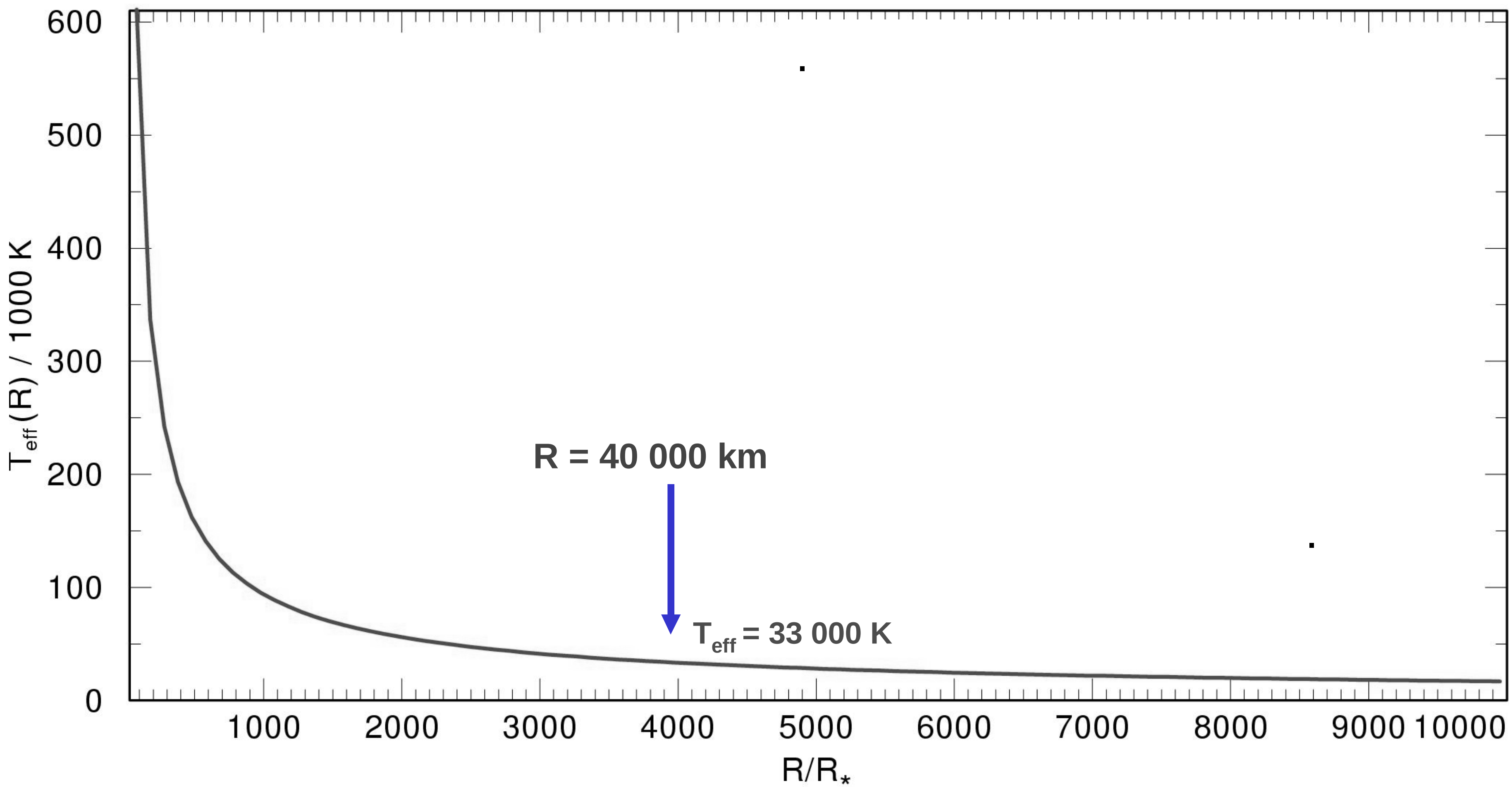
- Input parameters for disk model
  - **M_{NS}=1.4 $M_\odot$ (R_{NS}=9.7 km)**
  - **Inner and outer disk radii: 2000 km, 200 000 km (9 rings)**
  - **Accretion rate: $3 \cdot 10^{-9}$ $M_\odot$ /yr**
  - **Chemical composition:**

    a) pure iron

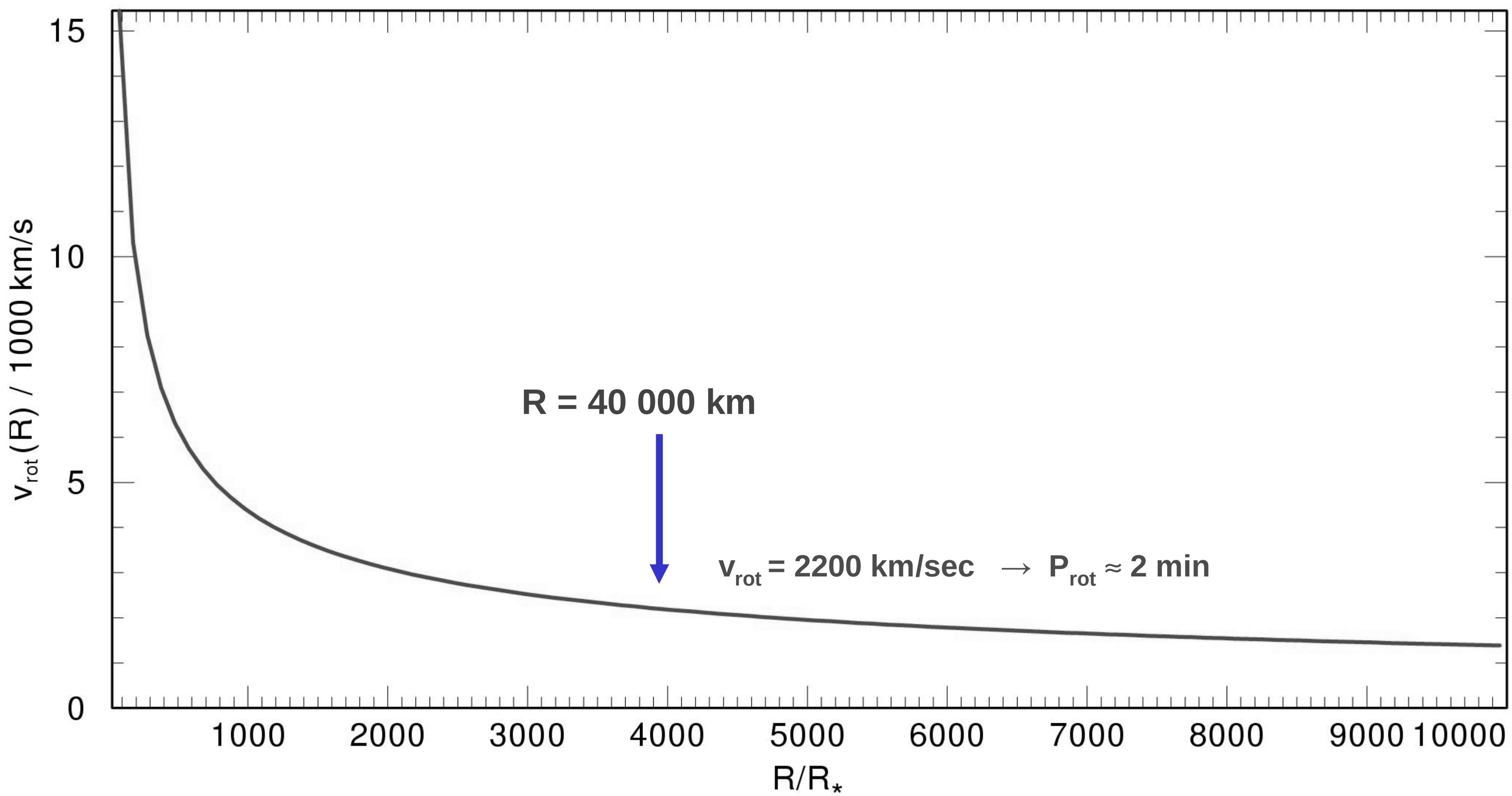
    b) silicon-burning ash: Si=0.1, S=0.1, Fe=0.8 (mass fractions)

- X-ray irradiation: by central source is currently neglected
- Computation of synthetic spectra; aims, among others: Check validity of LTE and blackbody assumptions for disk emission.
- First results: Modeling of UV/optical spectra

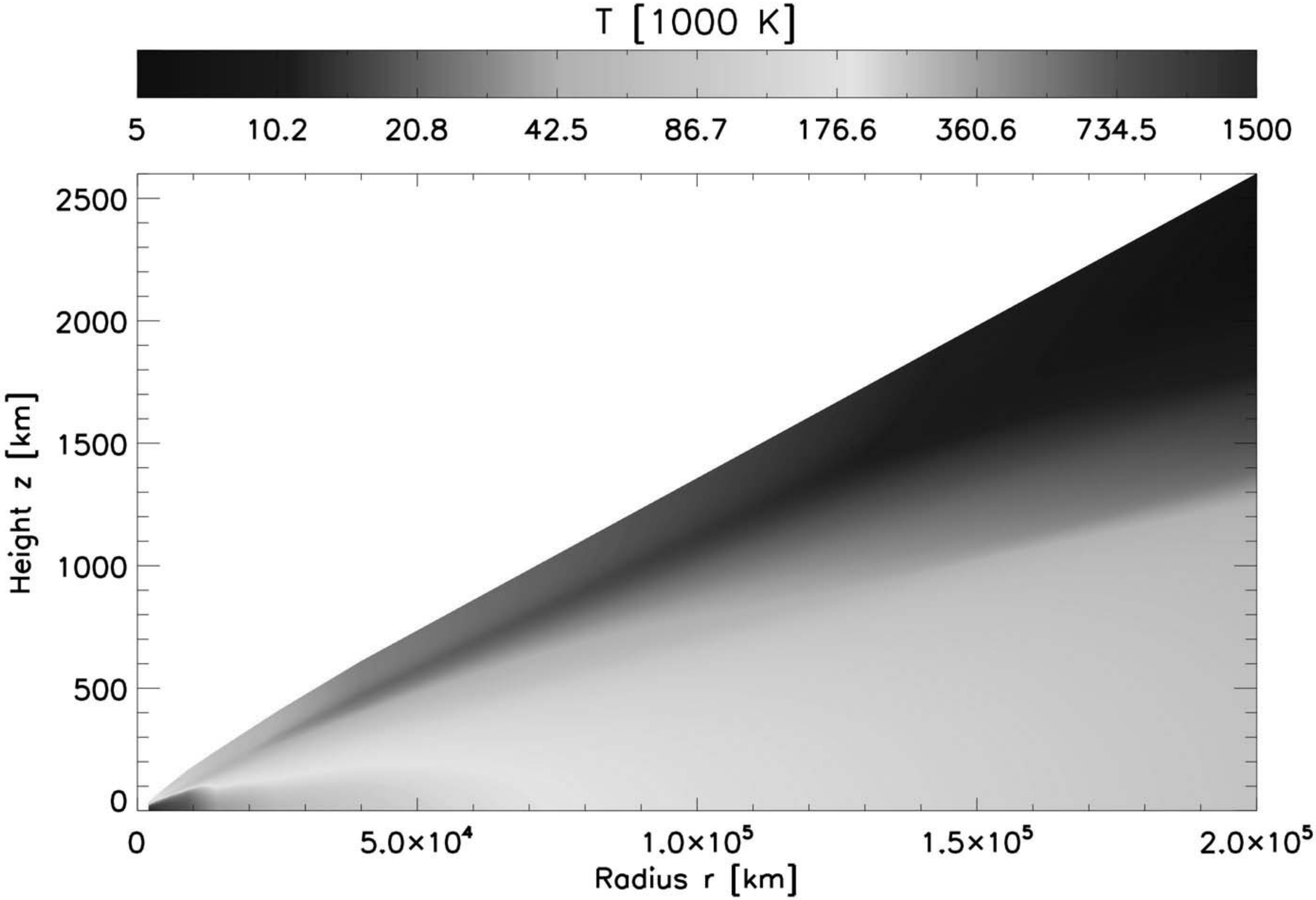
Radial disk structure: effective temperature T_{eff} (R)

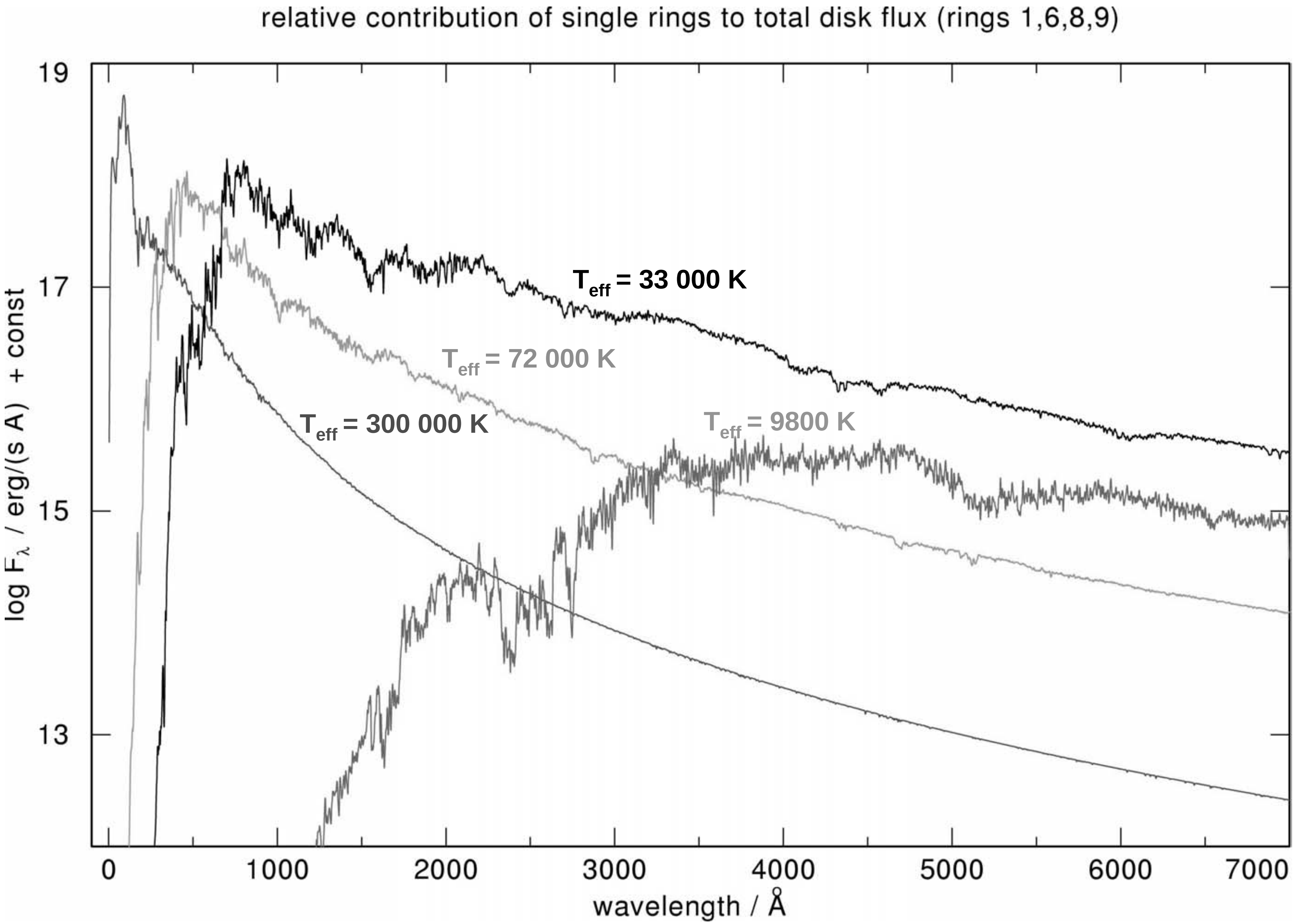


Radial disk structure: Kepler rotation velocity $v_{rot}(R)$



Temperature structure, cut through disk vertical to midplane



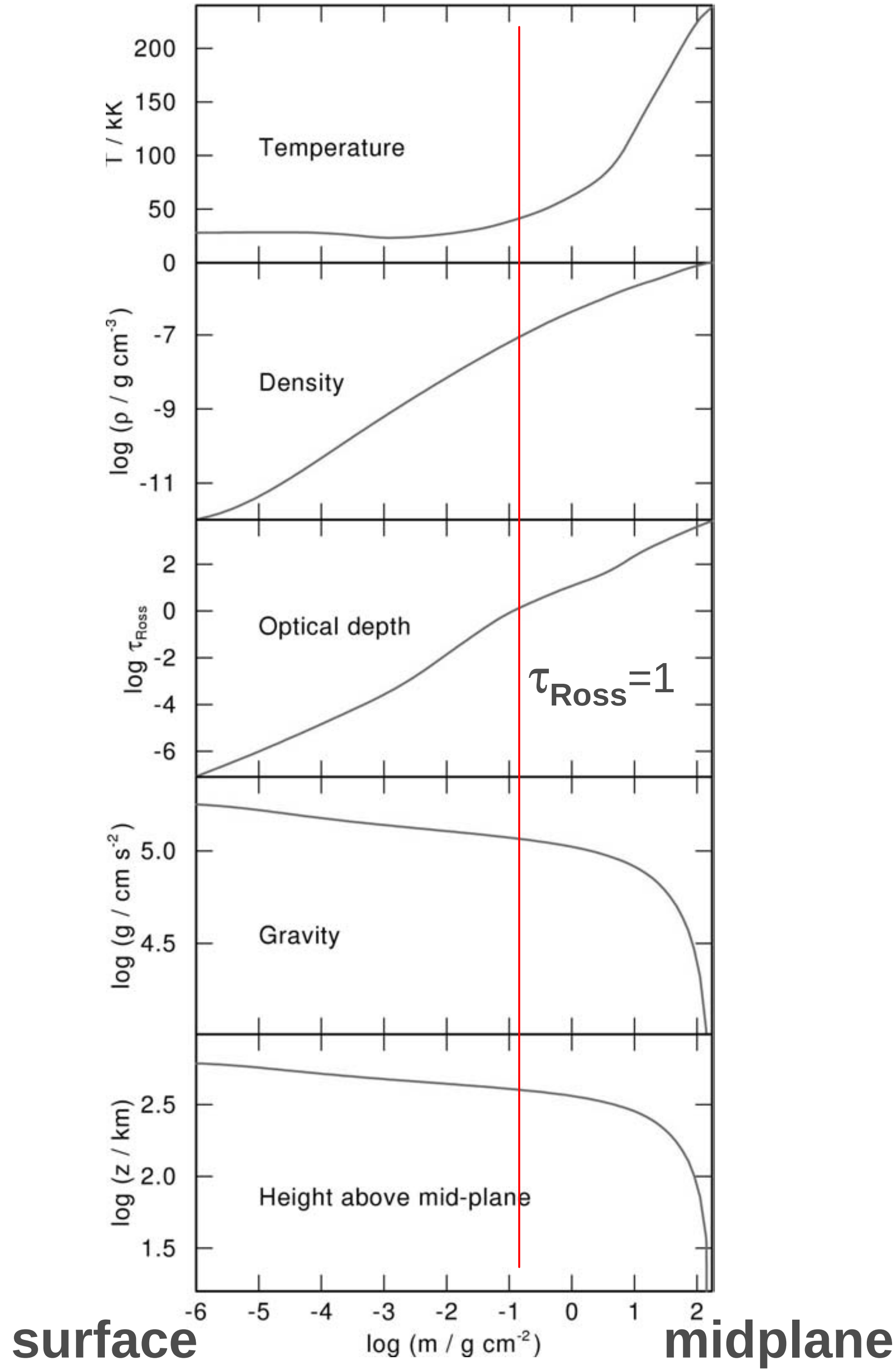


relative contribution of single rings to total disk flux (rings 1,6,8,9)
19
17
15
13
log F_λ / erg/(s A) + const
0
1000
2000
3000
4000
5000
6000
7000
wavelength / Å
T_{eff} = 33 000 K
T_{eff} = 72 000 K
T_{eff} = 300 000 K
T_{eff} = 9800 K

Vertical stratification of disk at R = 40 000 km
(ring 8, T_{eff} = 33 000 K)

τ_{Ross}=1

z = 400 km above midplane
T = 39 000 K
log g = 5.1
log ρ = - 7.1, $n_e = 2.9 \cdot 10^{15}$ (cgs)



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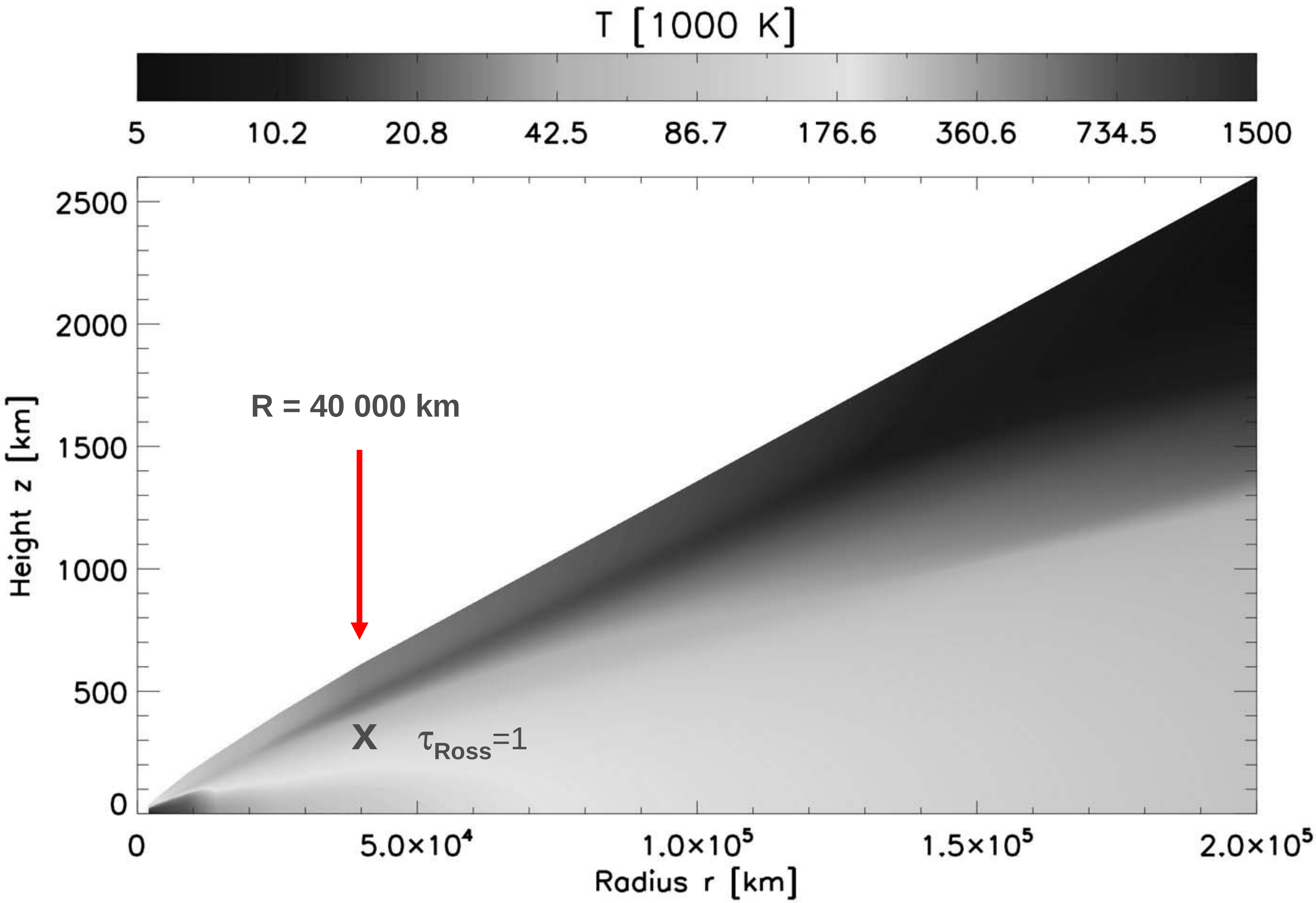
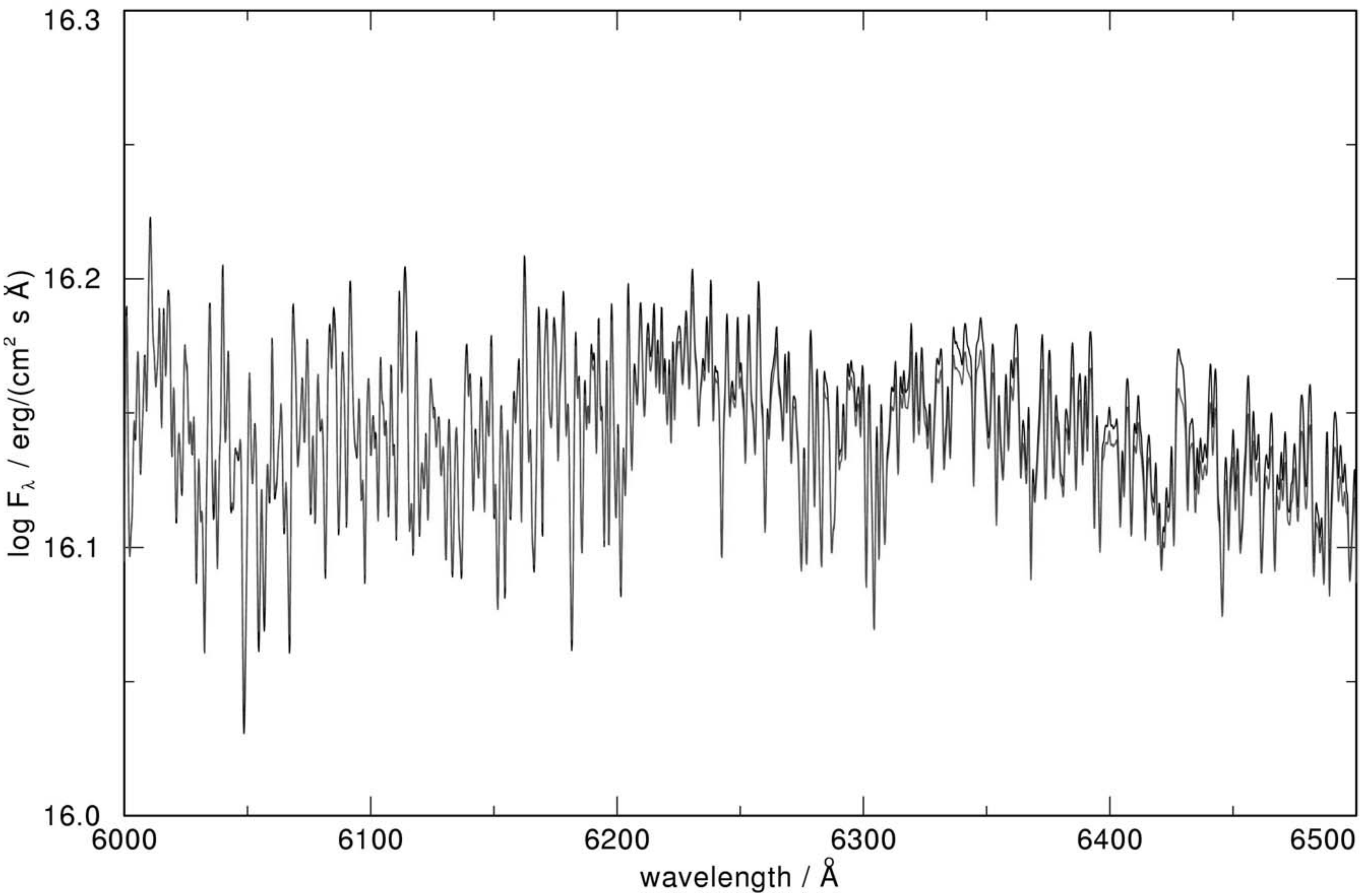
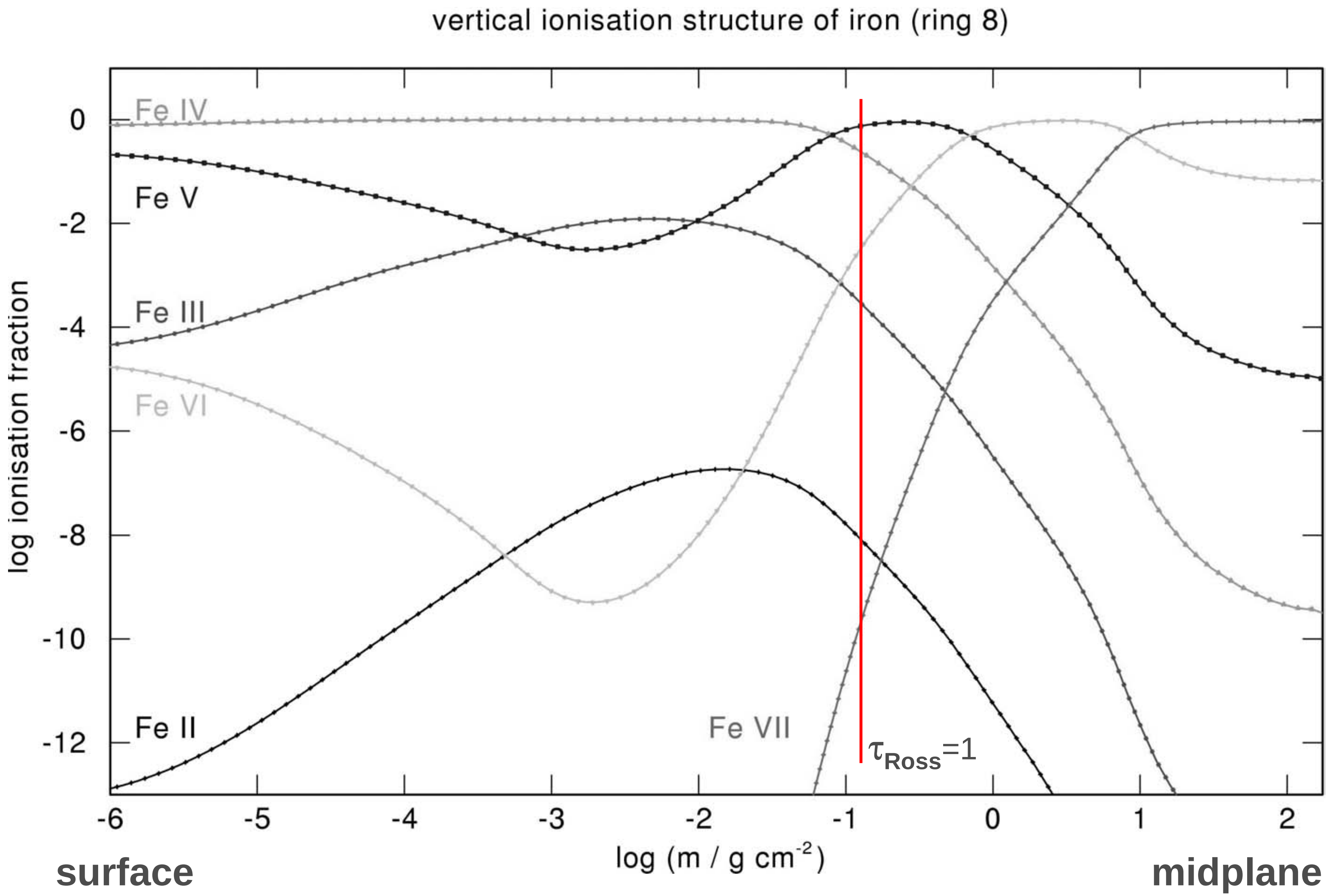


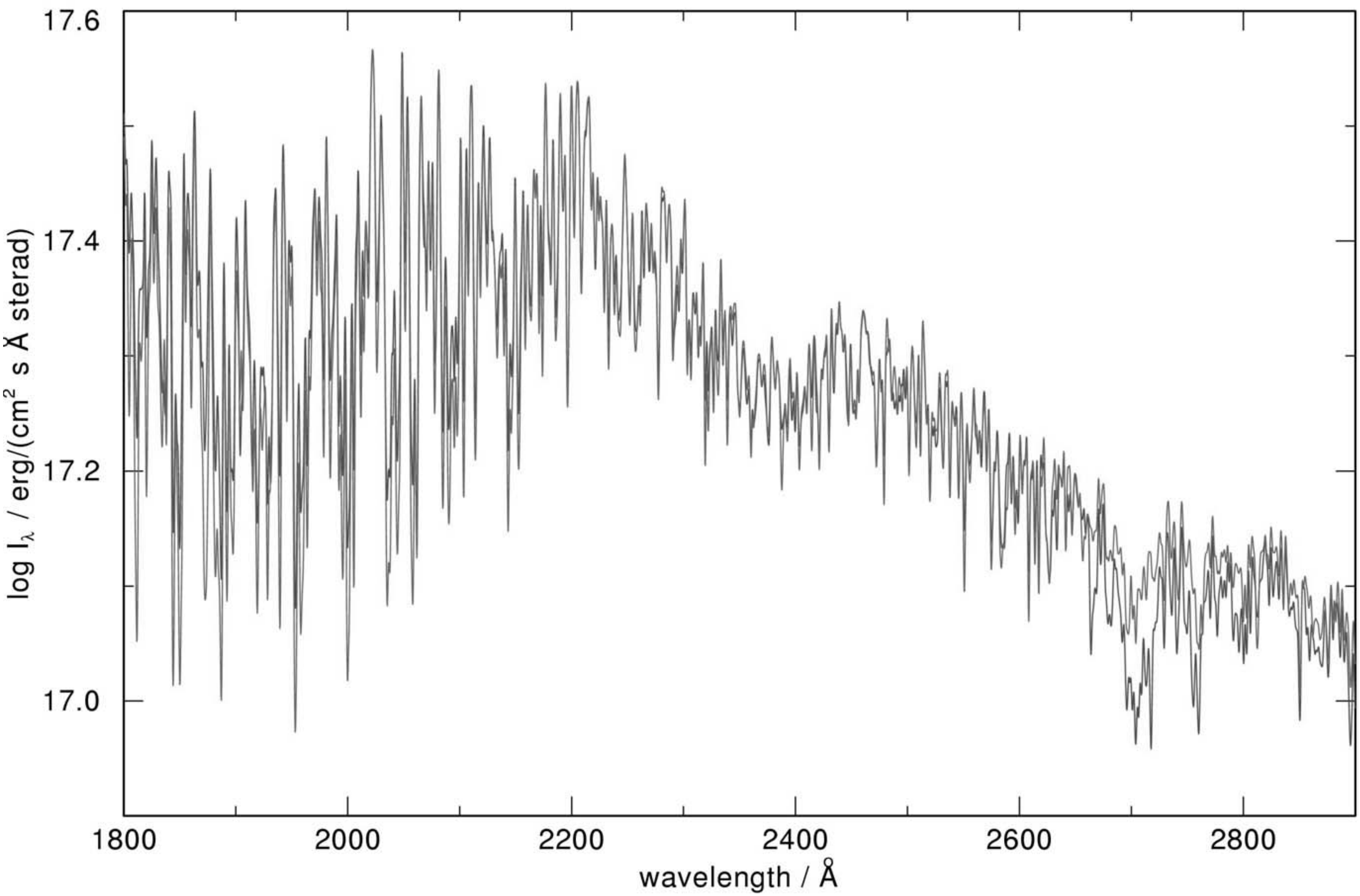
Effect of disk composition: pure Fe vs. Si-burning ash (ring 8)



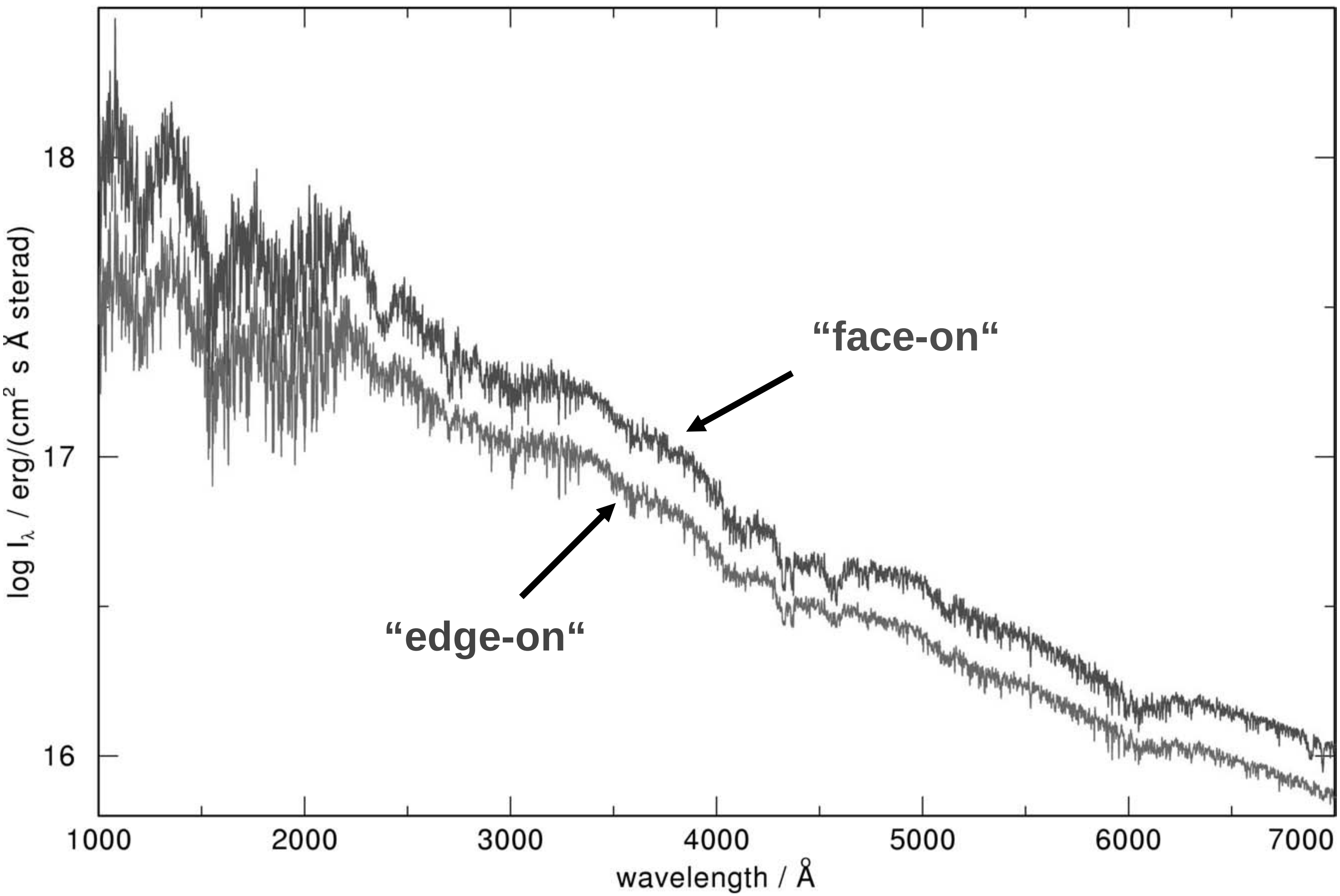


vertical ionisation structure of iron (ring 8)
Fe IV
Fe V
Fe III
Fe VI
Fe II
Fe VII
$\tau_{Ross}=1$
0
-2
-4
-6
-8
-10
-12
log ionisation fraction
-6
-5
-4
-3
-2
-1
0
1
2
log (m / g cm^{-2})
surface
midplane

LTE vs. non-LTE (ring 8, specific intensity at i = 87º)



Limb darkening (ring 8, specific intensity at i = 87º and i = 18º)



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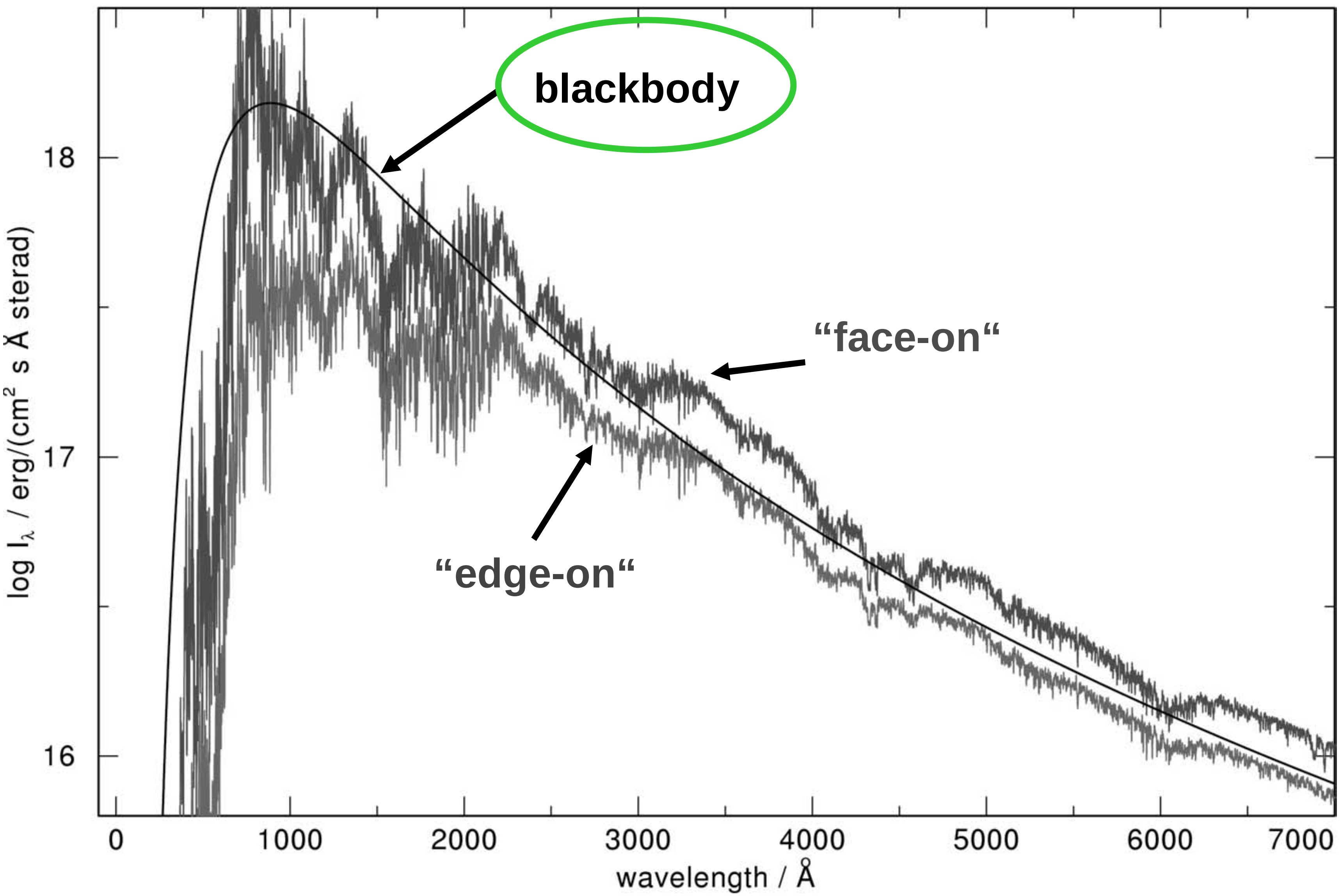
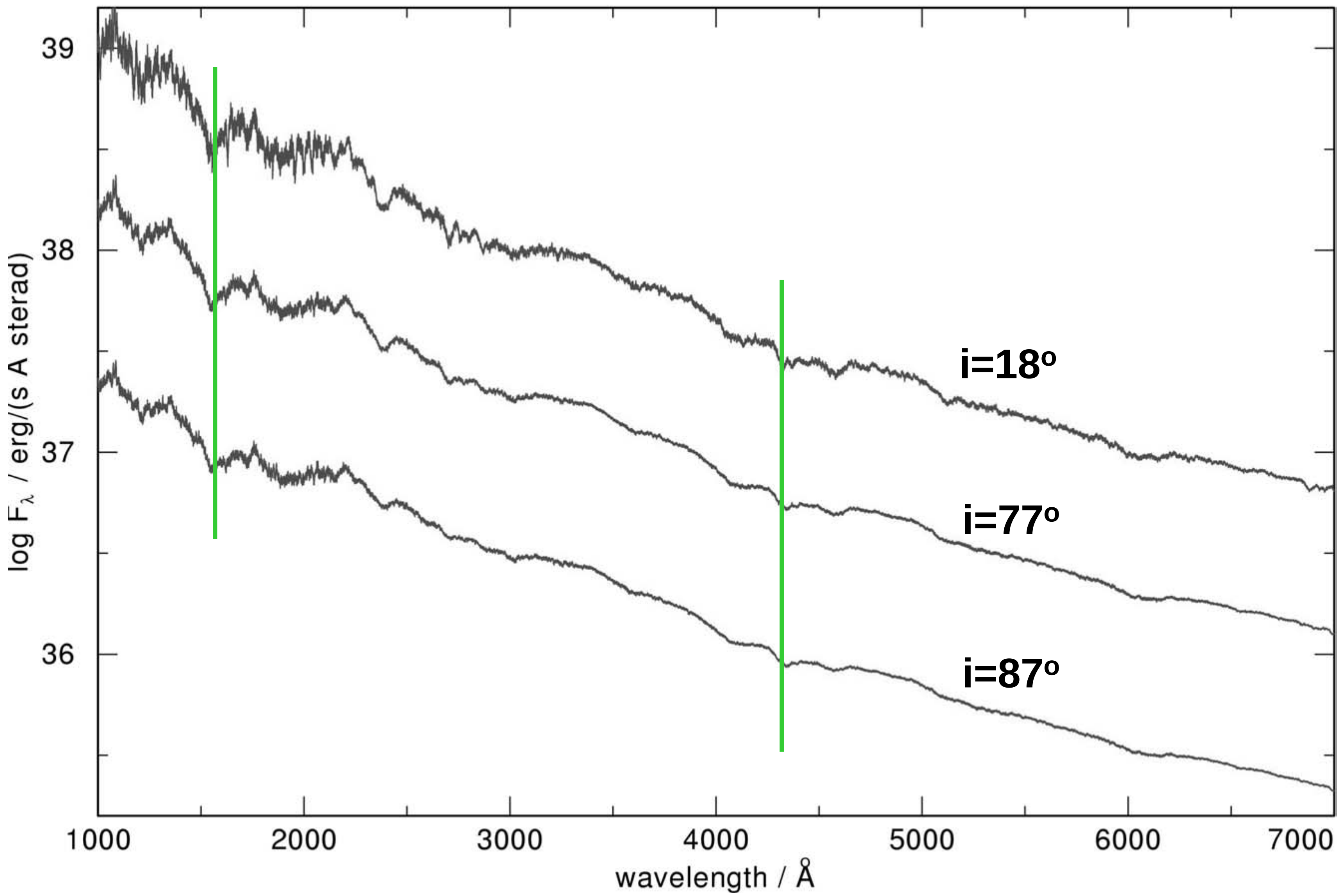


Complete disk spectrum, Kepler rotation included, different inclinations



Summary

- Overall disk spectrum independent of detailed chemical composition as long as iron is the main constituent: no difference between pure Fe and Si-burning ash composition. Fe opacities are dominant.
- Overall disk spectrum not influenced by non-LTE effects. However, equivalent widths of individual line (blends) can change by a factor of ≈2.
- Limb darkening affects the overall disk spectrum. Flux can be reduced by about a factor of ≈2 when disk is seen almost edge-on (in addition to geometry factor).

- Depending on inclination, the disk flux can be a factor of ≈2 greater or less compared to a black-body radiating disk.
- Strong iron line blanketing causes broad (>100 Å) spectral features that could be detectable even from edge-on disks.

Future work

- Systematic parameter study of disk emission (accretion rate, disk extent, …)
- Disk irradiation by thermal X-ray emission from neutron star