Interpreting Spectra of High- and Intermediate-Mass Stars

David G. Whelan
Austin College

Sacramento Mountain Spectroscopy Workshop
22 February, 2019

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"Chp. 2"

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Scope

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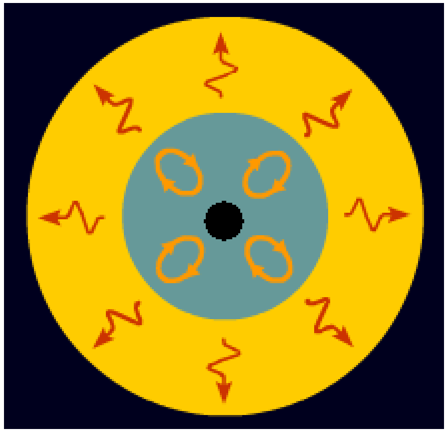
1. Physical Properties of Intermediate- and High-Mass Stars



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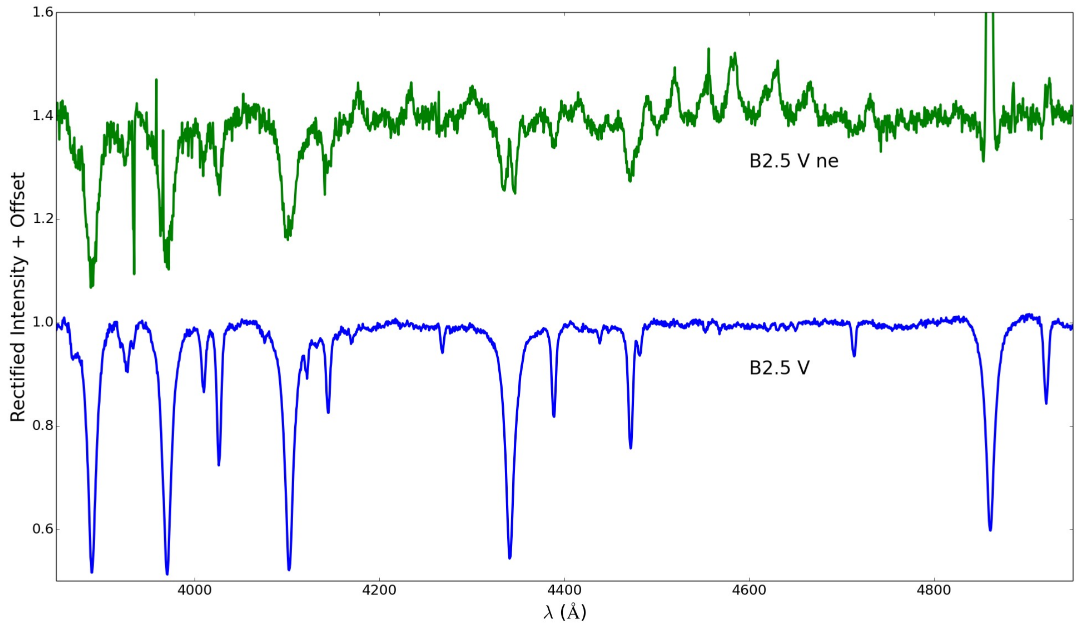
Scope

1. Physical Properties of Intermediate- and High-Mass Stars

2. Observable Properties of B-type and Emission-Line B-type (B*e*) Stellar Spectra



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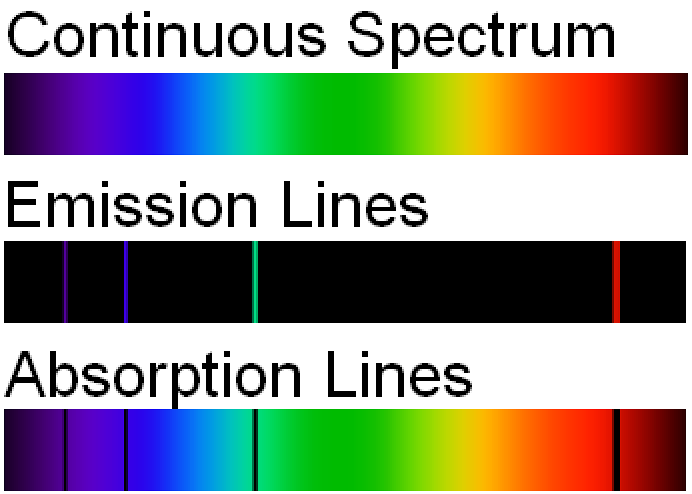
3. Emission *versus* Absorption: A Qualitative Look



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4. Emission *versus* Absorption: A Physical Approach

$$\frac{dI_\lambda}{d\tau} = -I_\lambda + S_\lambda$$

$$I_\lambda = I_\lambda^0 e^{-\tau_\lambda} + S_\lambda \left(1 - e^{-\tau_\lambda}\right)$$

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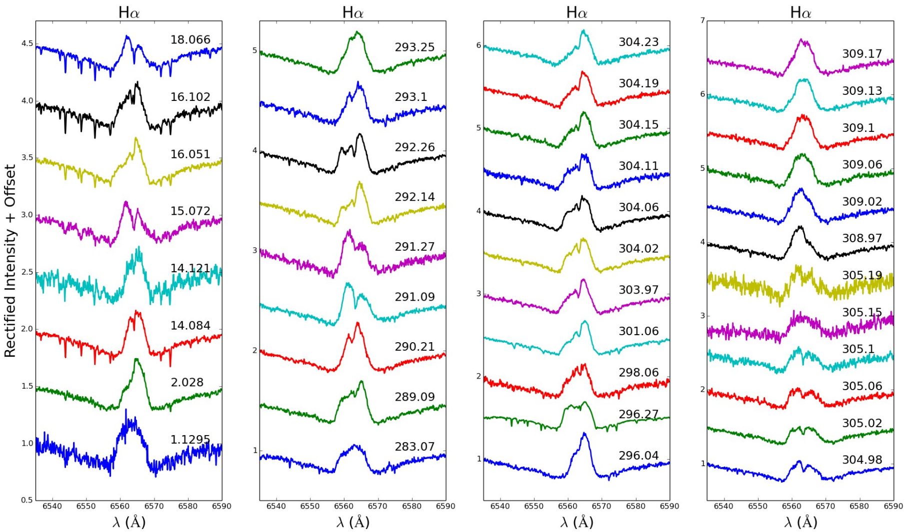
3. Emission *versus* Absorption: A Qualitative Look

4. Emission *versus* Absorption: A Physical Approach

5. Studying Rapid Spectroscopic Variability



1. Physical Properties of Intermediate- and High-Mass Stars

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A2 V - B3 V: Intermediate - Mass Stars

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A2 V - B3 V: Intermediate - Mass Stars

Spec Type	Mass (M_{sol})	Radius (R_{sol})	T_{eff} (K)
A2			
B3			

Data from: David Gray's *The Observation and Analysis of Stellar Photospheres*
Richard Gray & Christopher Corbally's *Stellar Spectral Classification*

1. Physical Properties of Intermediate- and High-Mass Stars

A2 V - B3 V: Intermediate - Mass Stars

Spec Type	Mass (M_{sol})	Radius (R_{sol})	T_{eff} (K)
A2	2.2		
B3			

Data from: David Gray's *The Observation and Analysis of Stellar Photospheres*
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1. Physical Properties of Intermediate- and High-Mass Stars

A2 V - B3 V: Intermediate - Mass Stars

Spec Type	Mass (M_{sol})	Radius (R_{sol})	T_{eff} (K)
A2	2.2	1.75	
B3			

Data from: David Gray's *The Observation and Analysis of Stellar Photospheres*
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1. Physical Properties of Intermediate- and High-Mass Stars

A2 V - B3 V: Intermediate - Mass Stars

Spec Type	Mass (M_{sol})	Radius (R_{sol})	T_{eff} (K)
A2	2.2	1.75	8,900
B3			

Data from: David Gray's *The Observation and Analysis of Stellar Photospheres*
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A2 V - B3 V: Intermediate - Mass Stars

Spec Type	Mass (M_{sol})	Radius (R_{sol})	T_{eff} (K)
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A2 V - B3 V: Intermediate - Mass Stars

Spec Type	Mass (M_{sol})	Radius (R_{sol})	T_{eff} (K)
A2	2.2	1.75	8,900
B3	6.3	3.5	

Data from: David Gray's *The Observation and Analysis of Stellar Photospheres*
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1. Physical Properties of Intermediate- and High-Mass Stars

A2 V - B3 V: Intermediate - Mass Stars

Spec Type	Mass (M_{sol})	Radius (R_{sol})	T_{eff} (K)
A2	2.2	1.75	8,900
B3	6.3	3.5	16,500

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Photospherically:

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Photospherically:

- Strong Hydrogen absorption lines

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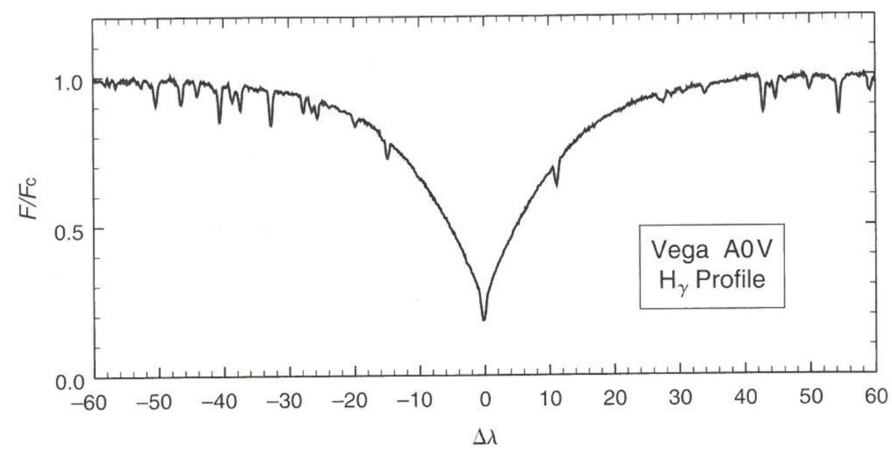

Gray, Fig. 11.5

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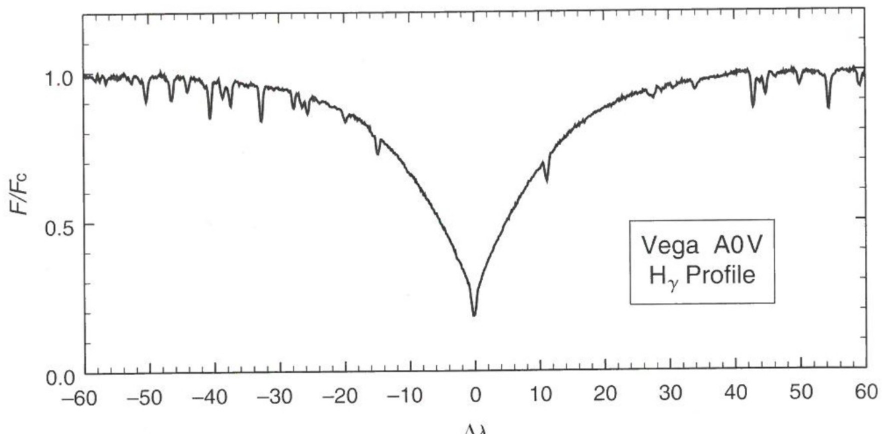
Photospherically:



Gray, Fig. 11.5

- Strong Hydrogen absorption lines
  - ➔ weakening with increasing temperature (max. near A1-2)

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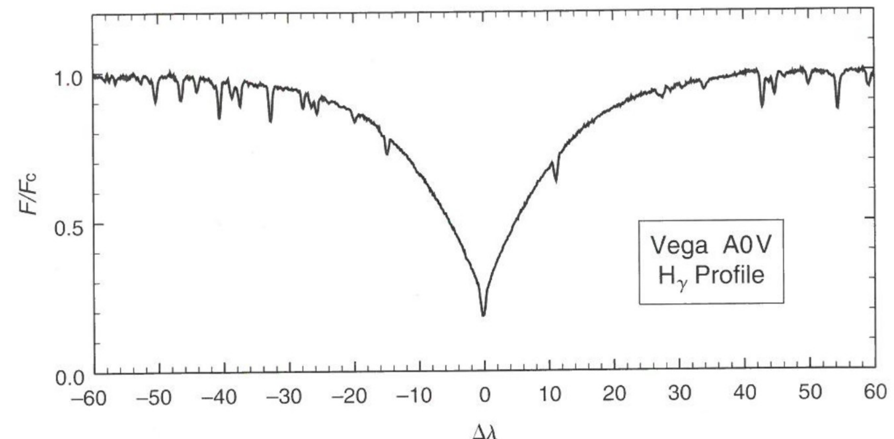

Gray, Fig. 11.5

Photospherically:

- Strong Hydrogen absorption lines
  - → weakening with increasing temperature (max. near A1-2)
- Strengthening Helium absorption lines

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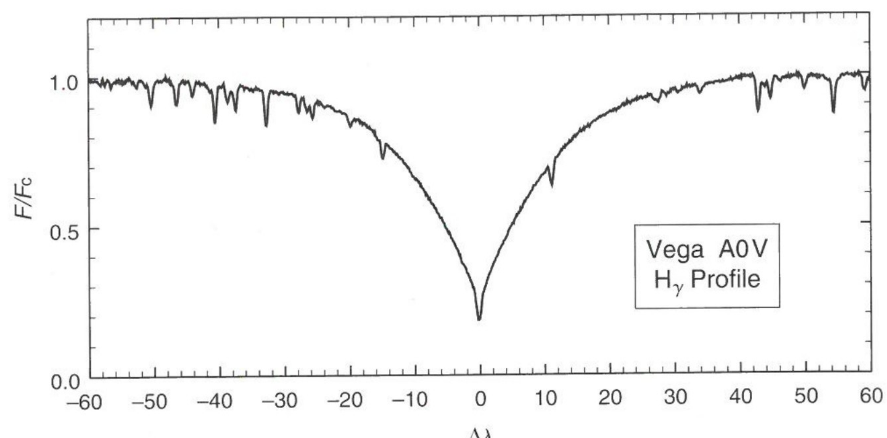
Photospherically:



Gray, Fig. 11.5

- Strong Hydrogen absorption lines
  - weakening with increasing temperature (max. near A1-2)
- Strengthening Helium absorption lines
  - maximum near B3

1. Physical Properties of Intermediate- and High-Mass Stars

B2 V and Above: High-Mass Stars

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B2 V and Above: High-Mass Stars

Spec Type	Mass (M_{sol})	Radius (R_{sol})	T_{eff} (K)
B2			
O9			

Data from: David Gray's *The Observation and Analysis of Stellar Photospheres*
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1. Physical Properties of Intermediate- and High-Mass Stars

B2 V and Above: High-Mass Stars

Spec Type	Mass (M_{sol})	Radius (R_{sol})	T_{eff} (K)
B2	8.3		
O9			

Data from: David Gray's *The Observation and Analysis of Stellar Photospheres*
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1. Physical Properties of Intermediate- and High-Mass Stars

B2 V and Above: High-Mass Stars

Spec Type	Mass (M_{sol})	Radius (R_{sol})	T_{eff} (K)
B2	8.3	4.7	
O9			

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1. Physical Properties of Intermediate- and High-Mass Stars

B2 V and Above: High-Mass Stars

Spec Type	Mass (M_{sol})	Radius (R_{sol})	T_{eff} (K)
B2	8.3	4.7	19,500
O9			

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1. Physical Properties of Intermediate- and High-Mass Stars

B2 V and Above: High-Mass Stars

Spec Type	Mass (M_{sol})	Radius (R_{sol})	T_{eff} (K)
B2	8.3	4.7	19,500
O9	20?		

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B2 V and Above: High-Mass Stars

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B2	8.3	4.7	19,500
O9	20?	9	

Data from: David Gray's *The Observation and Analysis of Stellar Photospheres*
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1. Physical Properties of Intermediate- and High-Mass Stars

B2 V and Above: High-Mass Stars

Spec Type	Mass (M_{sol})	Radius (R_{sol})	T_{eff} (K)
B2	8.3	4.7	19,500
O9	20?	9	32,882

Data from: David Gray's *The Observation and Analysis of Stellar Photospheres*
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Photospherically:

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Photospherically:

- Weaker H lines

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Photospherically:

- Weaker H lines
- He ionization layer is near or at the surface

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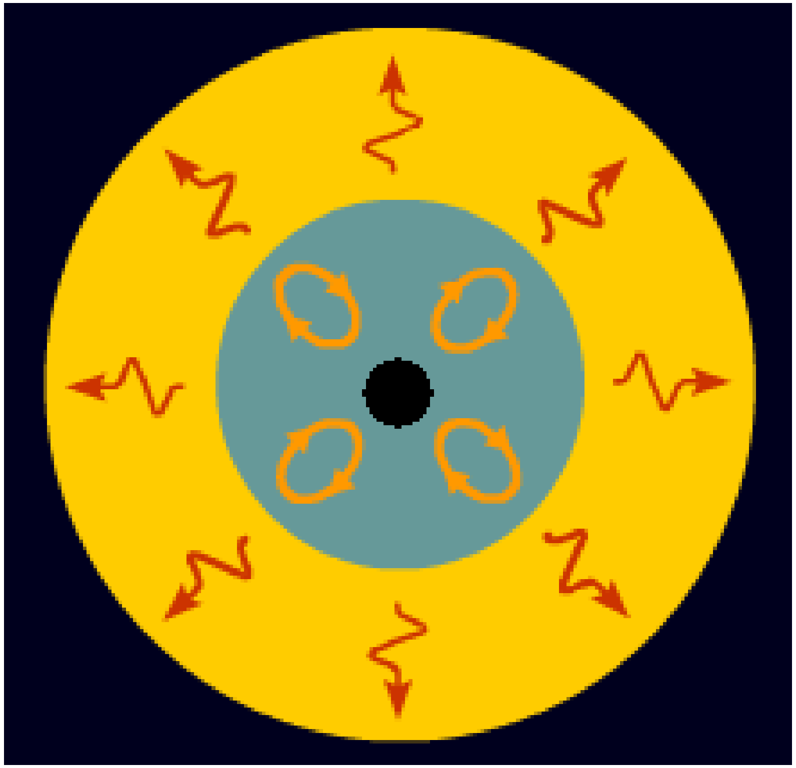
Photospherically:

- Weaker H lines
- He ionization layer is near or at the surface

NOT Considering O8 and above:

- Convective interior, puffier stars



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2. Observable Properties of B-type and Be Stars

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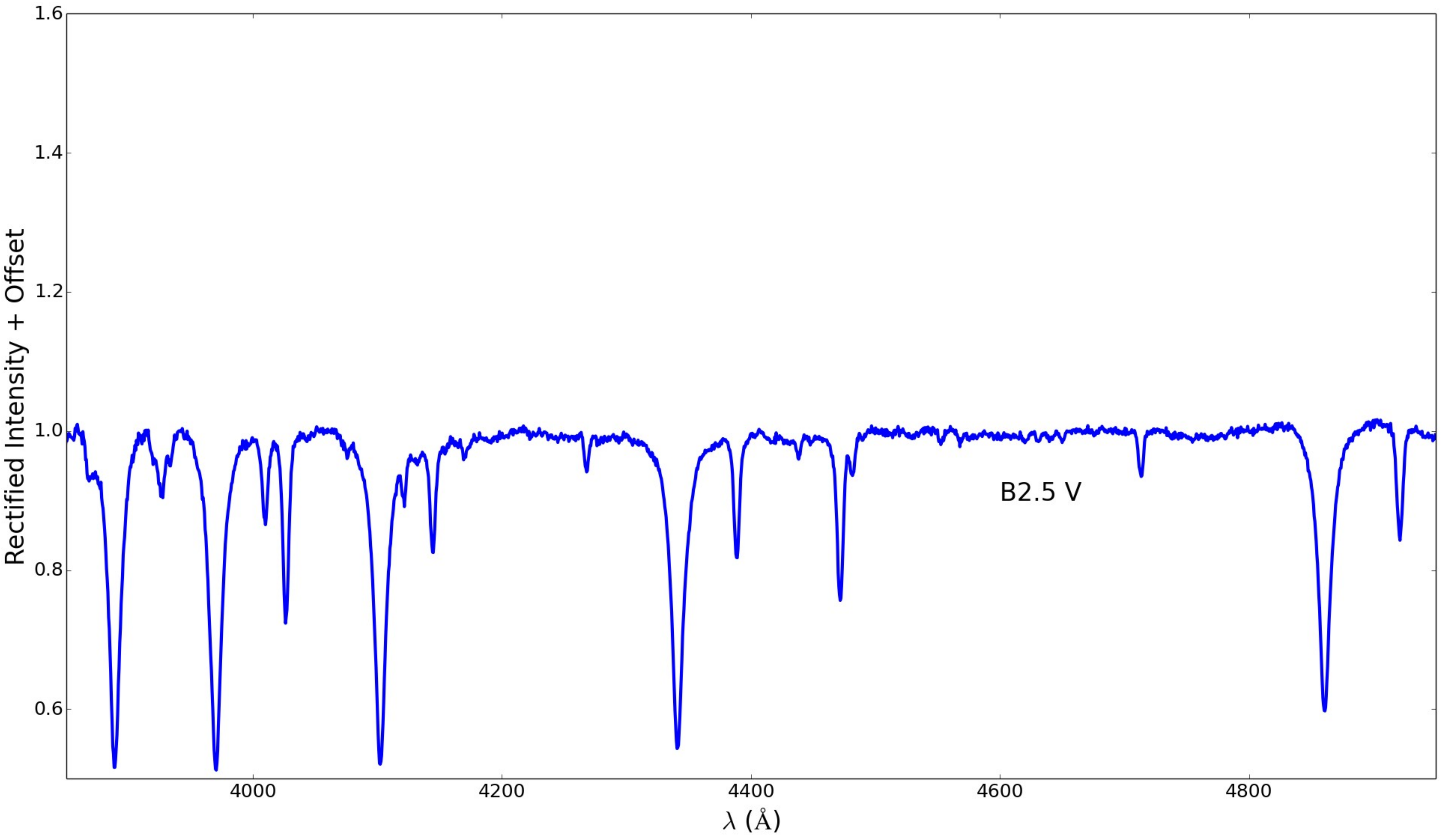

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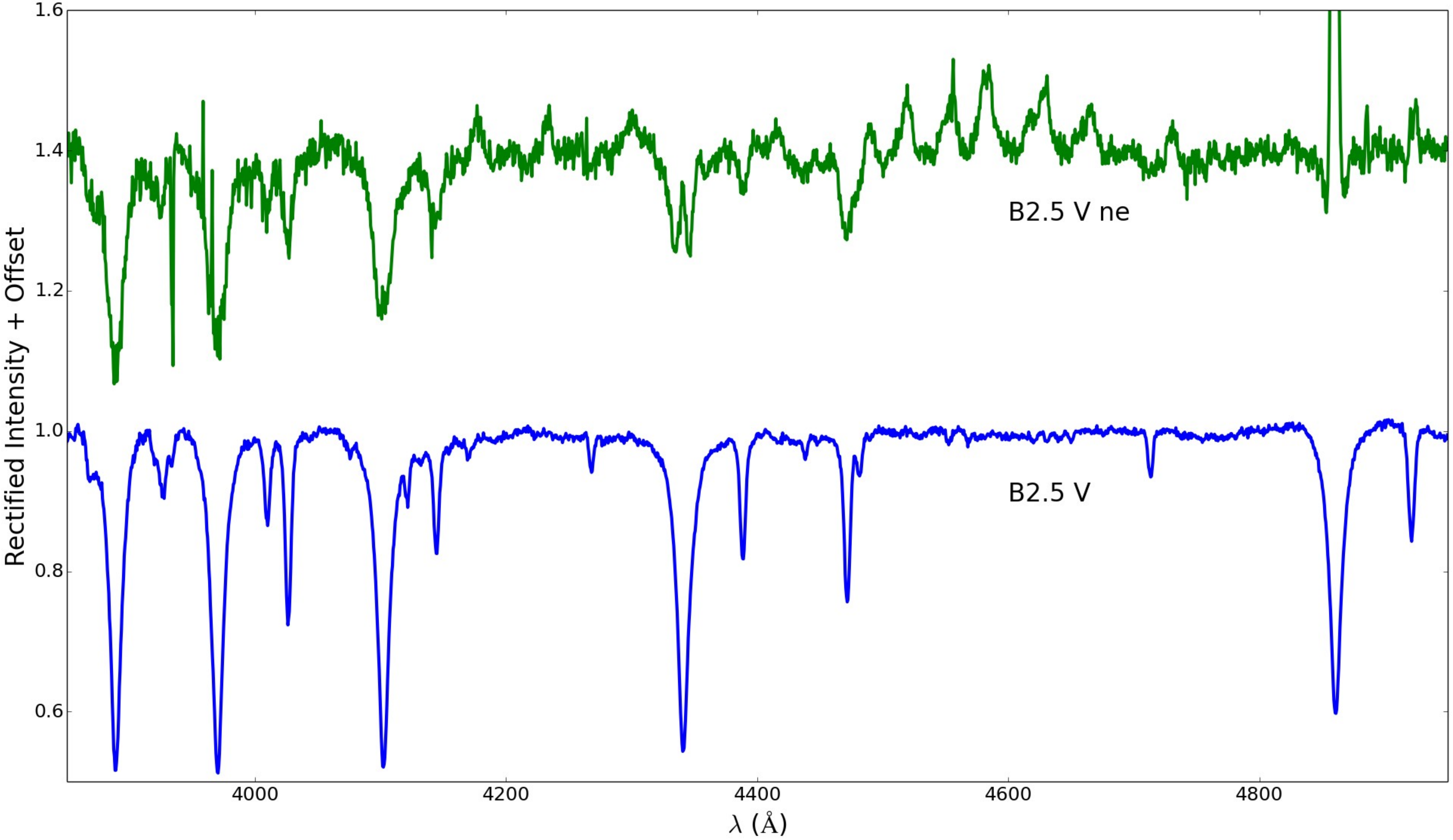

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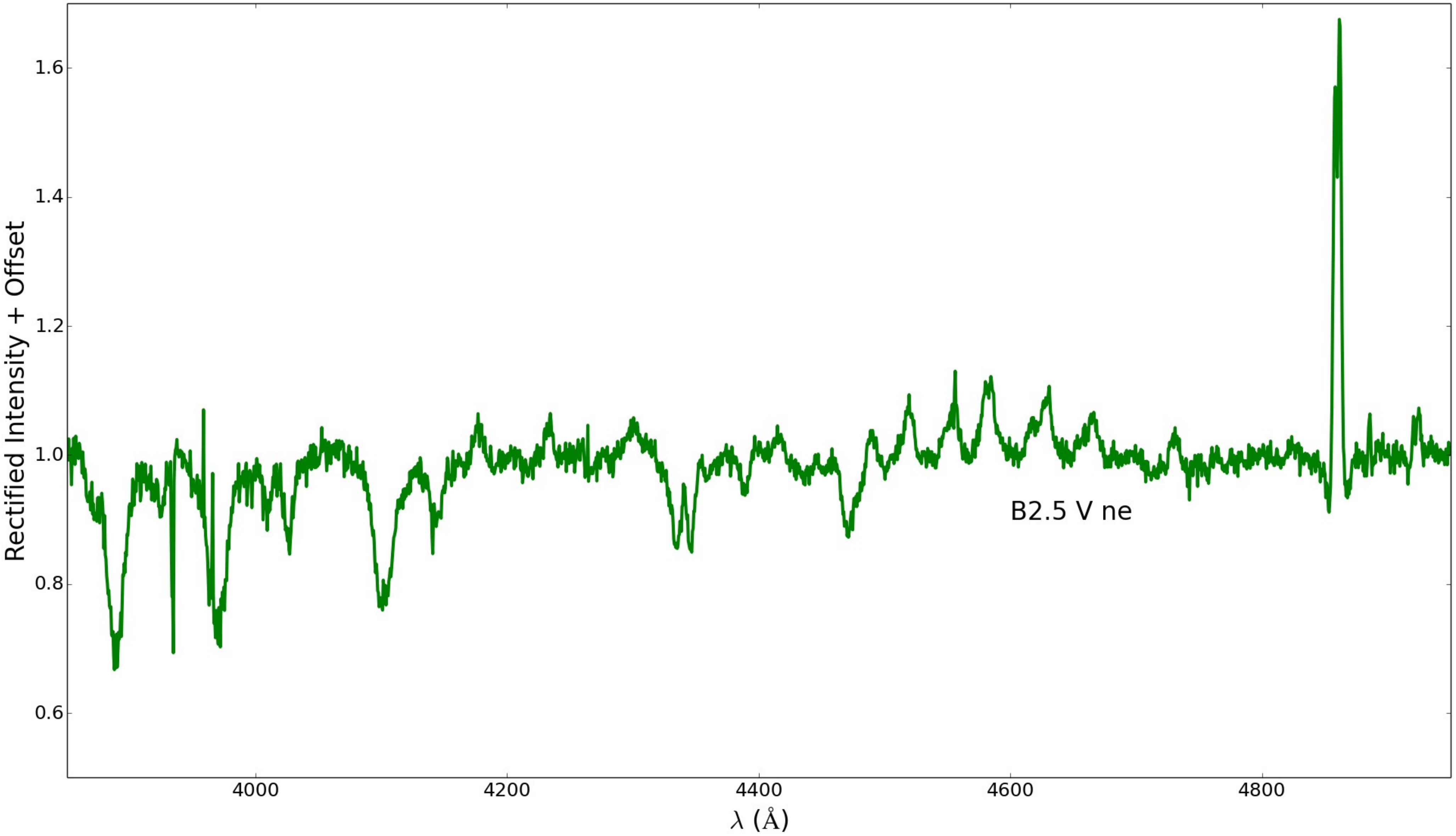

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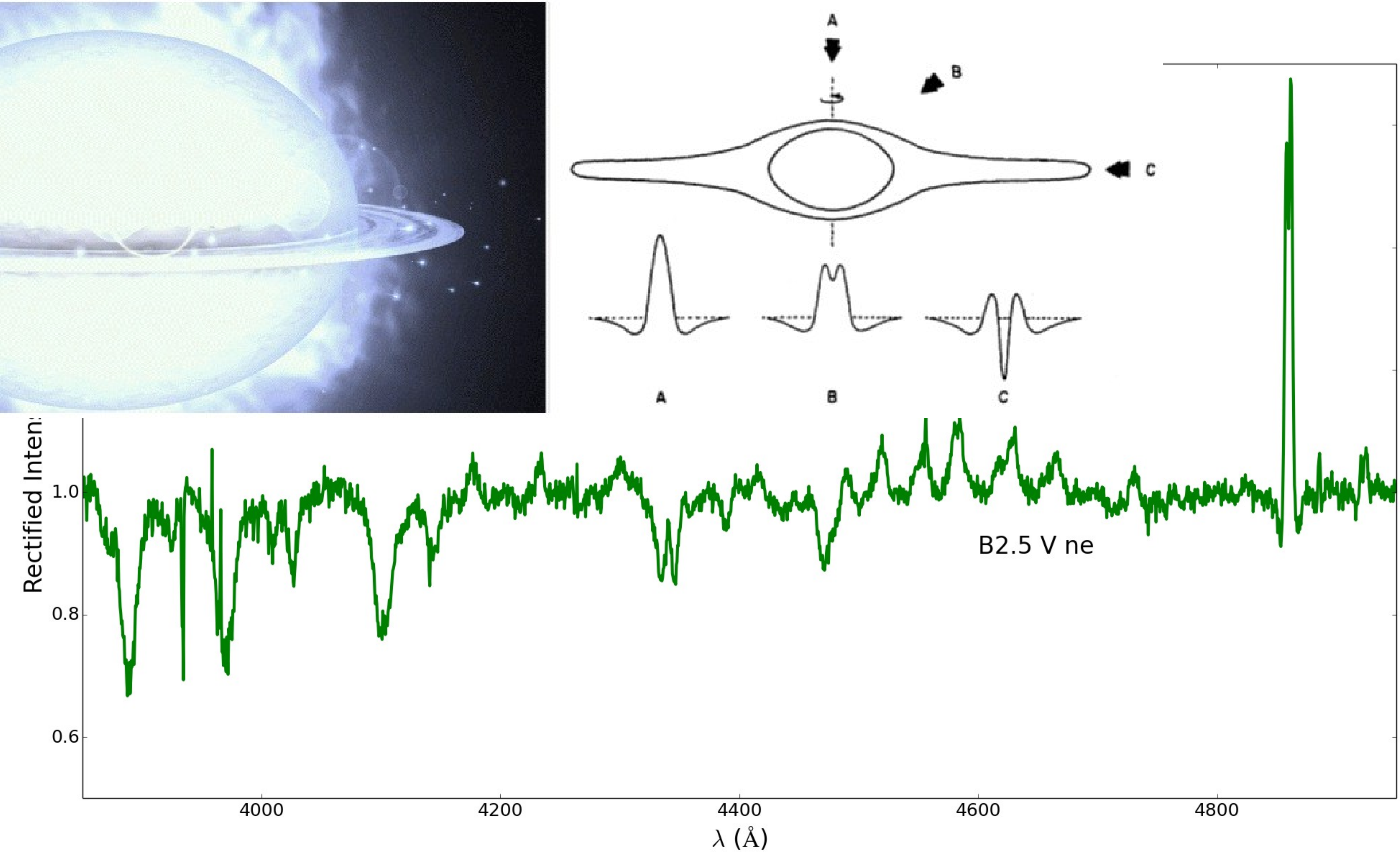

http://lasp.colorado.edu/~cranmer/cranmer_st_hot.html

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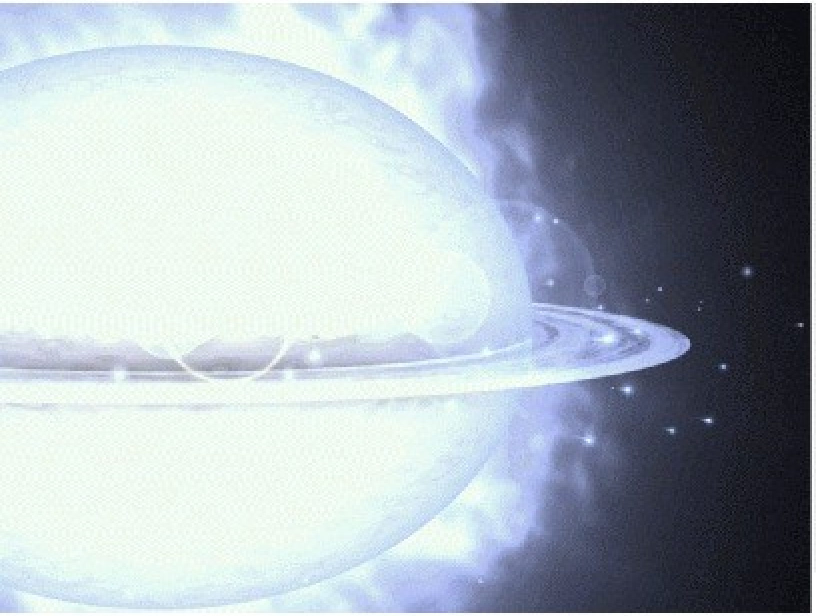

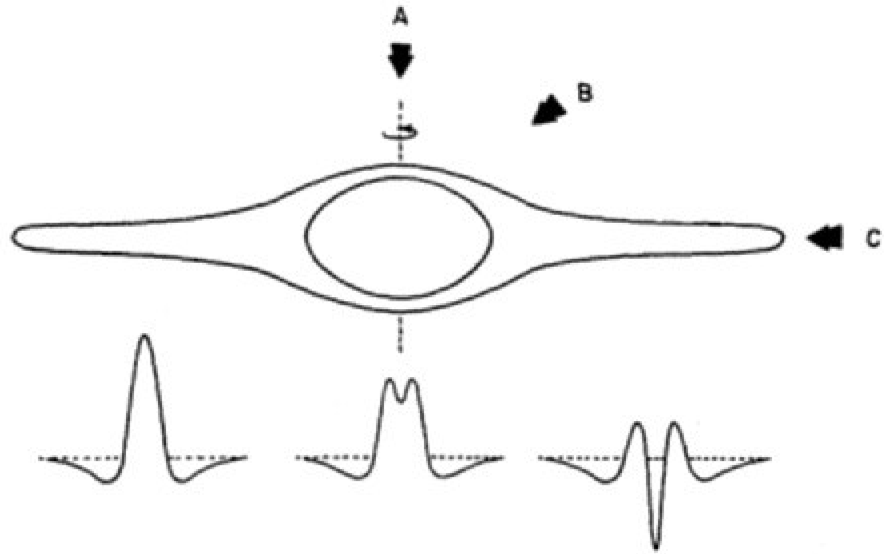

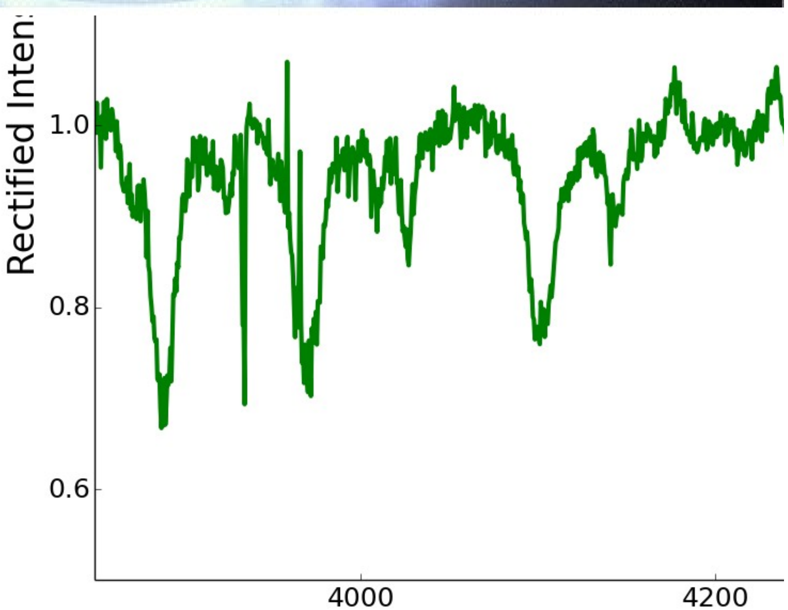

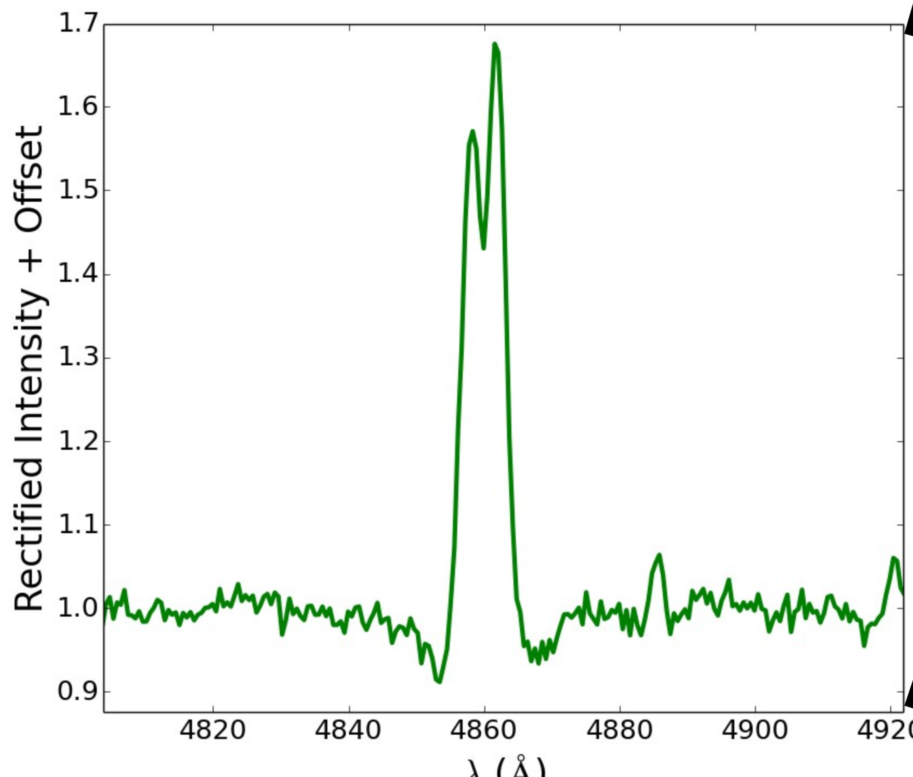

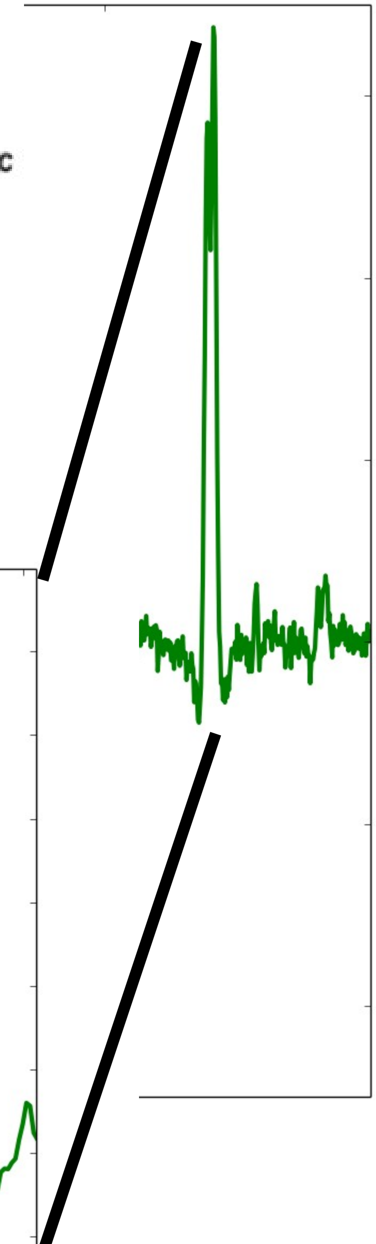

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3. Emission *versus* Absorption: A Qualitative Look

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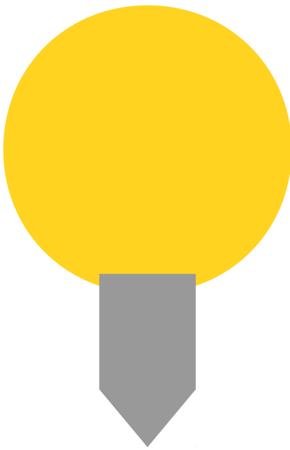
light source
(relatively hot)



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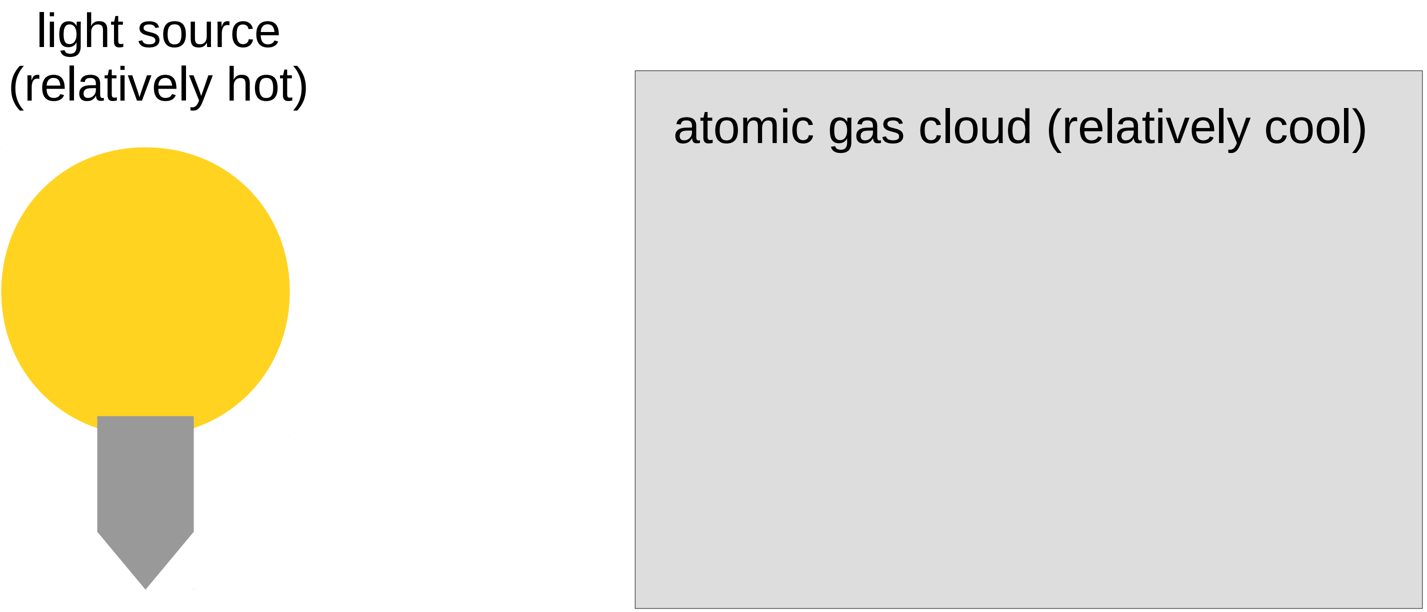

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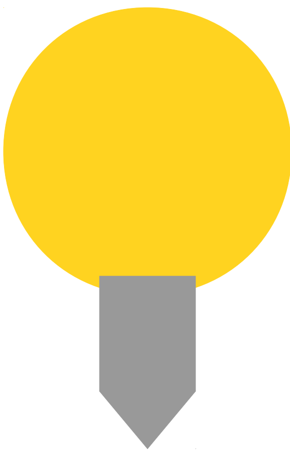

atomic gas cloud (relatively cool)

http://www.iankingimaging.com/images/products/originals/lhires.jpg

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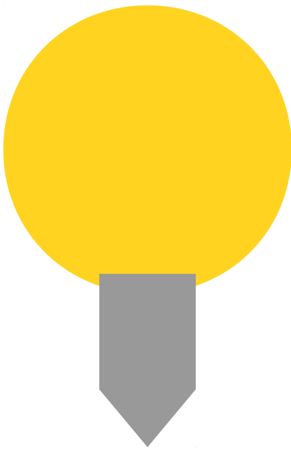

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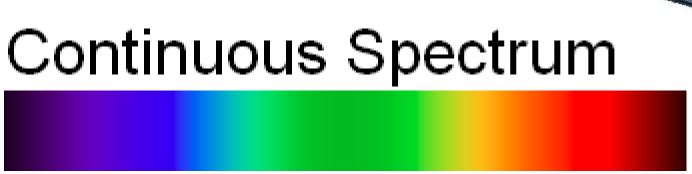

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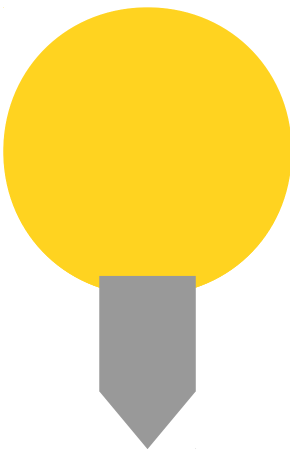

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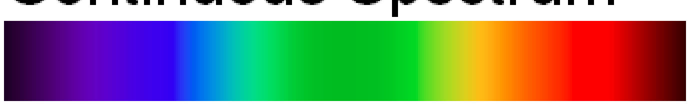
Continuous Spectrum



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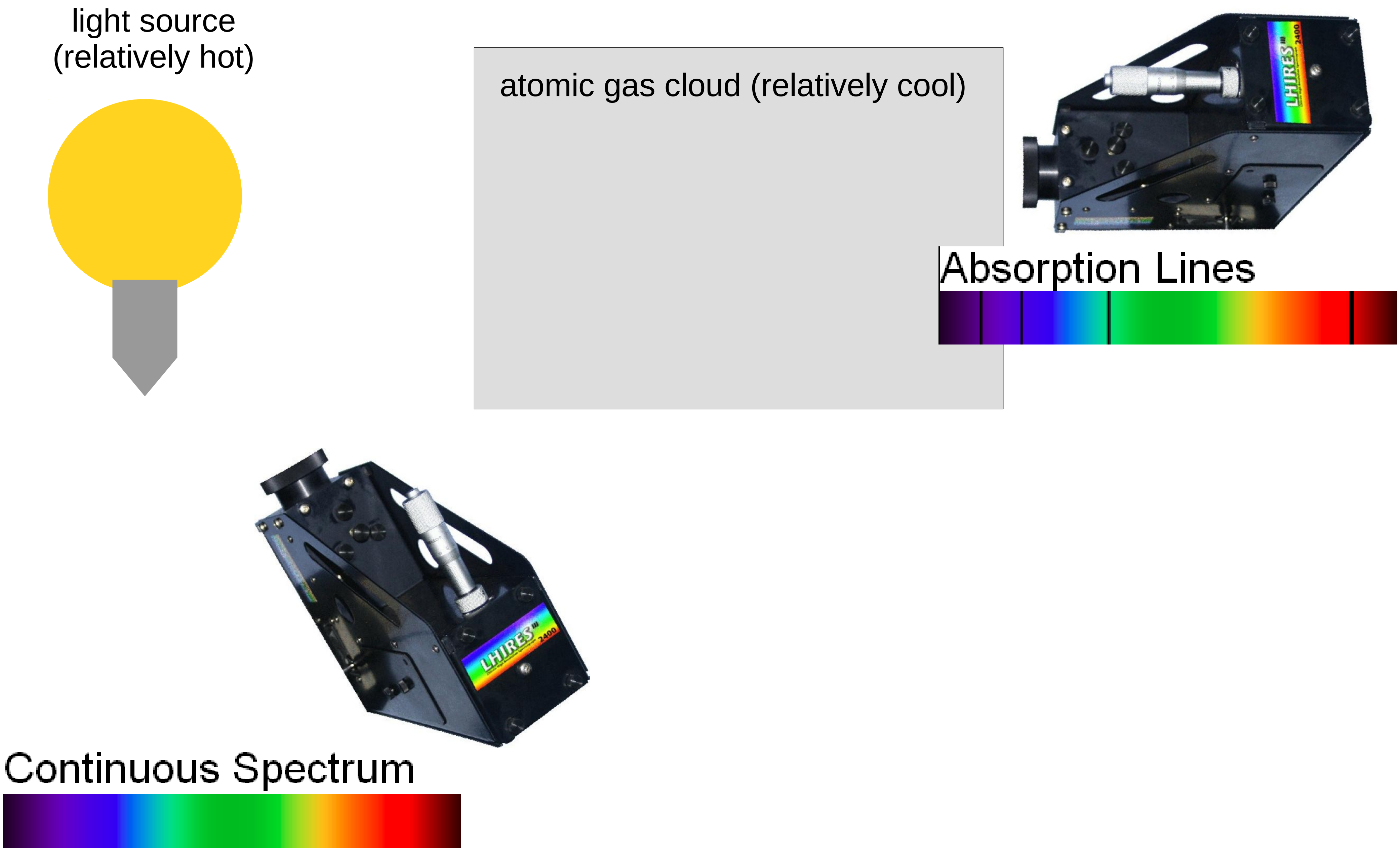

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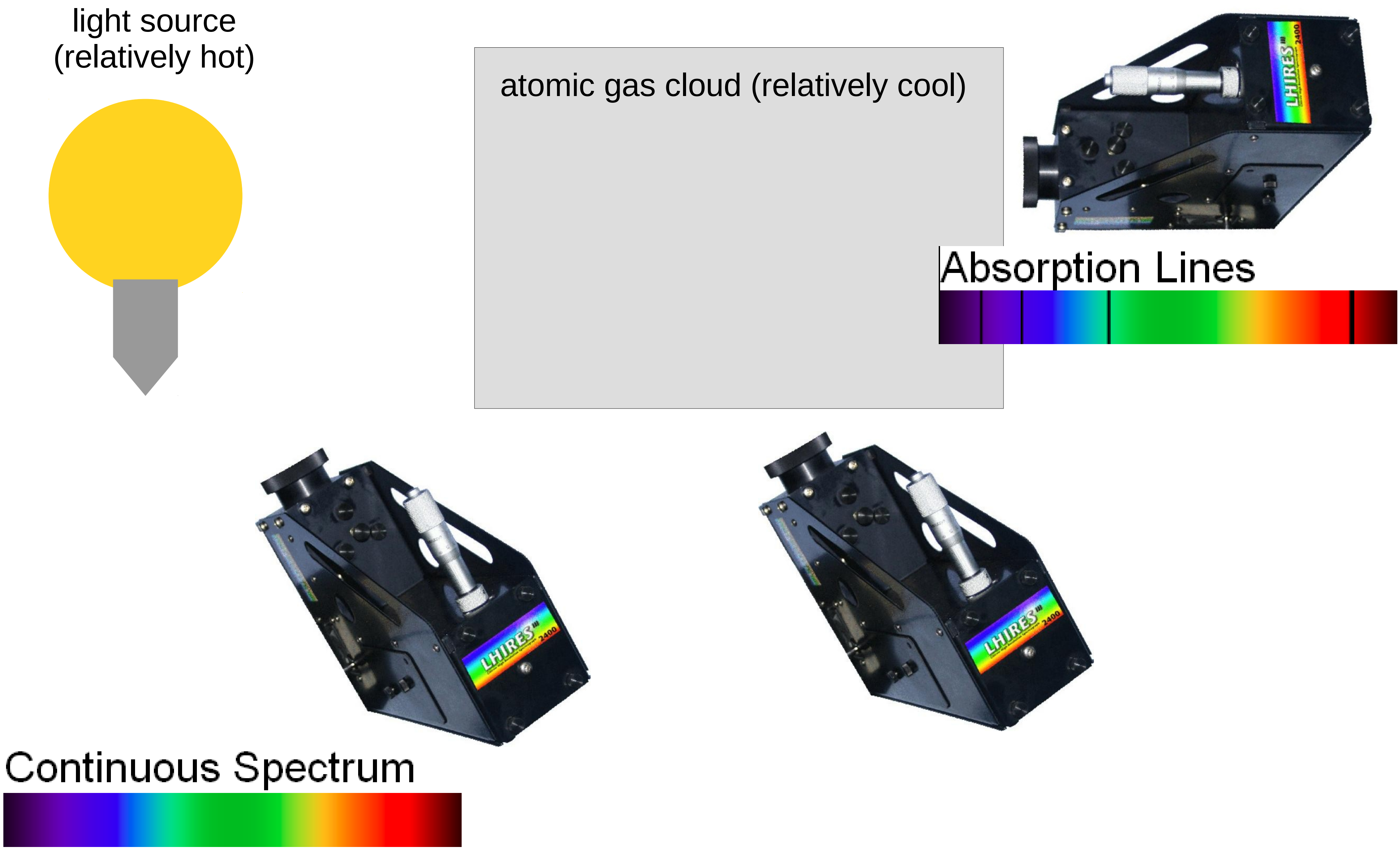

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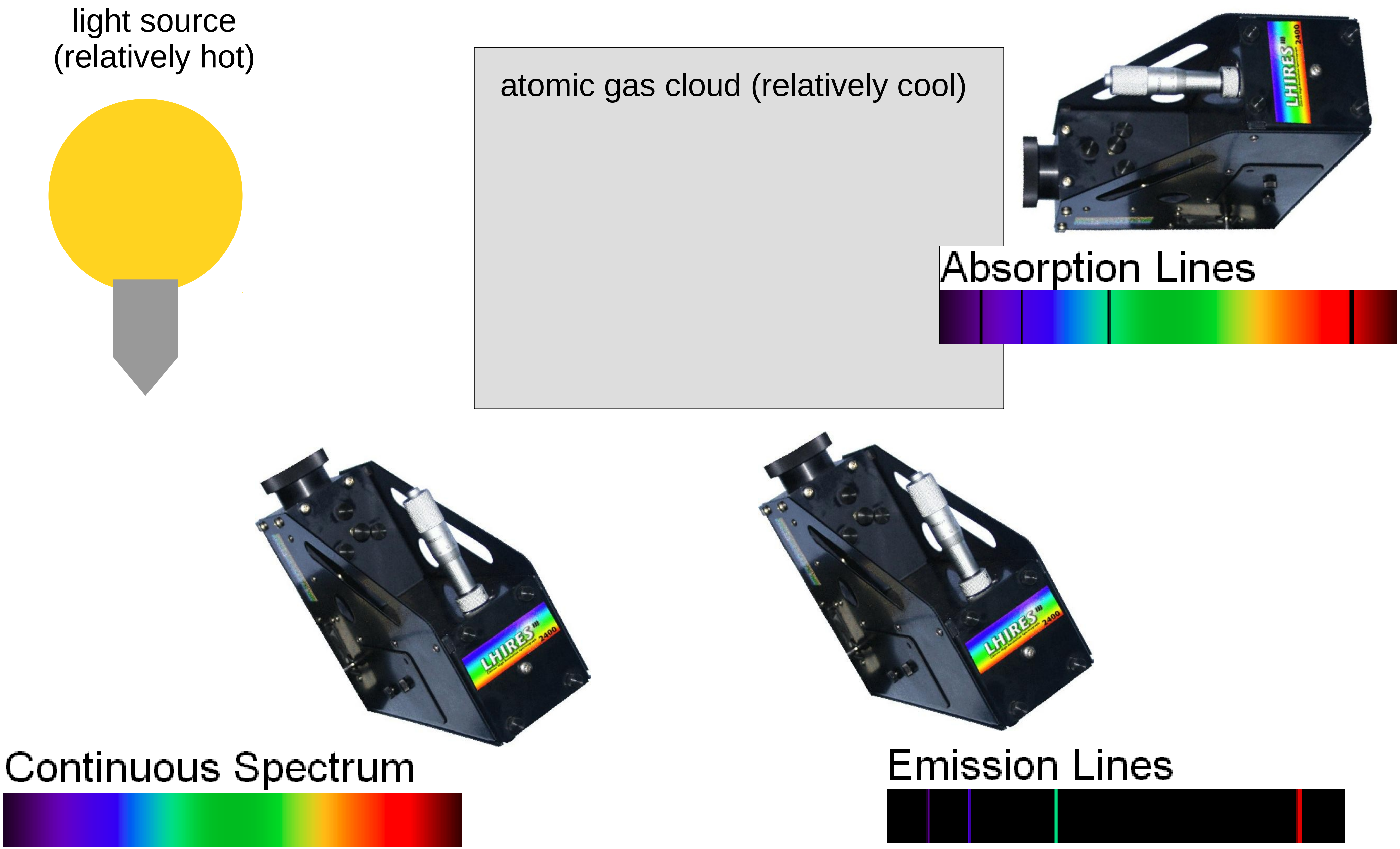

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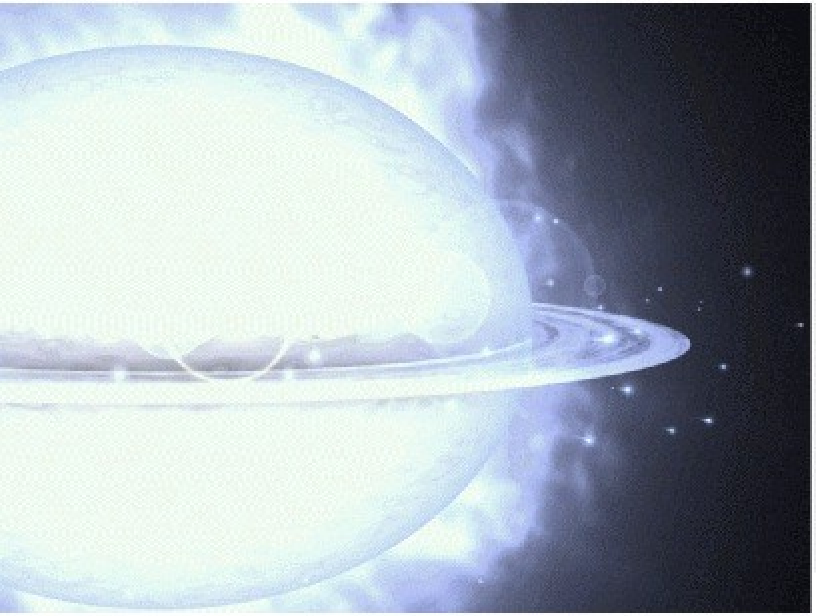

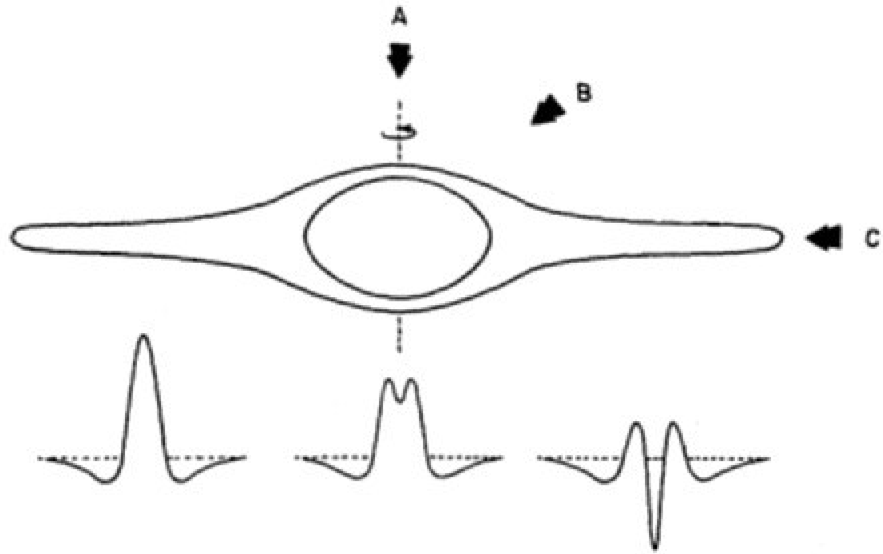

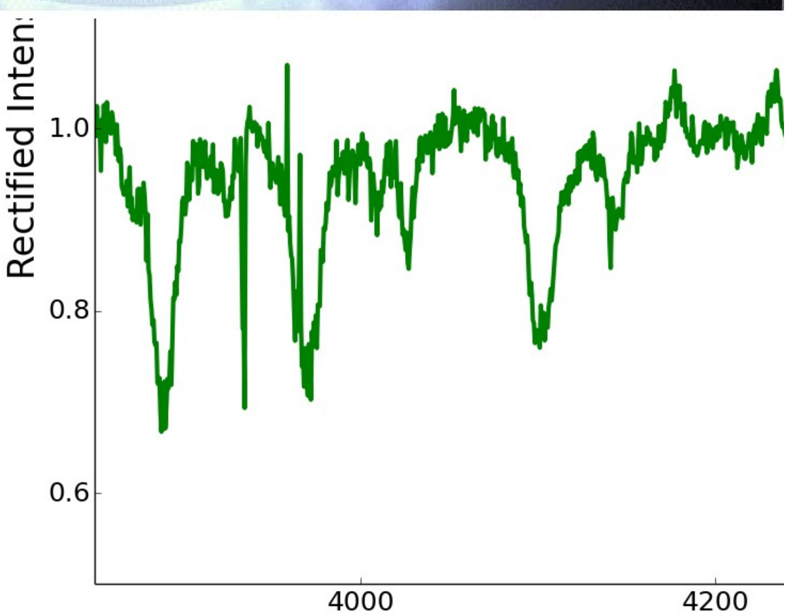

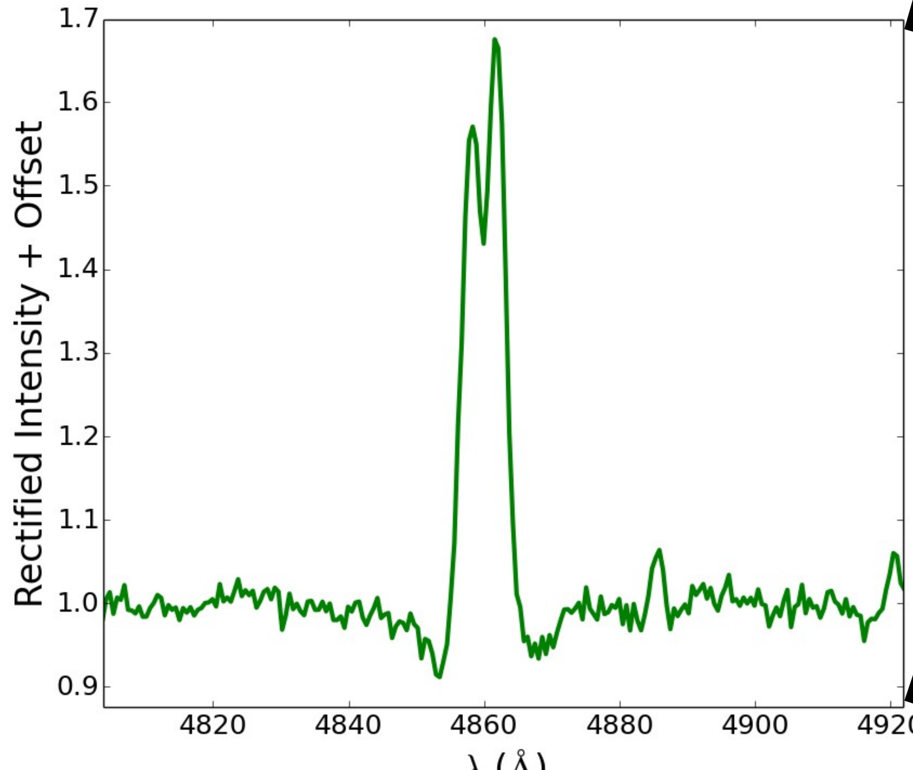

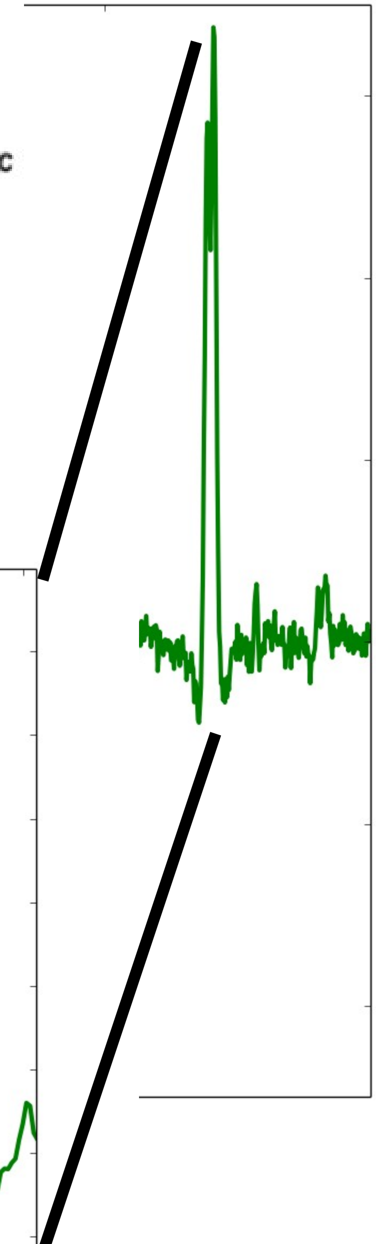

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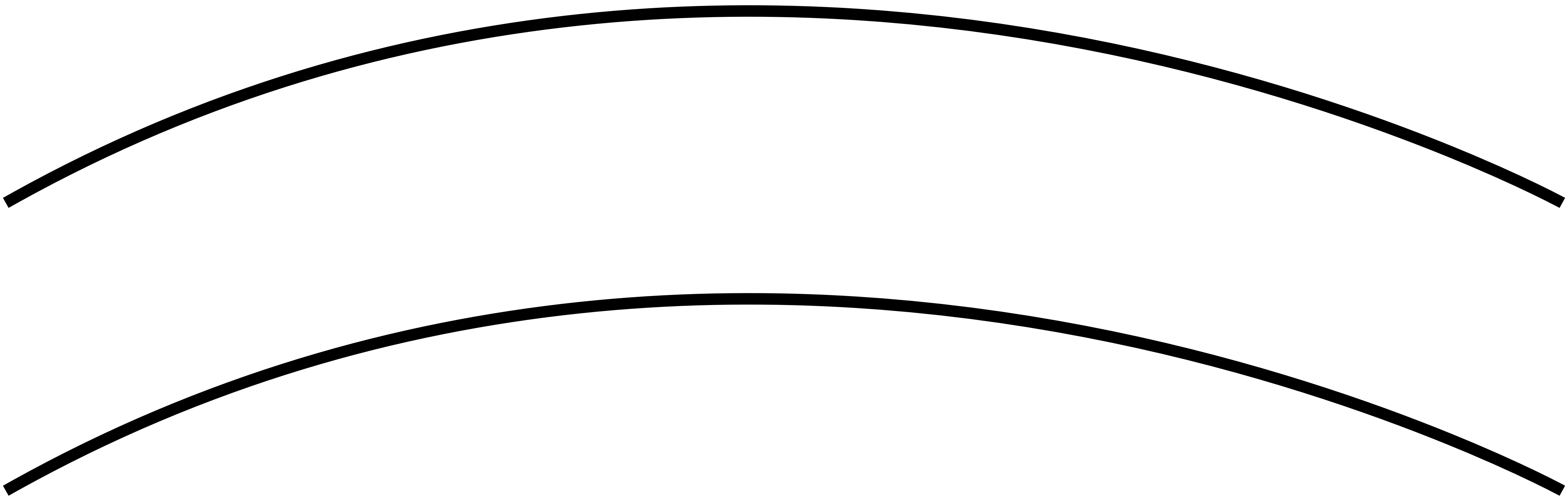

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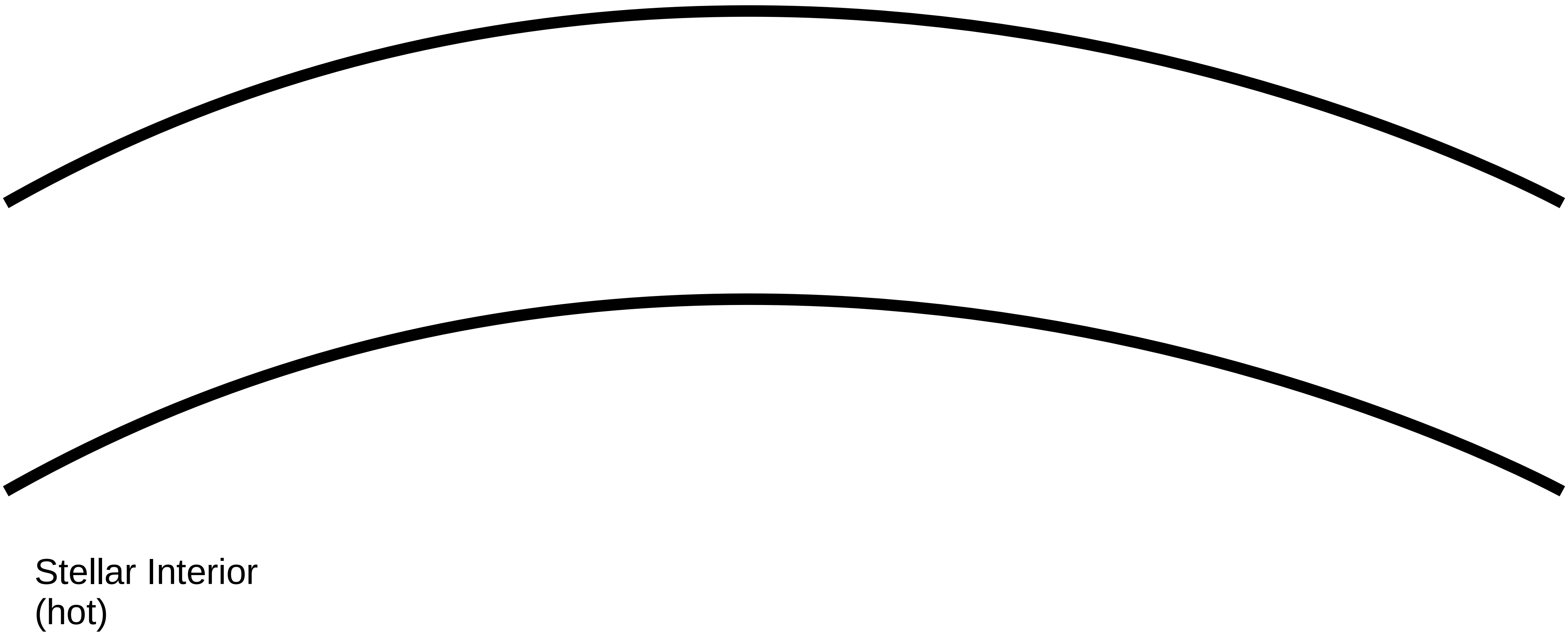

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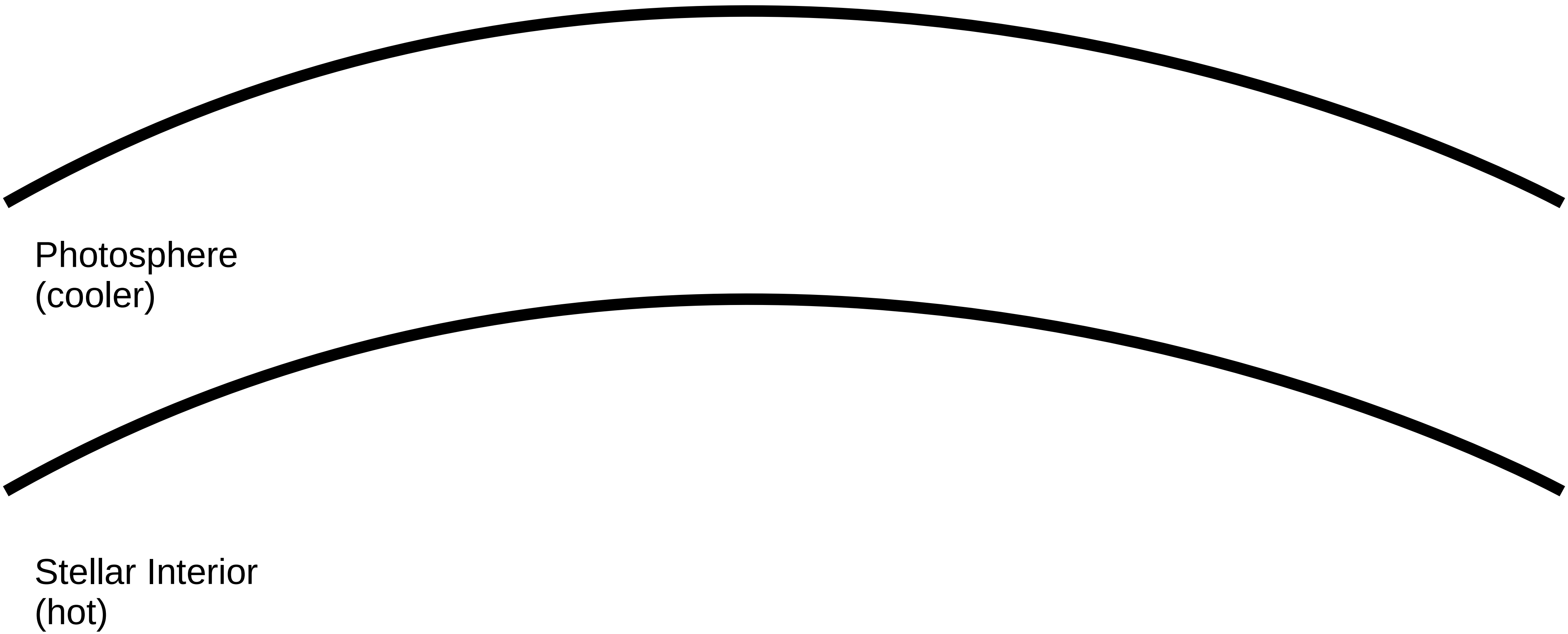

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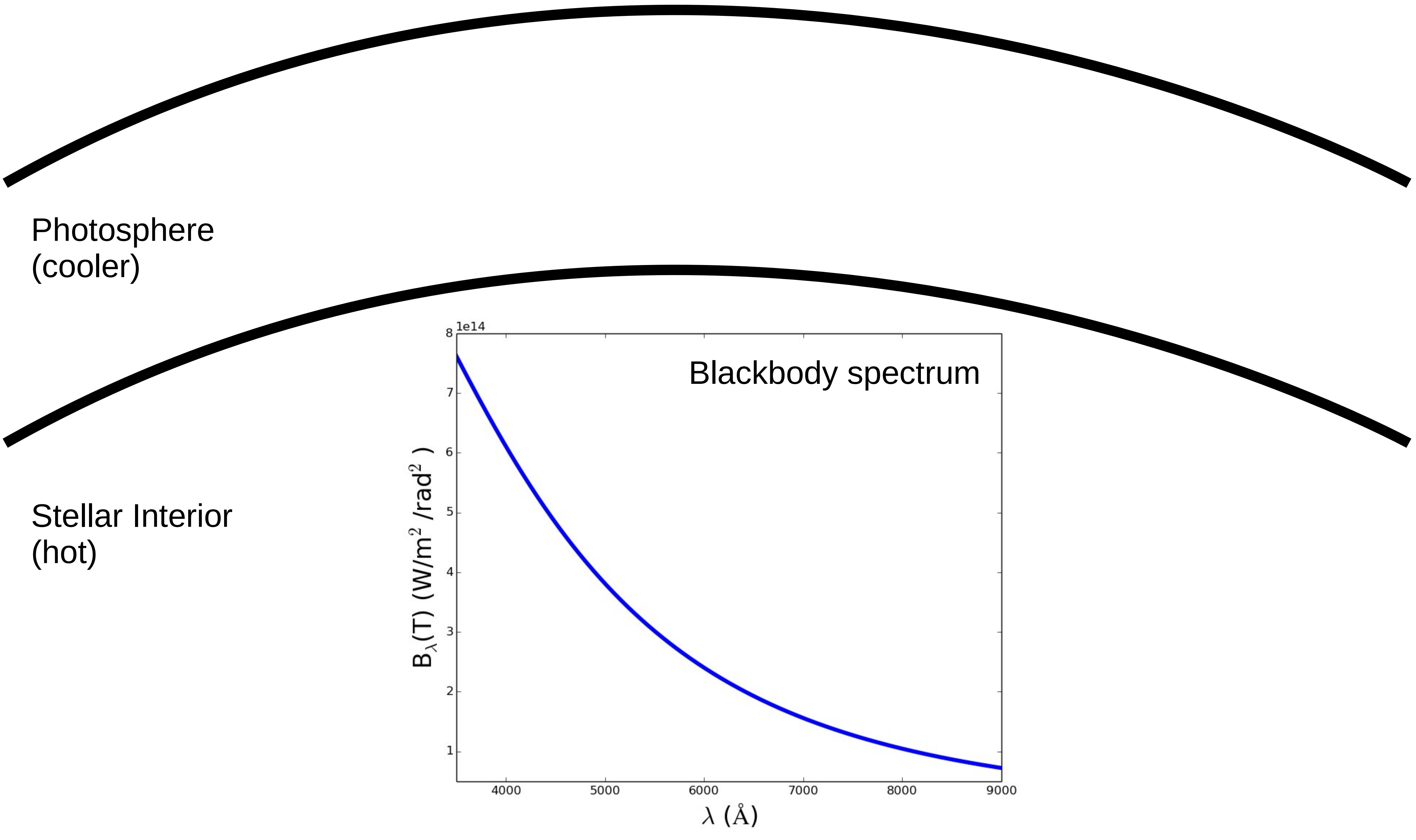
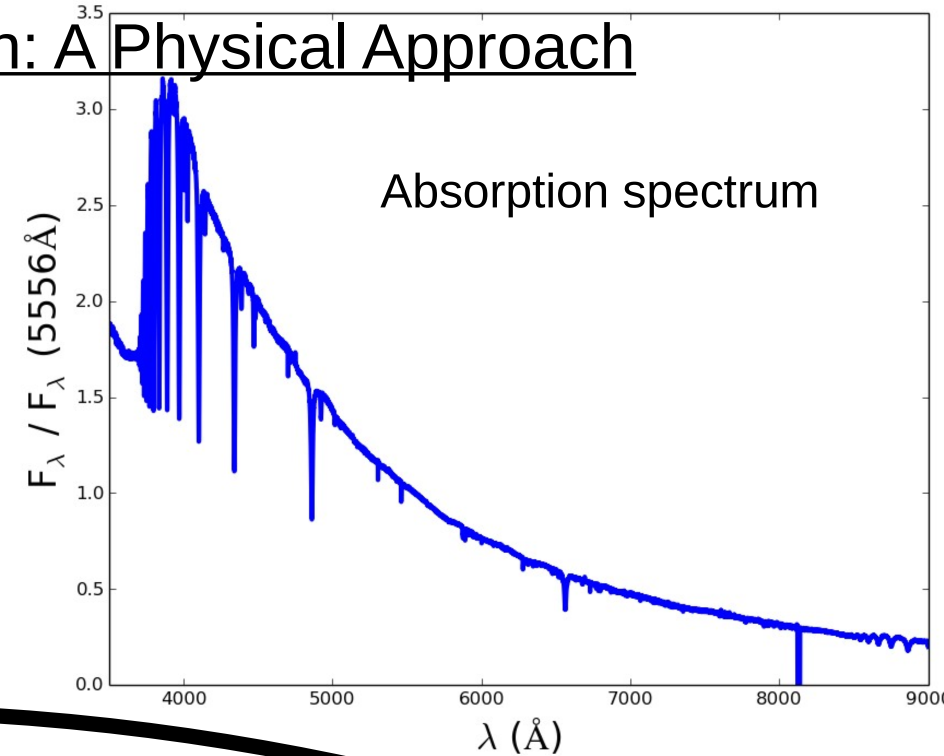
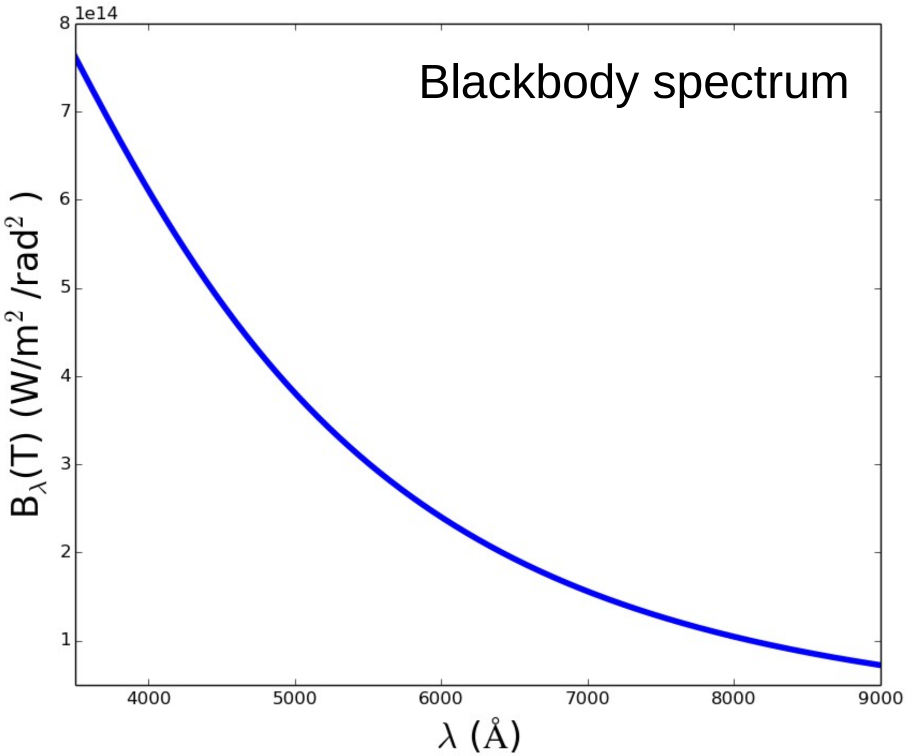


4. Emission *versus* Absorption: A Physical Approach

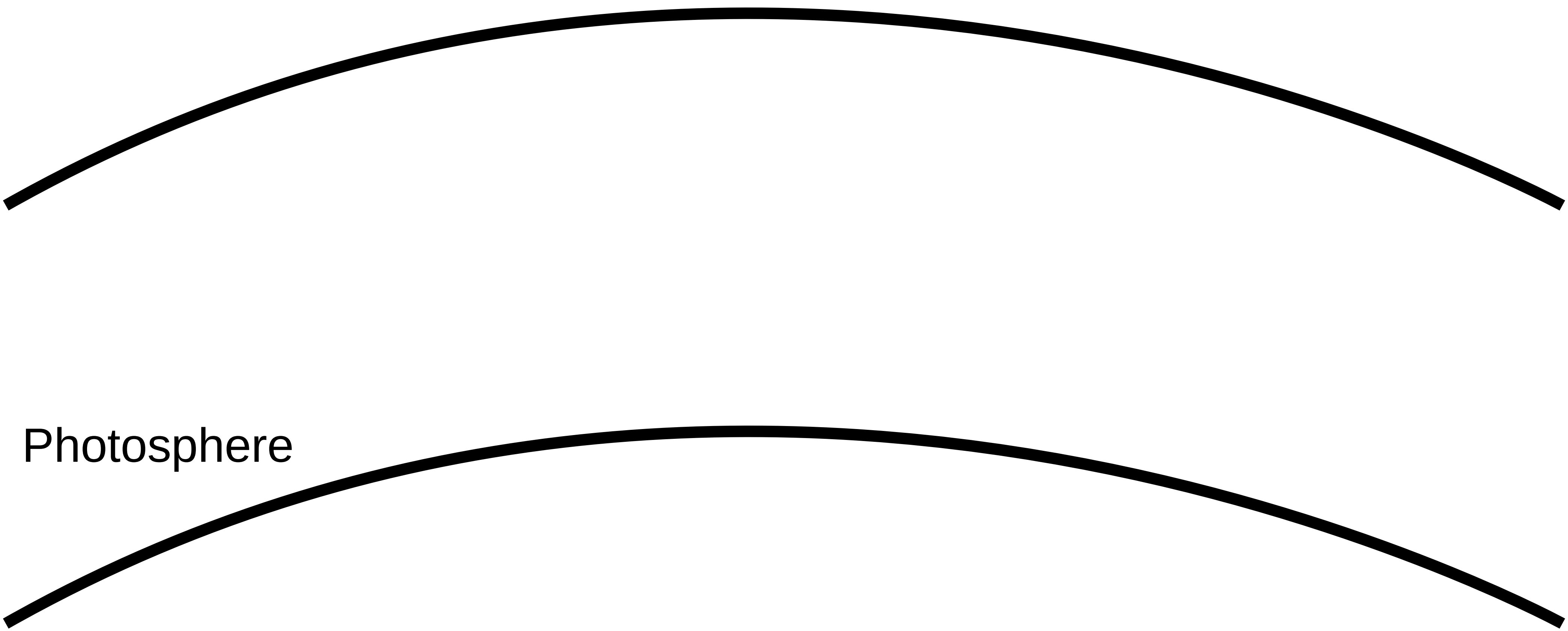


Photosphere
(cooler)

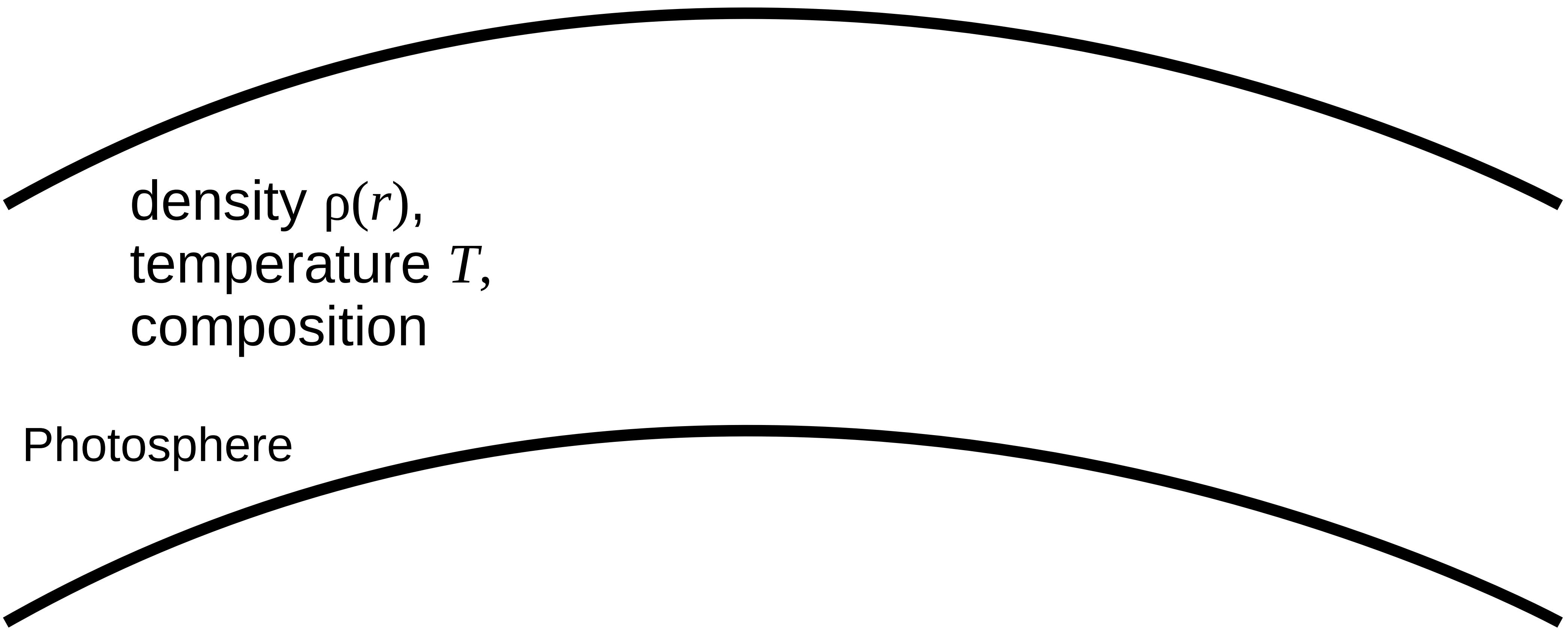


Stellar Interior
(hot)

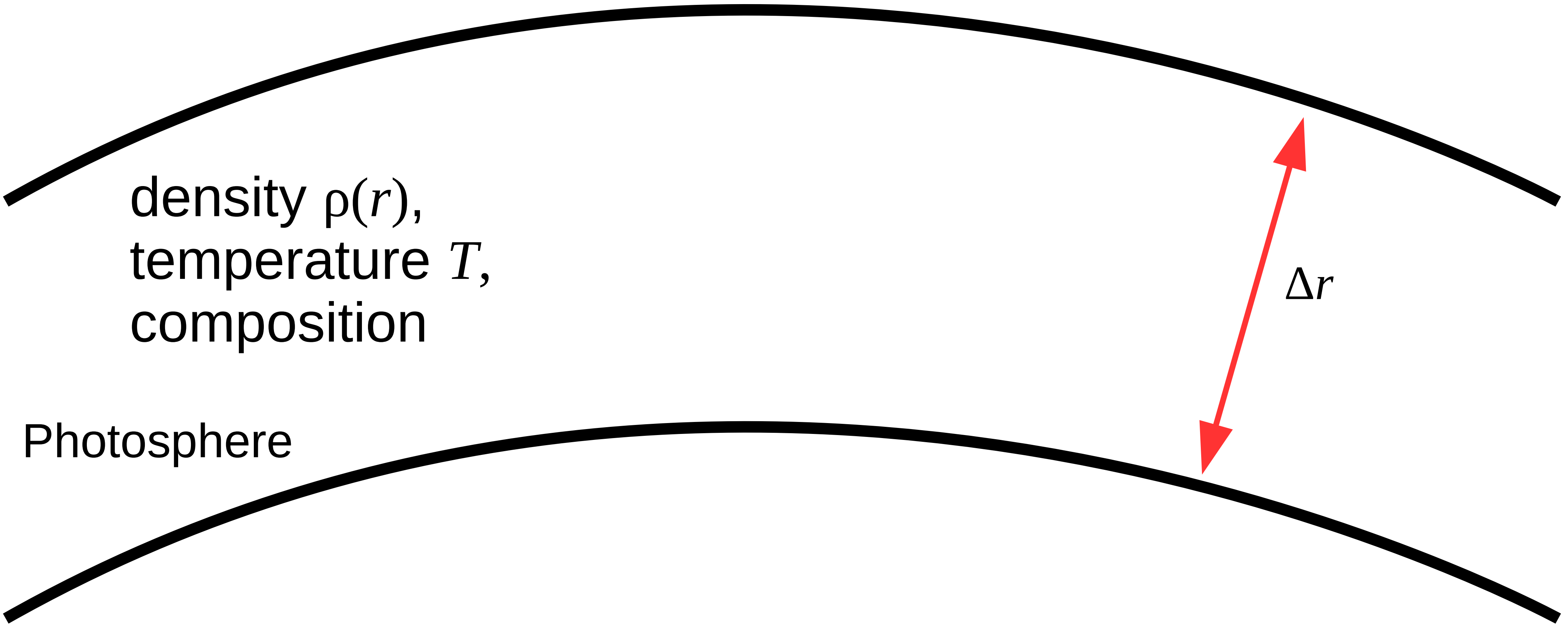
4. Emission *versus* Absorption: A Physical Approach



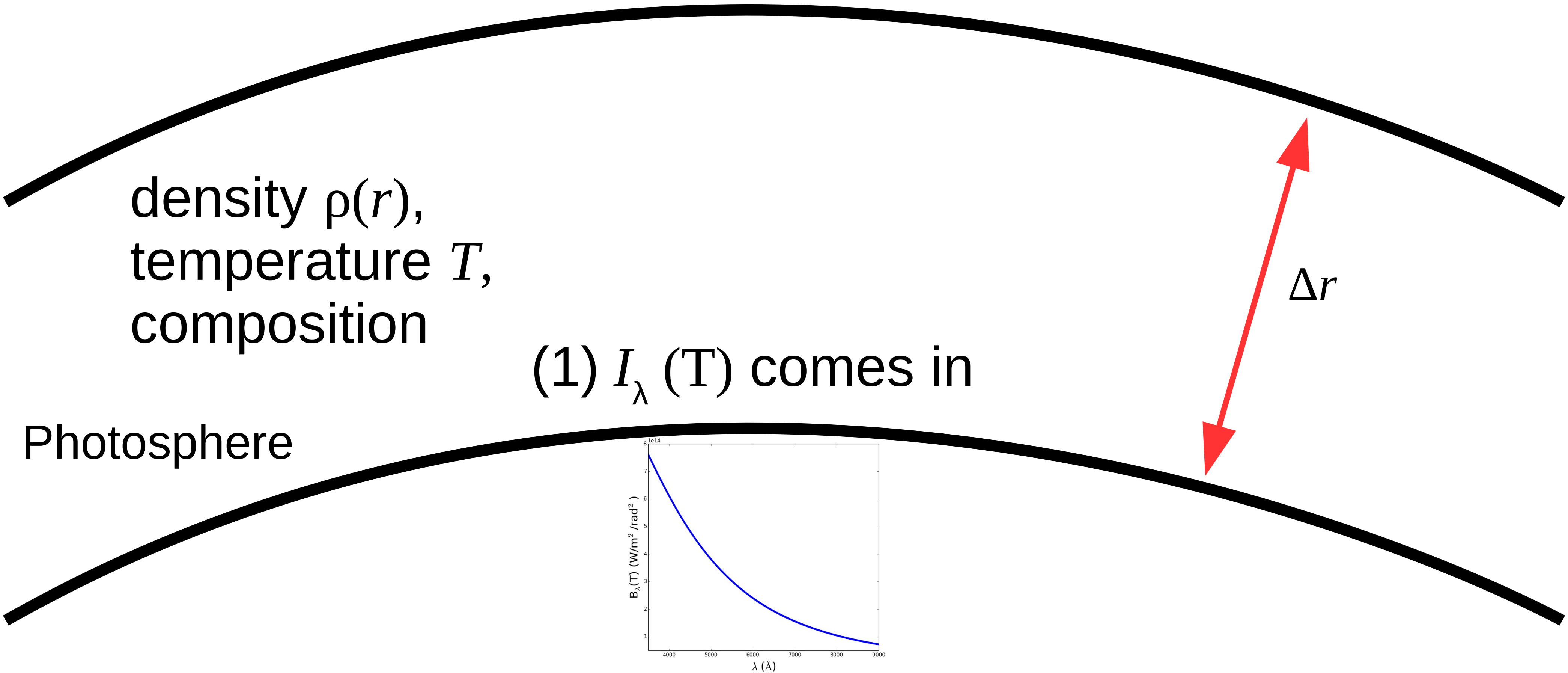
4. Emission *versus* Absorption: A Physical Approach



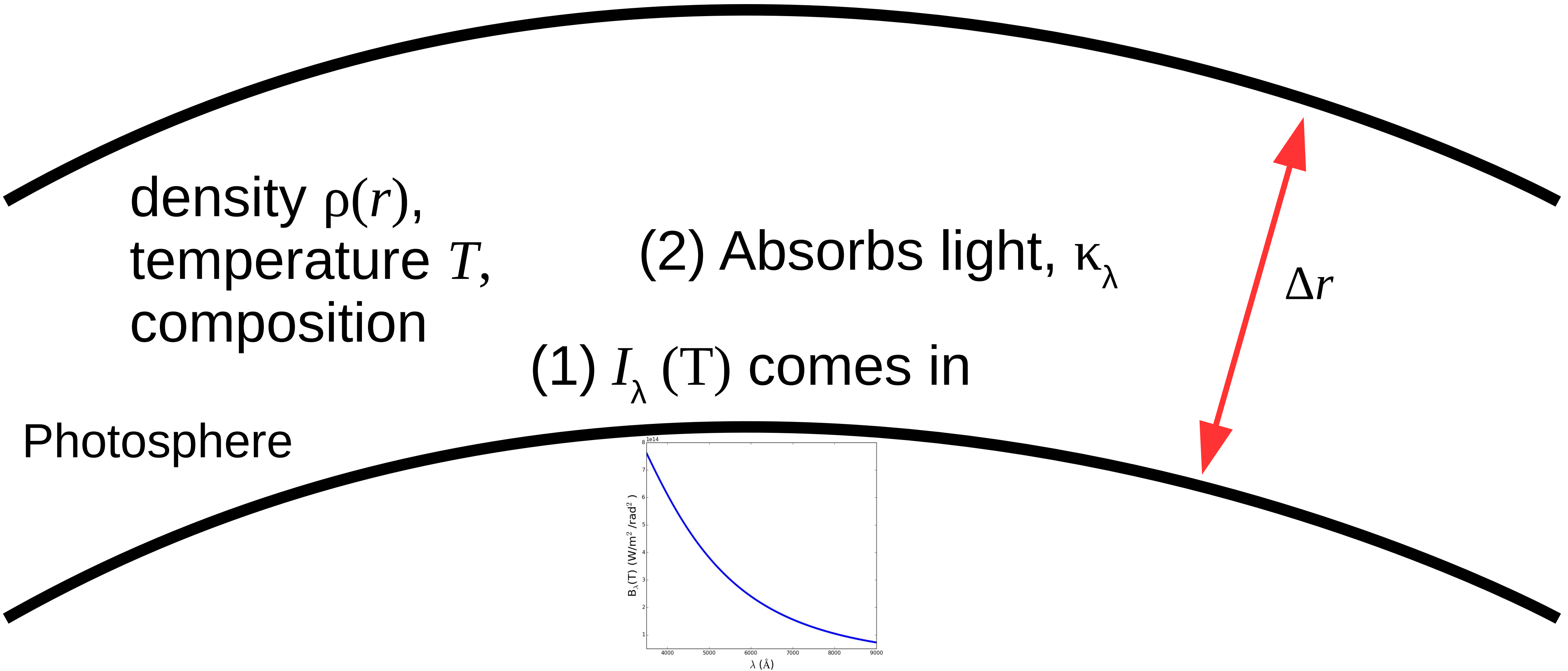
4. Emission *versus* Absorption: A Physical Approach



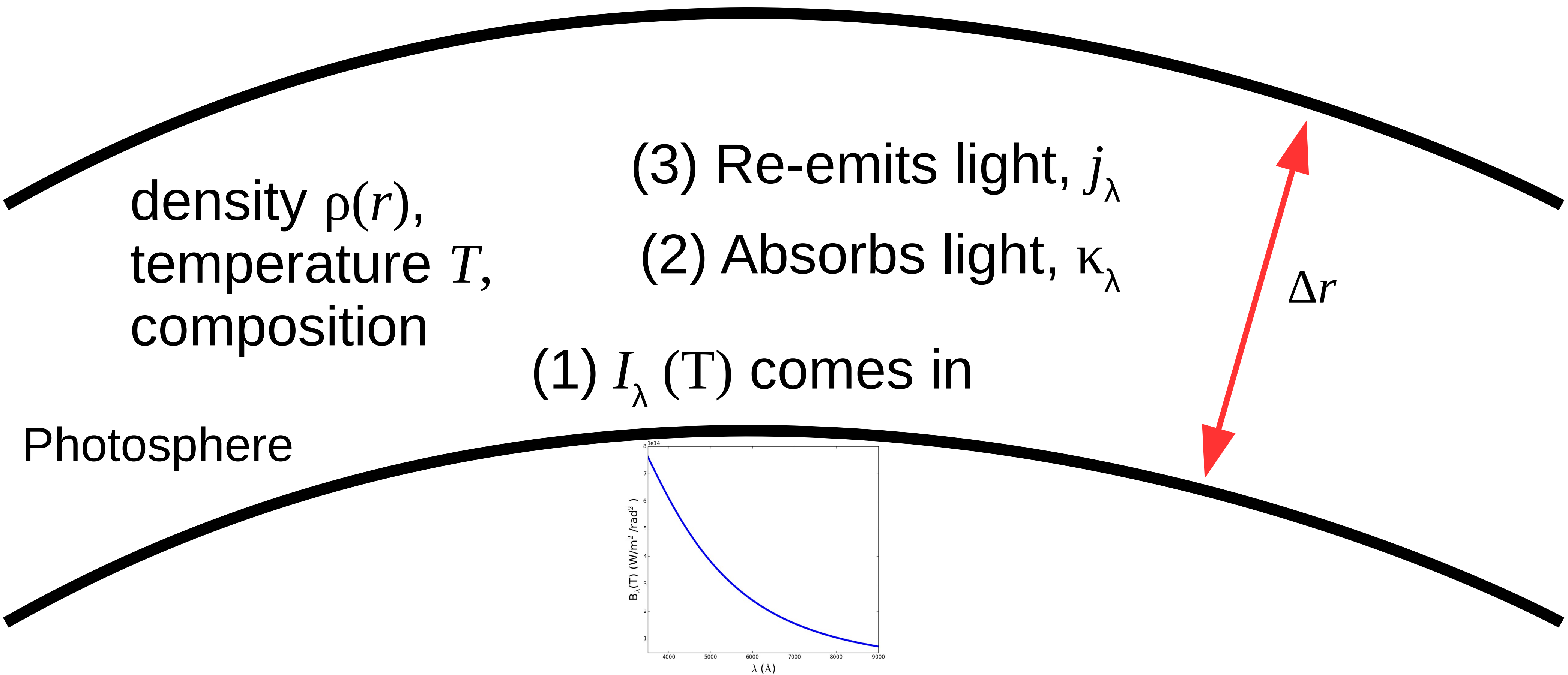
4. Emission *versus* Absorption: A Physical Approach



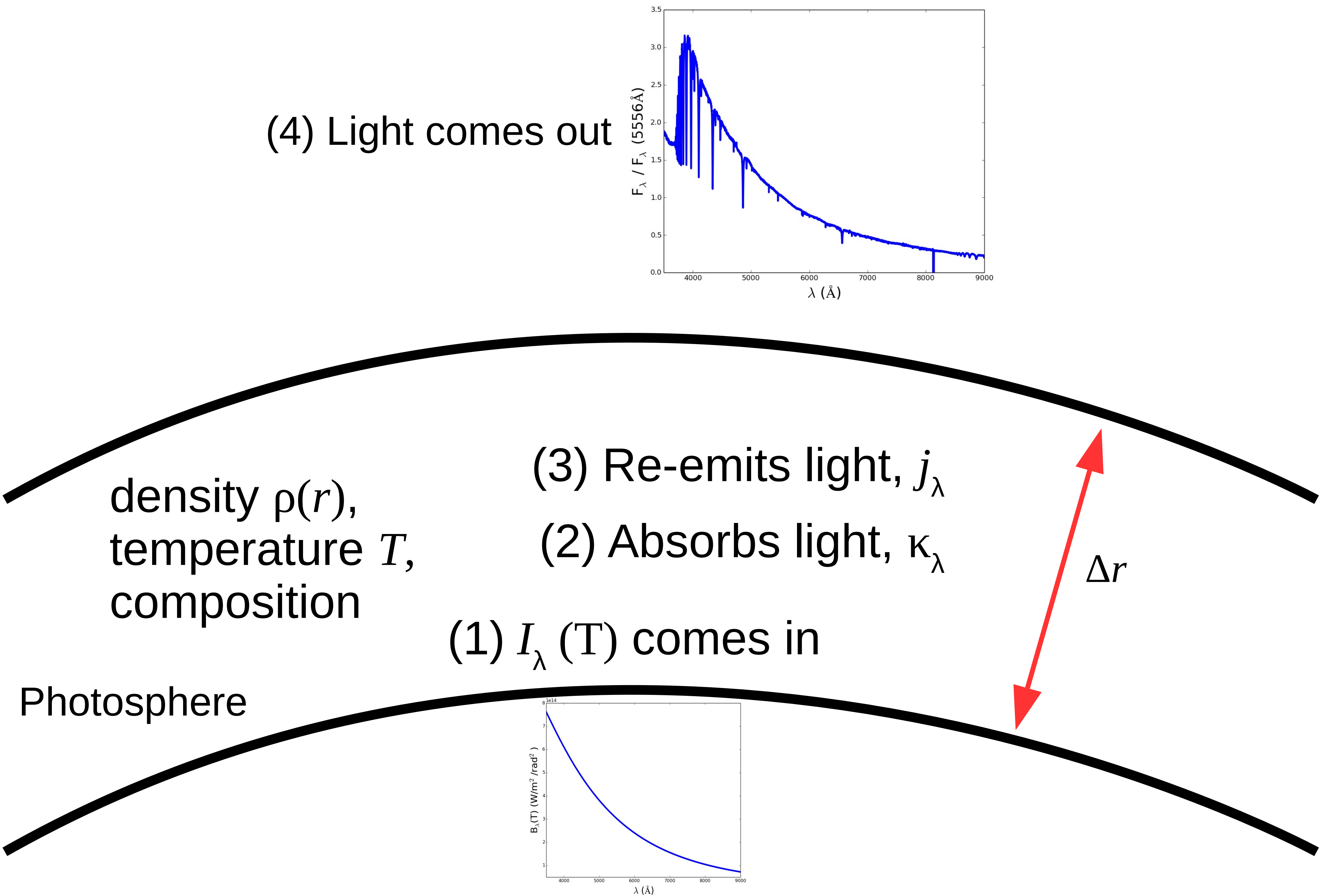
4. Emission *versus* Absorption: A Physical Approach



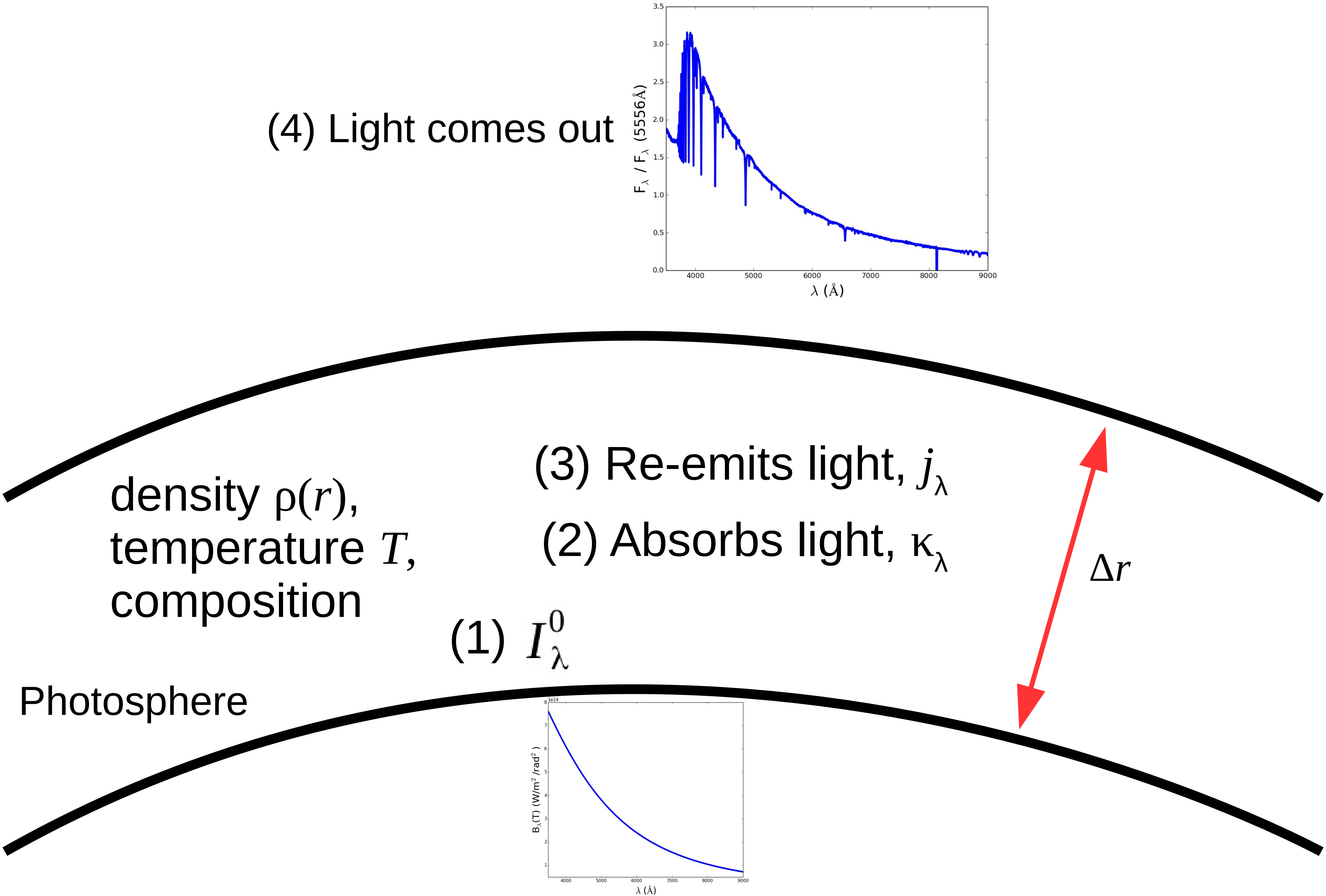
4. Emission *versus* Absorption: A Physical Approach



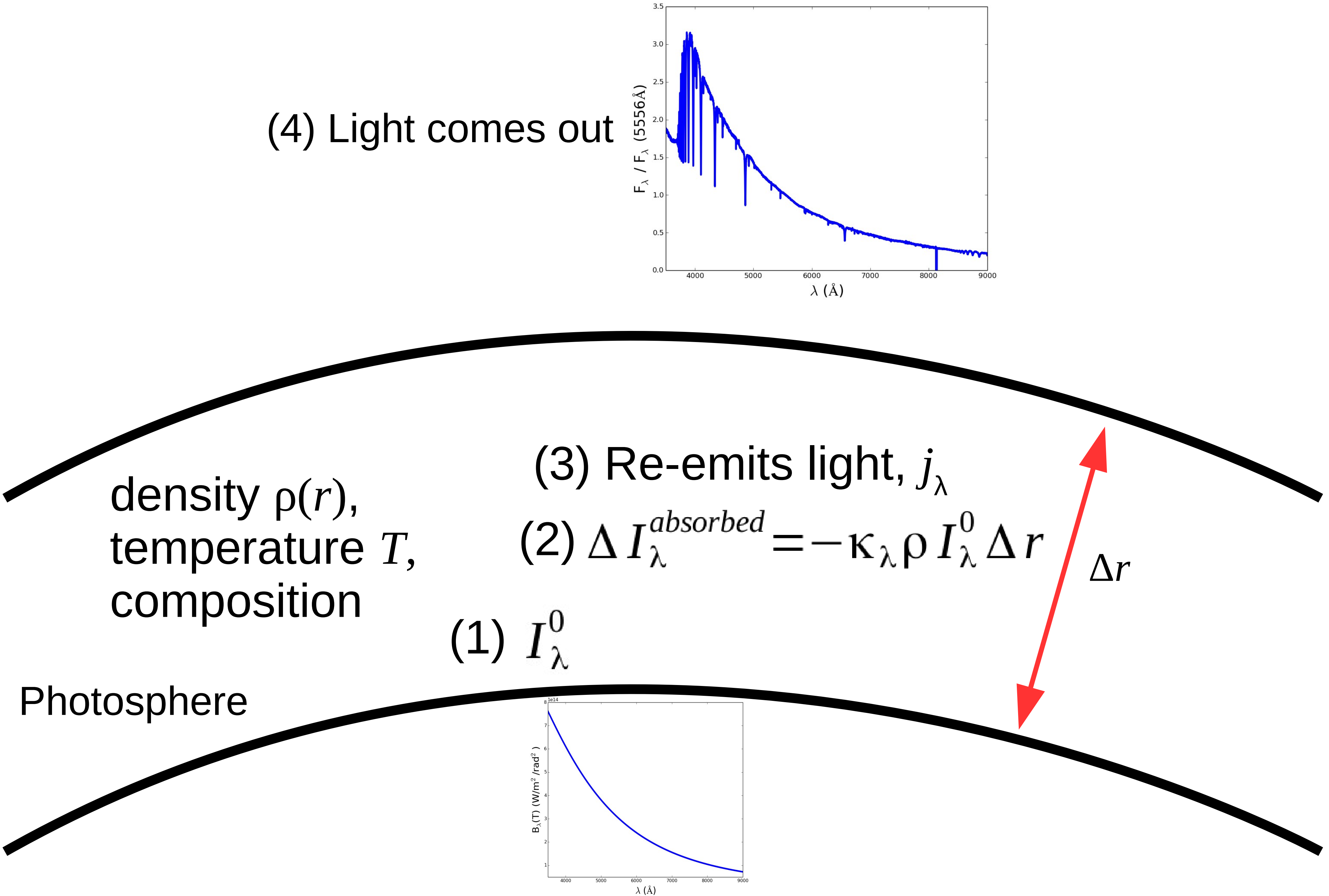
4. Emission *versus* Absorption: A Physical Approach



4. Emission *versus* Absorption: A Physical Approach

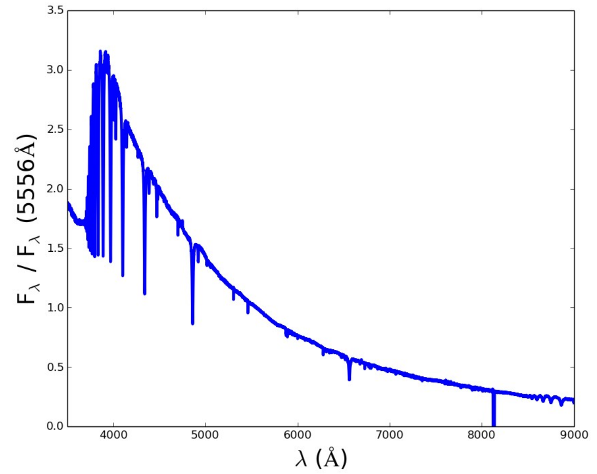


4. Emission *versus* Absorption: A Physical Approach



4. Emission *versus* Absorption: A Physical Approach

(4) Light comes out



(3) $\Delta I_\lambda^{emitted} = j_\lambda \rho \Delta r$

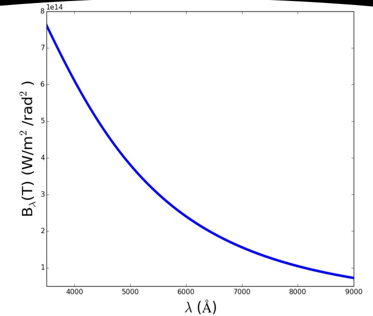
density $\rho(r)$, temperature T, composition

(2) $\Delta I_\lambda^{absorbed} = -\kappa_\lambda \rho I_\lambda^0 \Delta r$

Δr

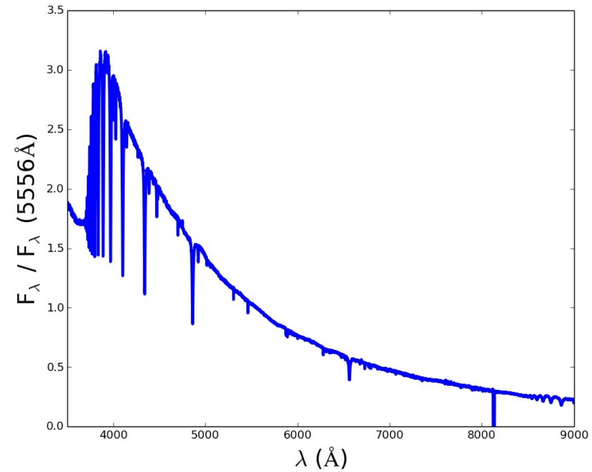
(1) I_λ^0

Photosphere



4. Emission *versus* Absorption: A Physical Approach

(4) $I_\lambda = I_\lambda^0 + \Delta I_\lambda^{absorbed} + \Delta I_\lambda^{emitted}$



density $\rho(r)$,
temperature T,
composition

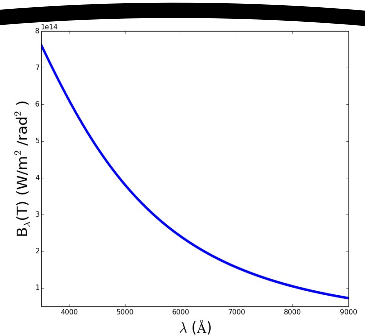
(3) $\Delta I_\lambda^{emitted} = j_\lambda \rho \Delta r$

(2) $\Delta I_\lambda^{absorbed} = -\kappa_\lambda \rho I_\lambda^0 \Delta r$

(1) I_λ^0

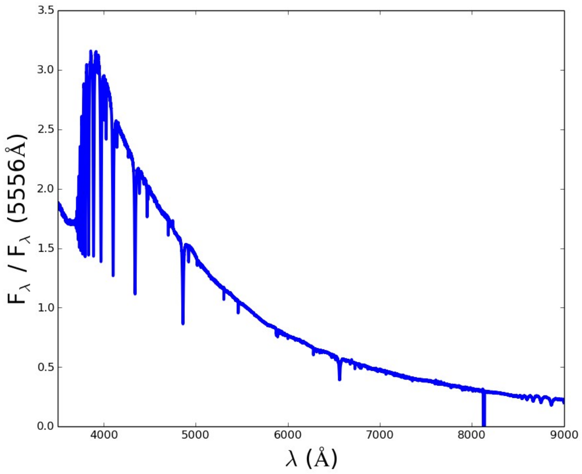
Δr

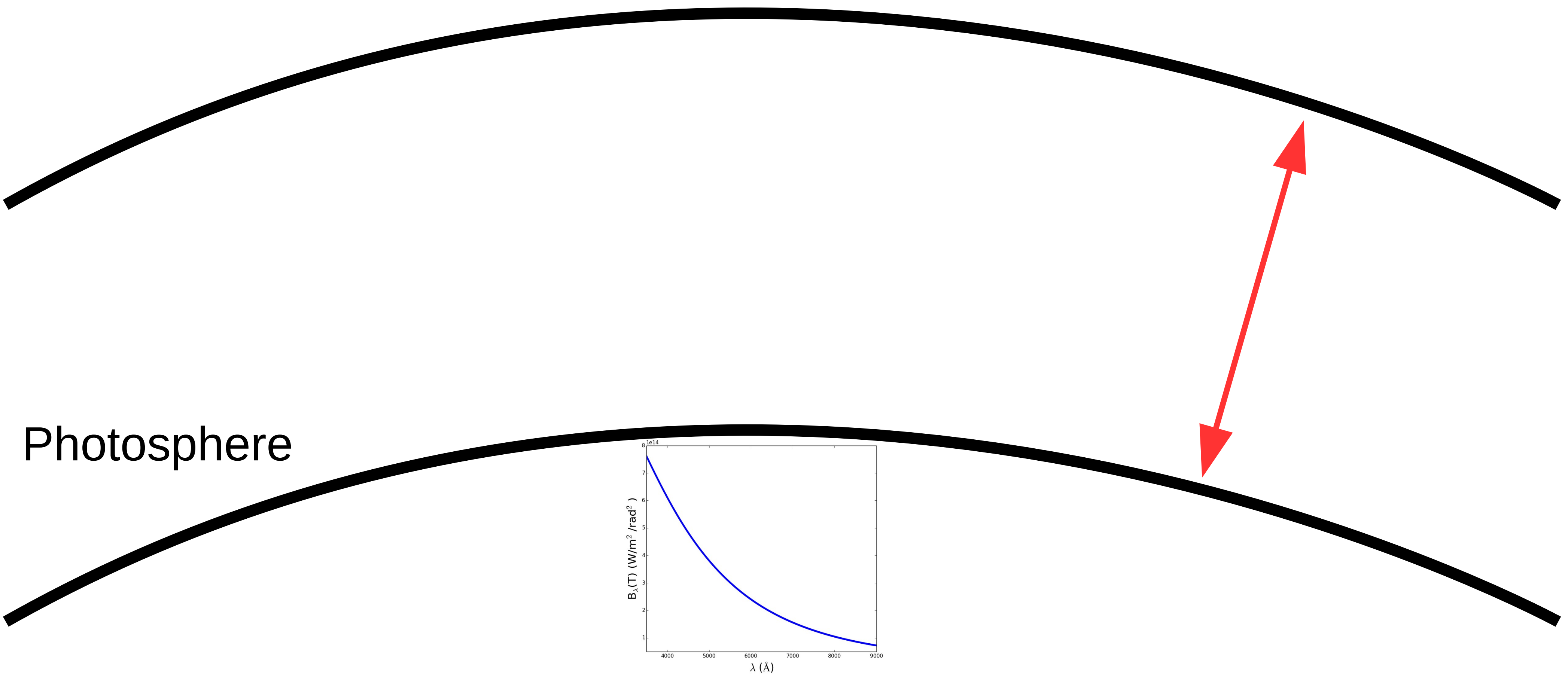
Photosphere



4. Emission *versus* Absorption: A Physical Approach

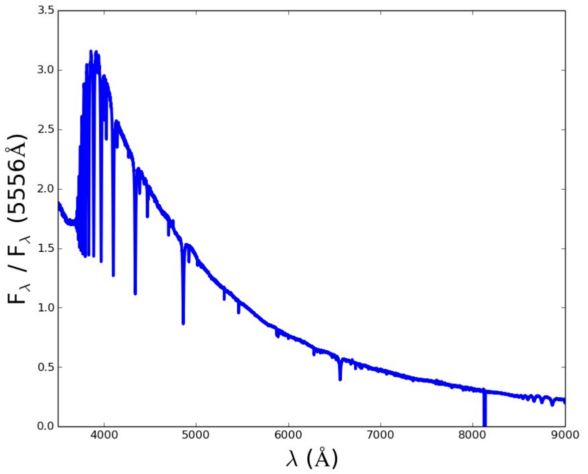
$$I_\lambda = I_\lambda^0 + \Delta I_\lambda^{absorbed} + \Delta I_\lambda^{emitted}$$





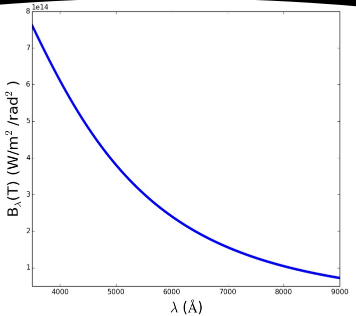
4. Emission *versus* Absorption: A Physical Approach

$$I_\lambda = I_\lambda^0 + \Delta I_\lambda^{absorbed} + \Delta I_\lambda^{emitted}$$



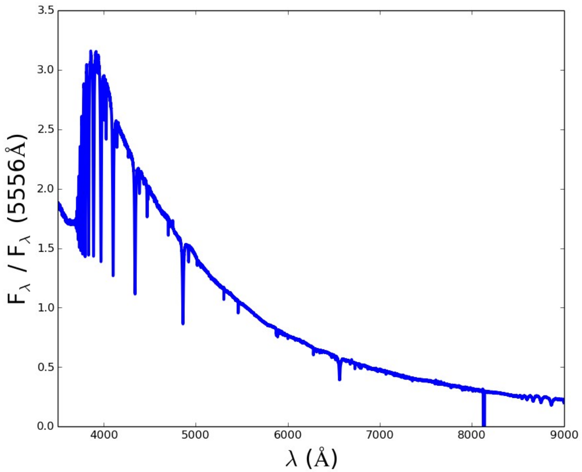
$$\Delta \tau_\lambda = \kappa_\lambda \rho \Delta r$$

Photosphere



4. Emission *versus* Absorption: A Physical Approach

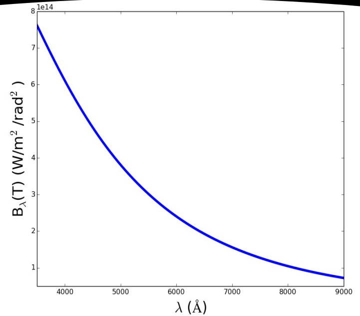
$$I_\lambda = I_\lambda^0 + \Delta I_\lambda^{absorbed} + \Delta I_\lambda^{emitted}$$



$$S_\lambda = \frac{j_\lambda}{\kappa_\lambda}$$

$$\Delta \tau_\lambda = \kappa_\lambda \rho \Delta r$$

Photosphere



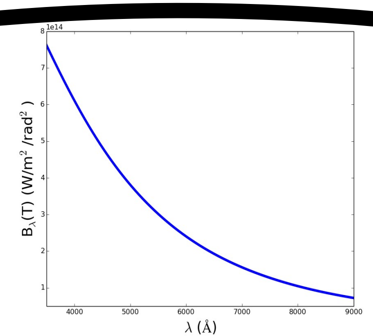
4. Emission *versus* Absorption: A Physical Approach

$$I_\lambda = I_\lambda^0 e^{-\tau_\lambda} + S_\lambda \left(1 - e^{-\tau_\lambda}\right)$$

$$S_\lambda = \frac{j_\lambda}{\kappa_\lambda}$$

$$\Delta \tau_\lambda = \kappa_\lambda \rho \Delta r$$

Photosphere



4. Emission *versus* Absorption: A Physical Approach

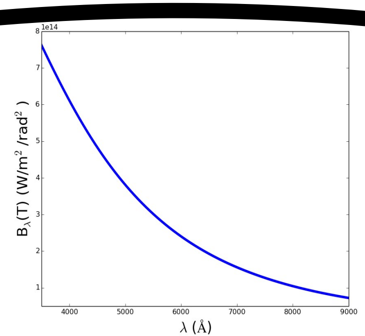
$$I_\lambda = I_\lambda^0 e^{-\tau_\lambda} + S_\lambda \left(1 - e^{-\tau_\lambda}\right)$$

(light taken out)

$$S_\lambda = \frac{j_\lambda}{\kappa_\lambda}$$

$$\Delta \tau_\lambda = \kappa_\lambda \rho \Delta r$$

Photosphere



4. Emission *versus* Absorption: A Physical Approach

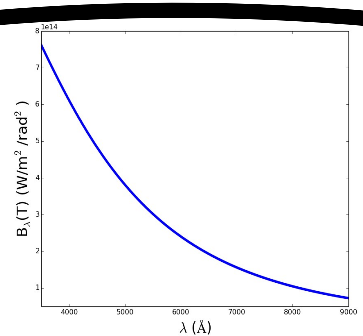
$$I_\lambda = I_\lambda^0 e^{-\tau_\lambda} + S_\lambda \left(1 - e^{-\tau_\lambda}\right)$$

(light taken out) (light added by the cloud)

$$S_\lambda = \frac{j_\lambda}{\kappa_\lambda}$$

$$\Delta \tau_\lambda = \kappa_\lambda \rho \Delta r$$

Photosphere



4. Emission *versus* Absorption: A Physical Approach

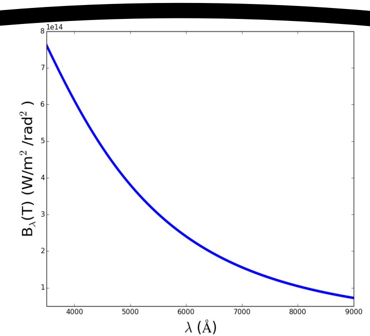
$$I_\lambda = I_\lambda^0 e^{-\tau_\lambda} + S_\lambda\left(1 - e^{-\tau_\lambda}\right)$$

(final intensity) (light taken out) (light added by the cloud)

$$S_\lambda = \frac{j_\lambda}{\kappa_\lambda}$$

$$\Delta\tau_\lambda = \kappa_\lambda \rho \Delta r$$

Photosphere



4. Emission *versus* Absorption: A Physical Approach

$$I_\lambda = I_\lambda^0 e^{-\tau_\lambda} + S_\lambda \left(1 - e^{-\tau_\lambda}\right)$$

4. Emission *versus* Absorption: A Physical Approach

$$I_\lambda = I_\lambda^0 e^{-\tau_\lambda} + S_\lambda\left(1 - e^{-\tau_\lambda}\right)$$

Limit A. The cloud layer is optically thick

4. Emission *versus* Absorption: A Physical Approach

$$I_\lambda = I_\lambda^0 e^{-\tau_\lambda} + S_\lambda \left(1 - e^{-\tau_\lambda}\right)$$

Limit A. The cloud layer is optically thick

$$\tau_\lambda \rightarrow \infty$$

4. Emission *versus* Absorption: A Physical Approach

$$I_\lambda = I_\lambda^0 e^{-\tau_\lambda} + S_\lambda \left(1 - e^{-\tau_\lambda}\right)$$

Limit A. The cloud layer is optically thick

$$\tau_\lambda \rightarrow \infty$$

$$e^{-\tau_\lambda} \rightarrow 0$$

4. Emission *versus* Absorption: A Physical Approach

$$I_\lambda = I_\lambda^0 e^{-\tau_\lambda} + S_\lambda \left(1 - e^{-\tau_\lambda}\right)$$

Limit A. The cloud layer is optically thick

$$\tau_\lambda \rightarrow \infty$$

$$e^{-\tau_\lambda} \rightarrow 0$$

$$I_\lambda \rightarrow S_\lambda$$

4. Emission *versus* Absorption: A Physical Approach

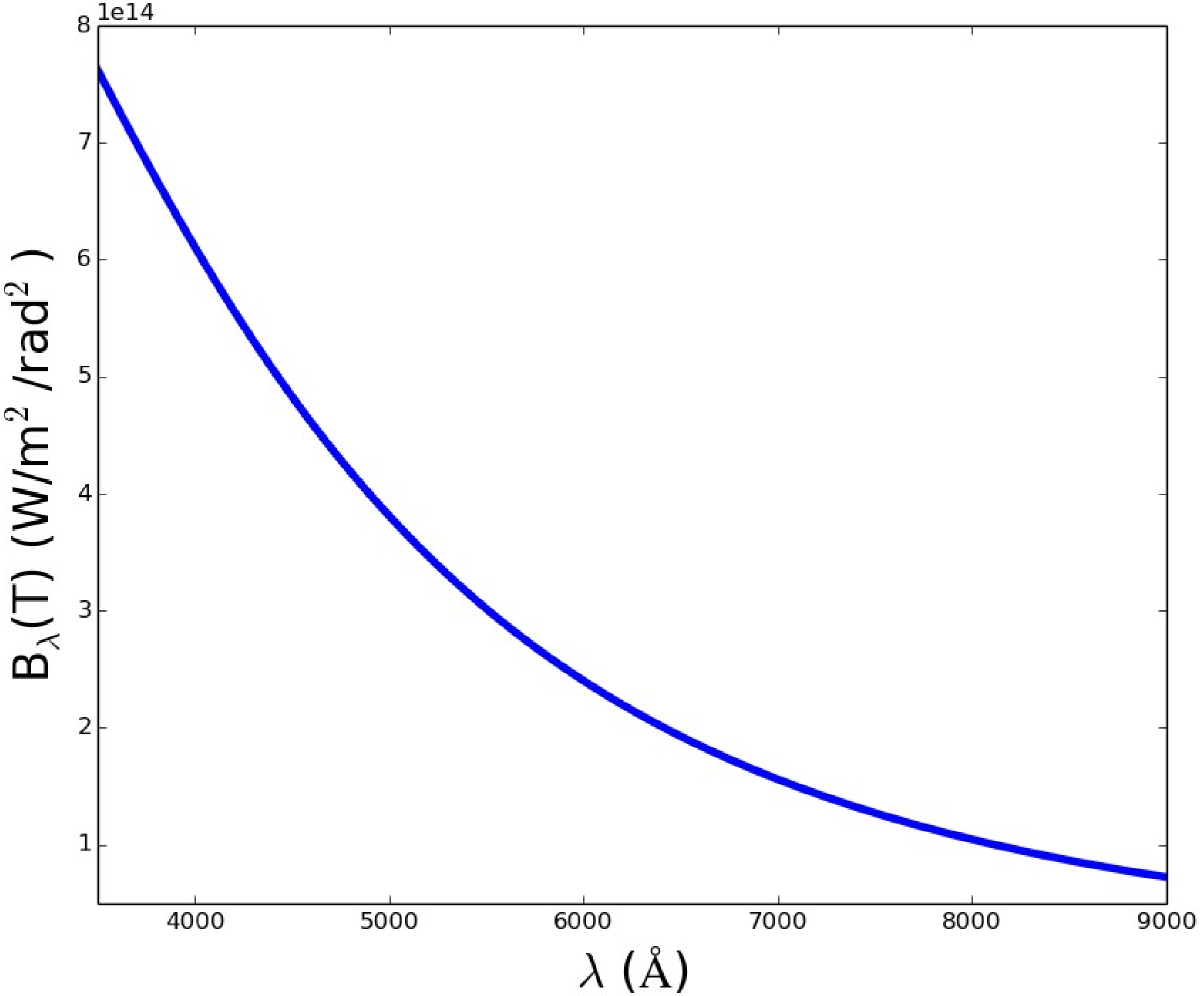
$$I_\lambda = I_\lambda^0 e^{-\tau_\lambda} + S_\lambda \left(1 - e^{-\tau_\lambda}\right)$$

Limit A. The cloud layer is optically thick

$$\tau_\lambda \rightarrow \infty$$

$$e^{-\tau_\lambda} \rightarrow 0$$

$$I_\lambda \rightarrow S_\lambda$$



4. Emission *versus* Absorption: A Physical Approach

$$I_\lambda = I_\lambda^0 e^{-\tau_\lambda} + S_\lambda \left(1 - e^{-\tau_\lambda}\right)$$

Limit B.

4. Emission *versus* Absorption: A Physical Approach

$$I_\lambda = I_\lambda^0 e^{-\tau_\lambda} + S_\lambda \left(1 - e^{-\tau_\lambda}\right)$$

Limit B. The cloud layer is optically thin

4. Emission *versus* Absorption: A Physical Approach

$$I_\lambda = I_\lambda^0 e^{-\tau_\lambda} + S_\lambda \left(1 - e^{-\tau_\lambda}\right)$$

Limit B. The cloud layer is optically thin

$$e^{-\tau_\lambda} \rightarrow 1 - \tau_\lambda$$

4. Emission *versus* Absorption: A Physical Approach

$$I_\lambda = I_\lambda^0 e^{-\tau_\lambda} + S_\lambda \left(1 - e^{-\tau_\lambda}\right)$$

Limit B. The cloud layer is optically thin

$$e^{-\tau_\lambda} \rightarrow 1 - \tau_\lambda$$

$$I_\lambda = I_\lambda^0 + [S_\lambda - I_\lambda^0]\,\tau_\lambda$$

4. Emission *versus* Absorption: A Physical Approach

$$I_\lambda = I_\lambda^0 + [S_\lambda - I_\lambda^0]\tau_\lambda$$

Limit B. The cloud layer is optically thin

Case I.

4. Emission *versus* Absorption: A Physical Approach

$$I_\lambda = I_\lambda^0 + [S_\lambda - I_\lambda^0]\tau_\lambda$$

Limit B. The cloud layer is optically thin

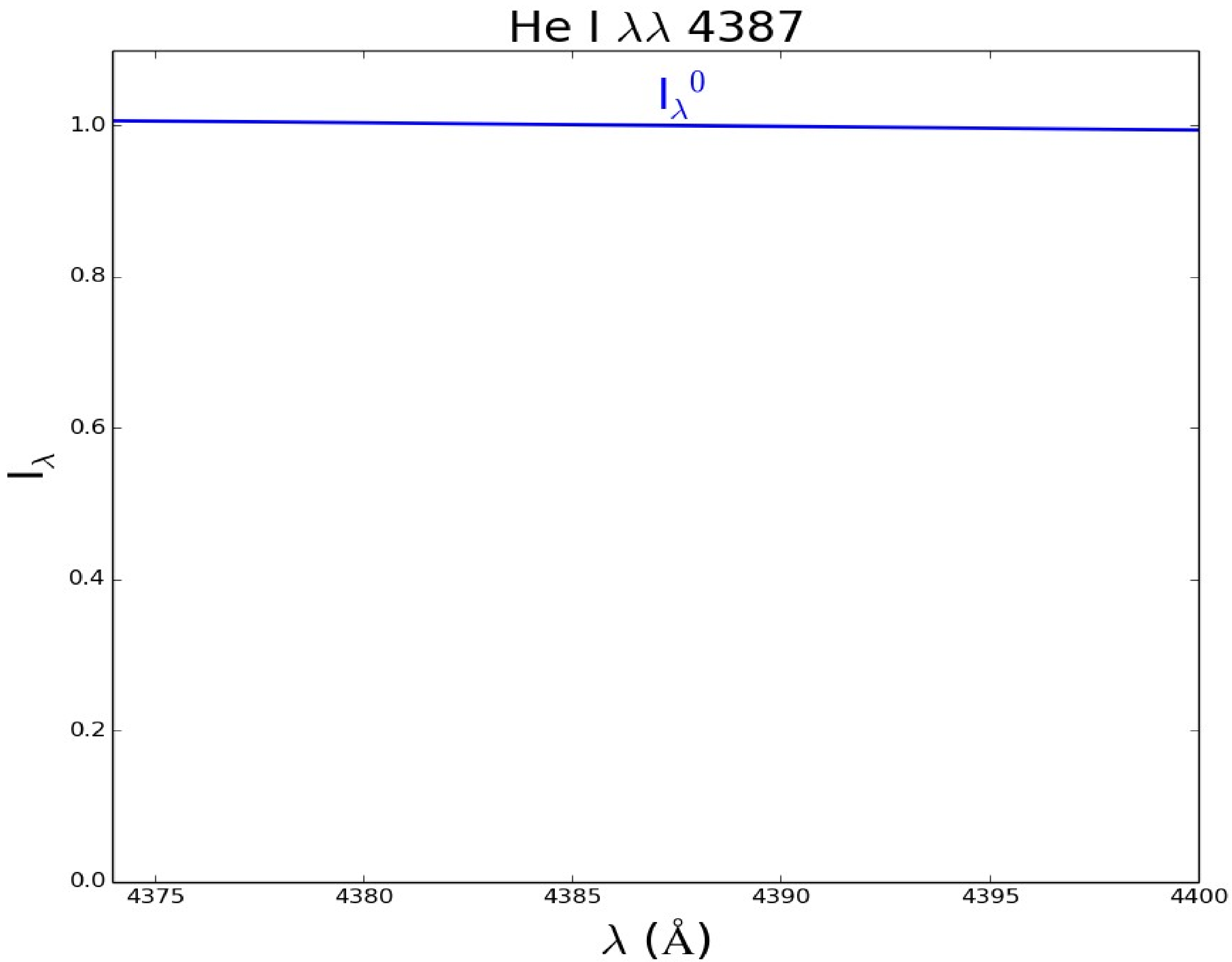
Case I. $I_\lambda^0 > S_\lambda$

4. Emission *versus* Absorption: A Physical Approach

$$I_\lambda = I_\lambda^0 + [S_\lambda - I_\lambda^0]\tau_\lambda$$

Limit B. The cloud layer is optically thin

Case I. $I_\lambda^0 > S_\lambda$

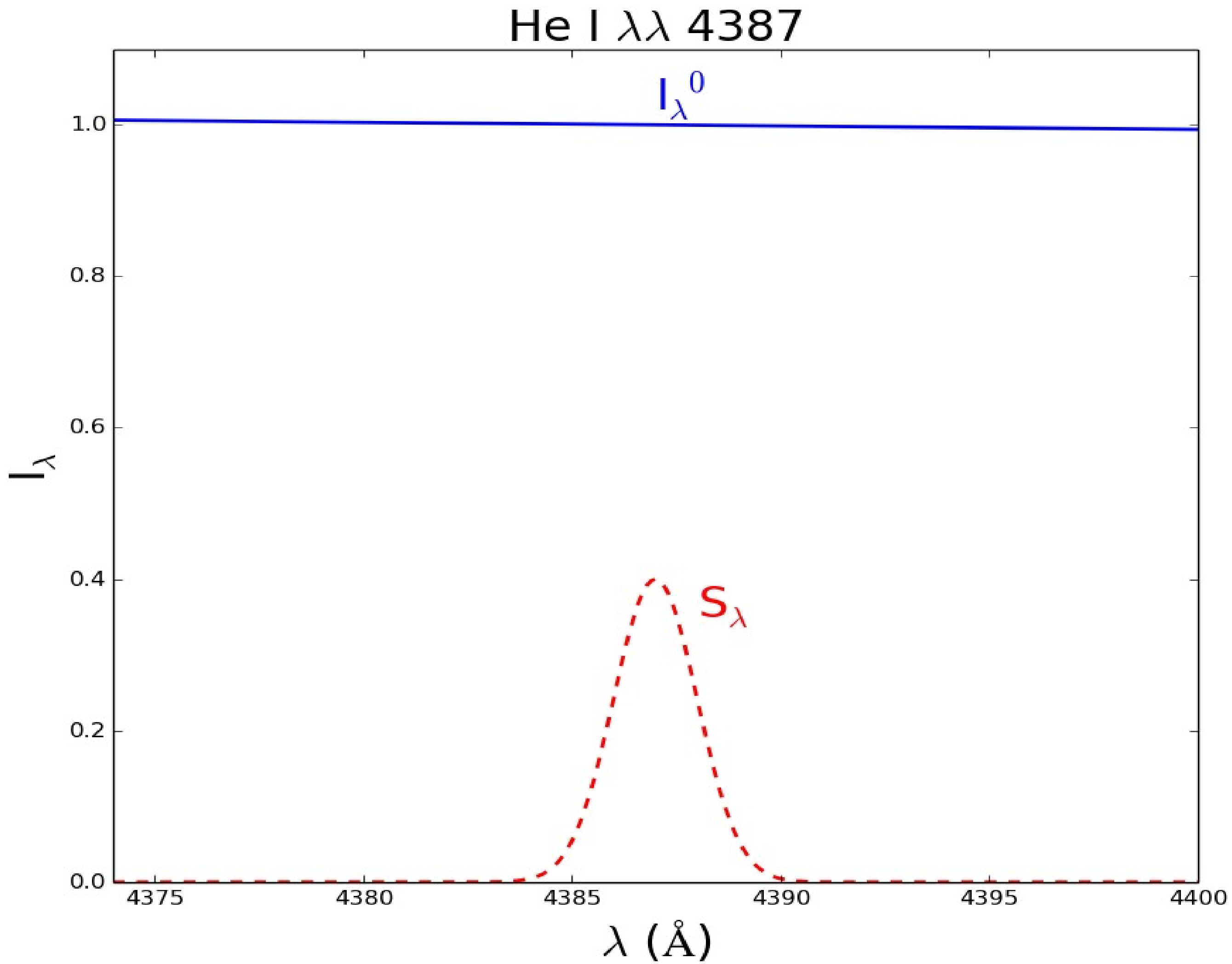


4. Emission *versus* Absorption: A Physical Approach

$$I_\lambda = I_\lambda^0 + [S_\lambda - I_\lambda^0]\tau_\lambda$$

Limit B. The cloud layer is optically thin

Case I. $I_\lambda^0 > S_\lambda$

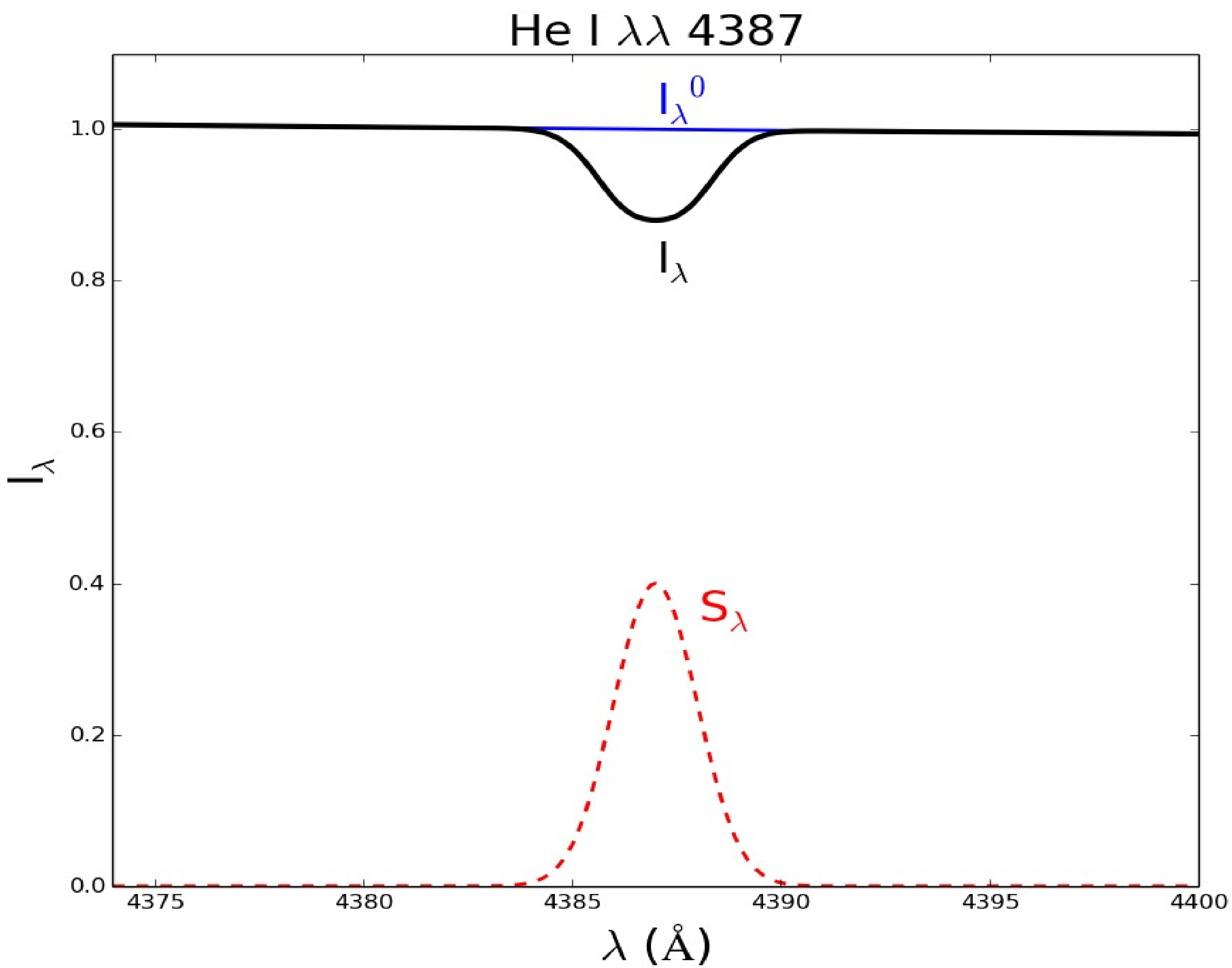


4. Emission *versus* Absorption: A Physical Approach

$$I_\lambda = I_\lambda^0 + [S_\lambda - I_\lambda^0]\tau_\lambda$$

Limit B. The cloud layer is optically thin

Case I. $I_\lambda^0 > S_\lambda$

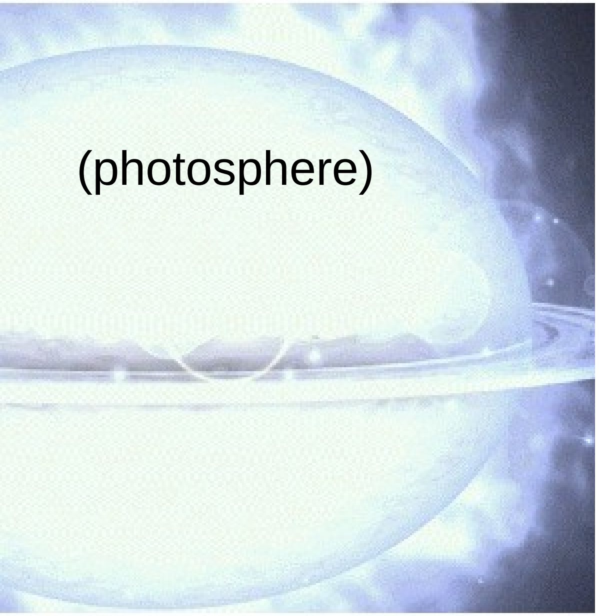


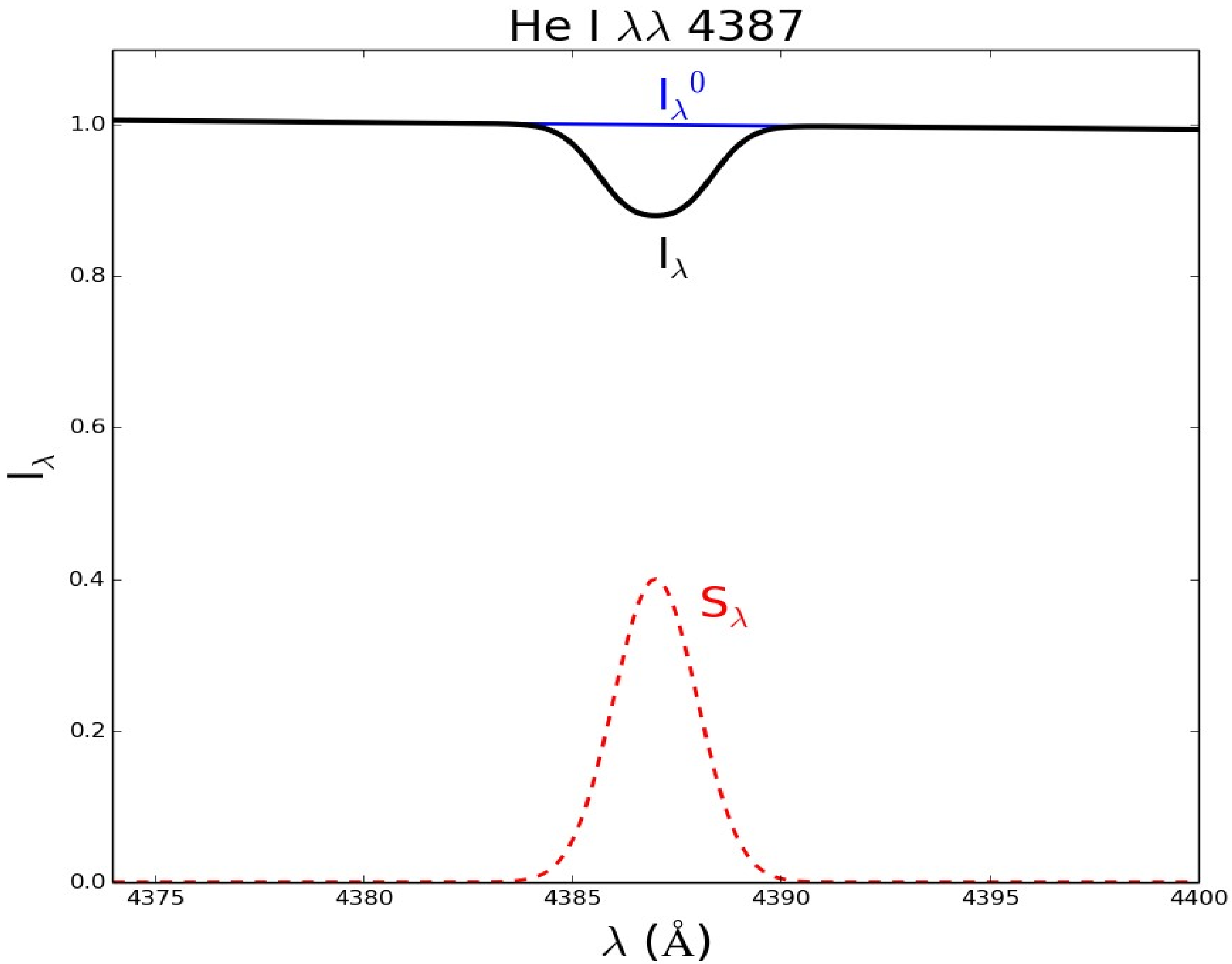
4. Emission *versus* Absorption: A Physical Approach

$$I_\lambda = I_\lambda^0 + [S_\lambda - I_\lambda^0]\tau_\lambda$$

Limit B. The cloud layer is optically thin

Case I. $I_\lambda^0 > S_\lambda$





4. Emission *versus* Absorption: A Physical Approach

$$I_\lambda = I_\lambda^0 + [S_\lambda - I_\lambda^0]\,\tau_\lambda$$

Limit B. The cloud layer is optically thin

Case II.

4. Emission *versus* Absorption: A Physical Approach

$$I_\lambda = I_\lambda^0 + [S_\lambda - I_\lambda^0]\tau_\lambda$$

Limit B. The cloud layer is optically thin

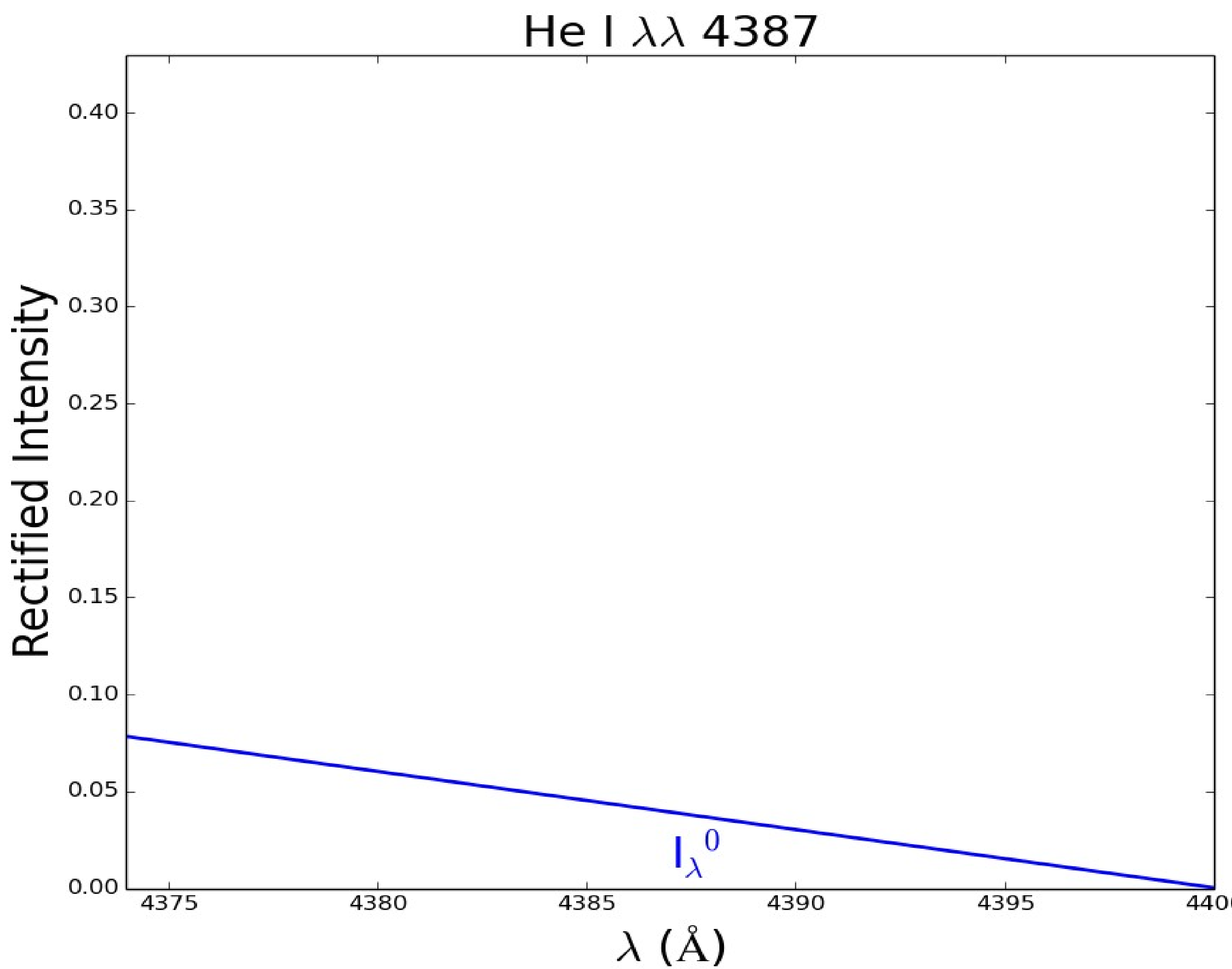
Case II. $I_\lambda{}^0 < S_\lambda$

4. Emission *versus* Absorption: A Physical Approach

$$I_\lambda = I_\lambda^0 + [S_\lambda - I_\lambda^0]\tau_\lambda$$

Limit B. The cloud layer is optically thin

Case II. $I_\lambda^0 < S_\lambda$

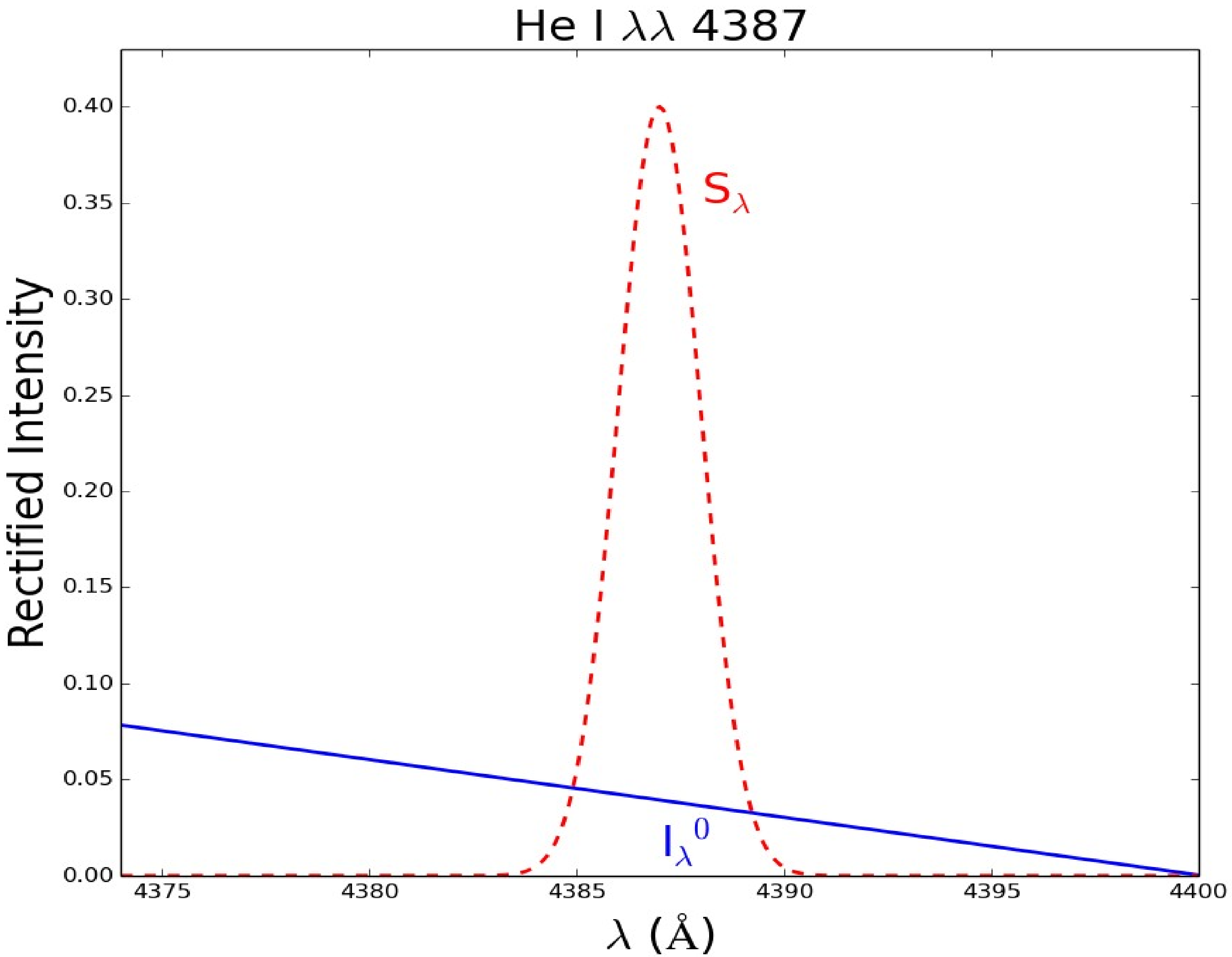


4. Emission *versus* Absorption: A Physical Approach

$$I_\lambda = I_\lambda^0 + [S_\lambda - I_\lambda^0]\tau_\lambda$$

Limit B. The cloud layer is optically thin

Case II. $I_\lambda^0 < S_\lambda$

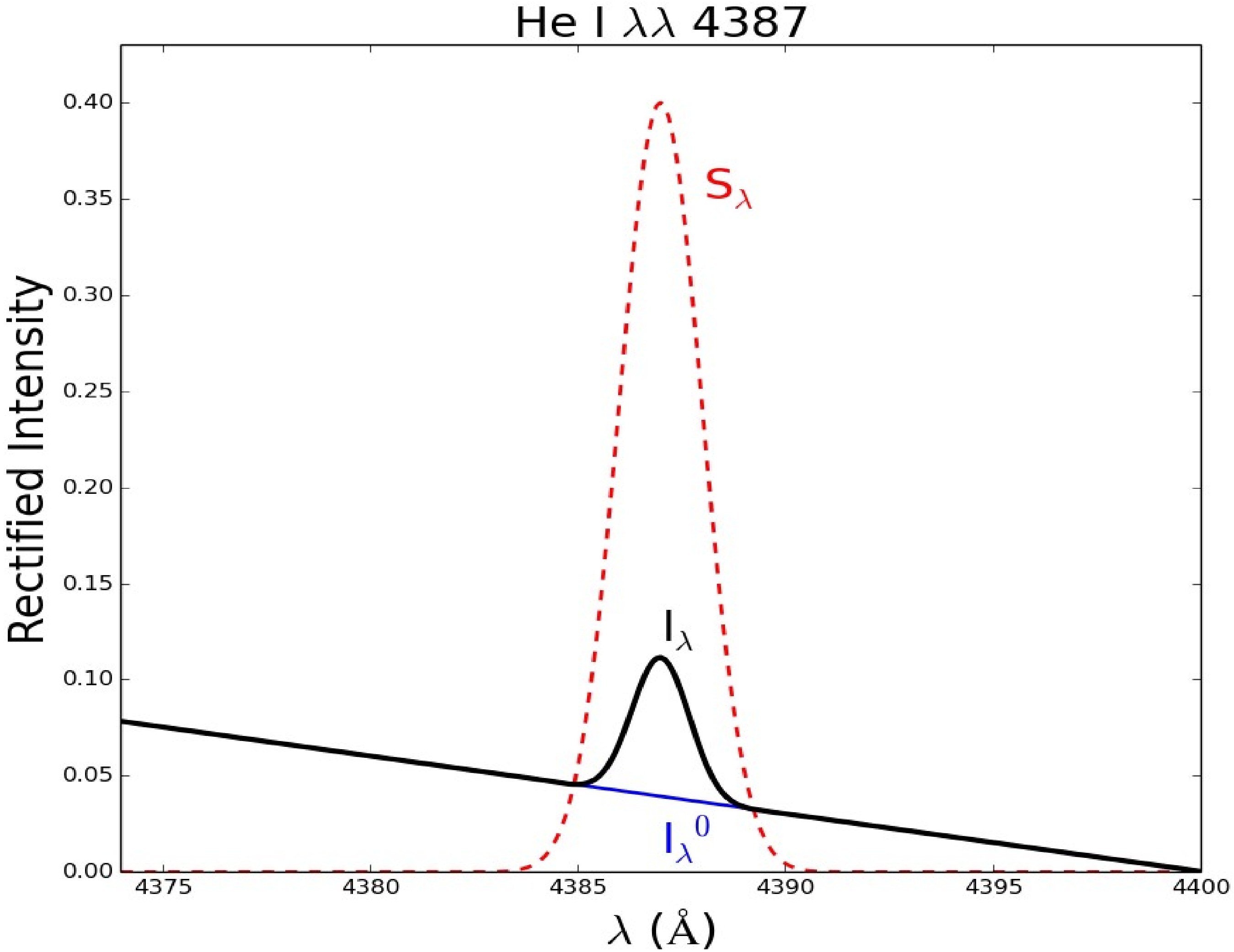


4. Emission *versus* Absorption: A Physical Approach

$$I_\lambda = I_\lambda^0 + [S_\lambda - I_\lambda^0]\tau_\lambda$$

Limit B. The cloud layer is optically thin

Case II. $I_\lambda^0 < S_\lambda$

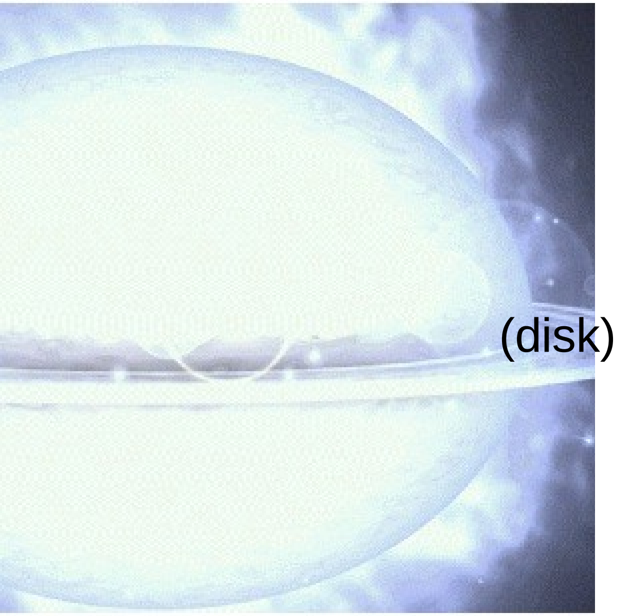


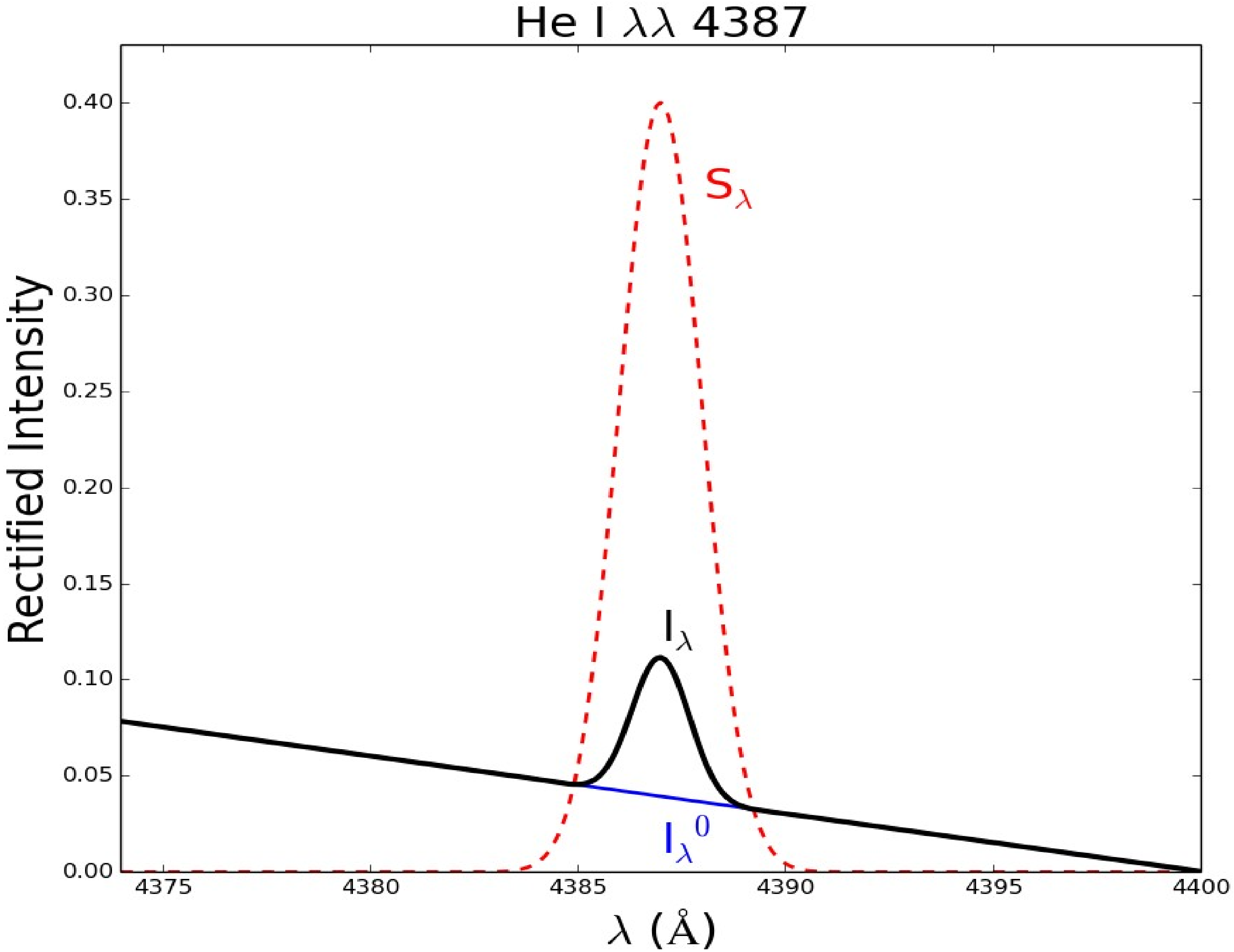
4. Emission *versus* Absorption: A Physical Approach

$$I_\lambda = I_\lambda^0 + [S_\lambda - I_\lambda^0]\tau_\lambda$$

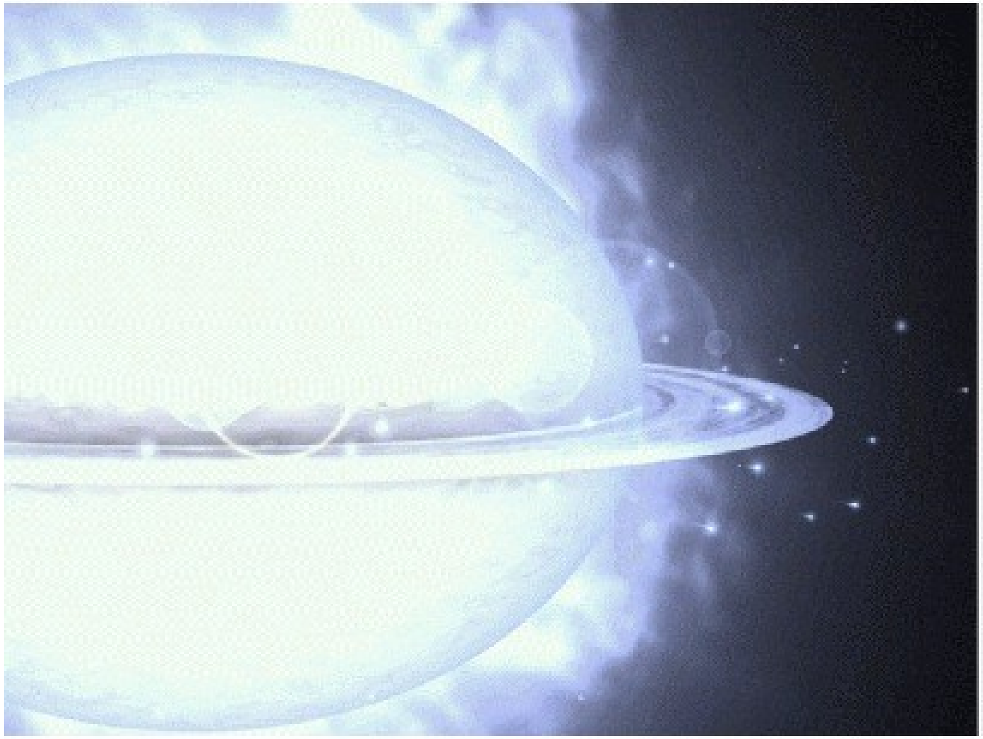
Limit B. The cloud layer is optically thin

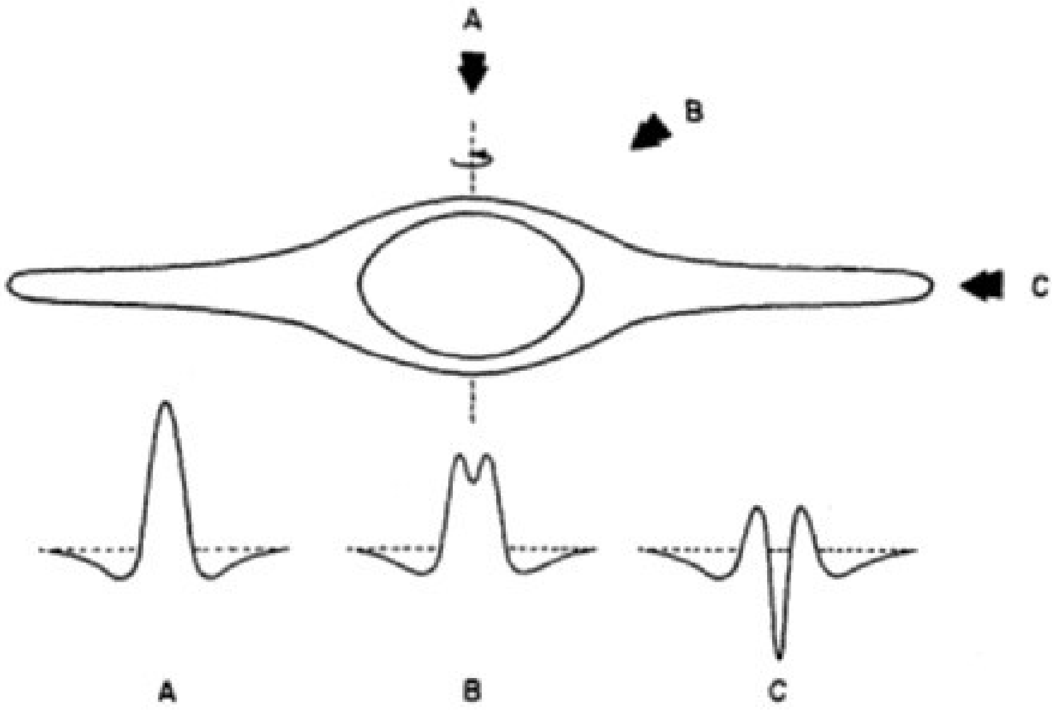
Case II. $I_\lambda^0 < S_\lambda$



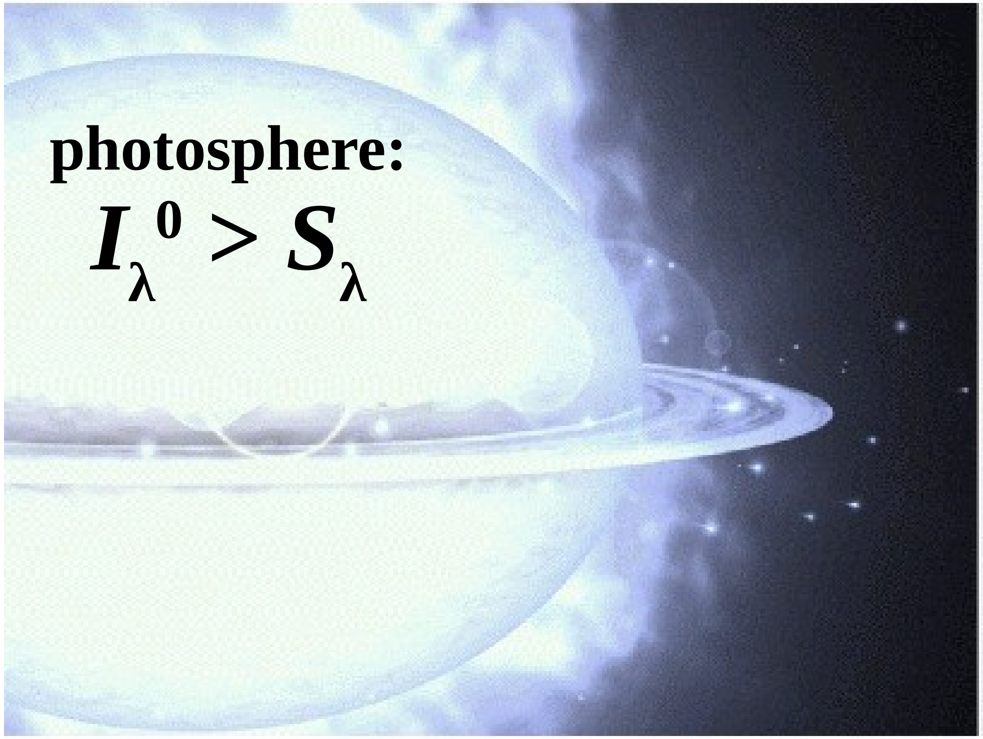


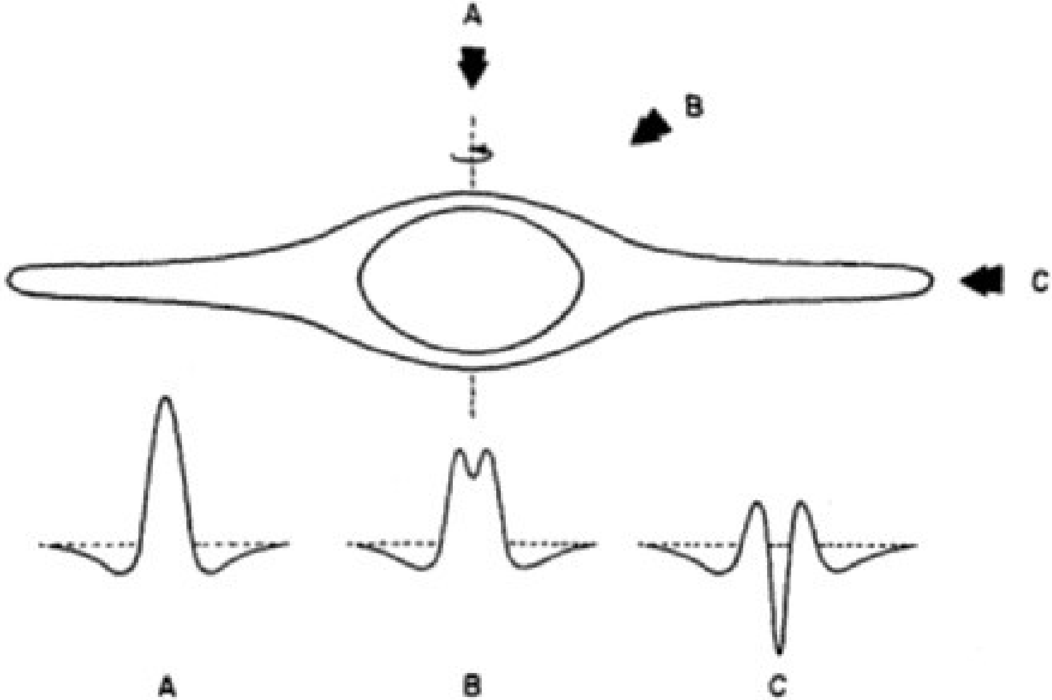
4. Emission *versus* Absorption: A Physical Approach



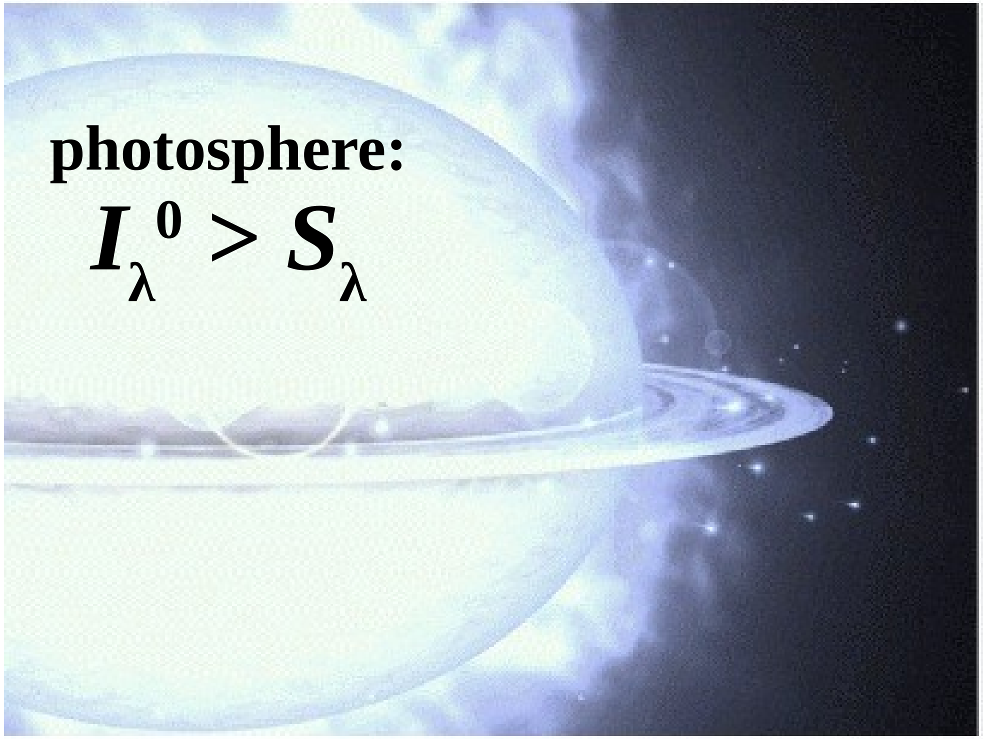


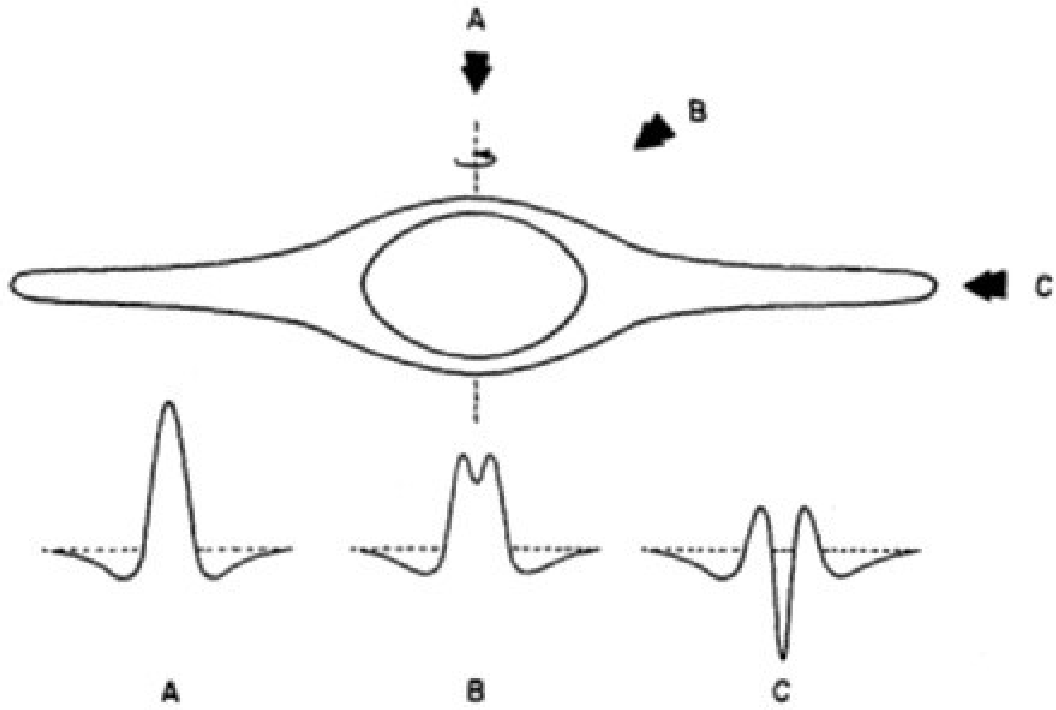
4. Emission *versus* Absorption: A Physical Approach

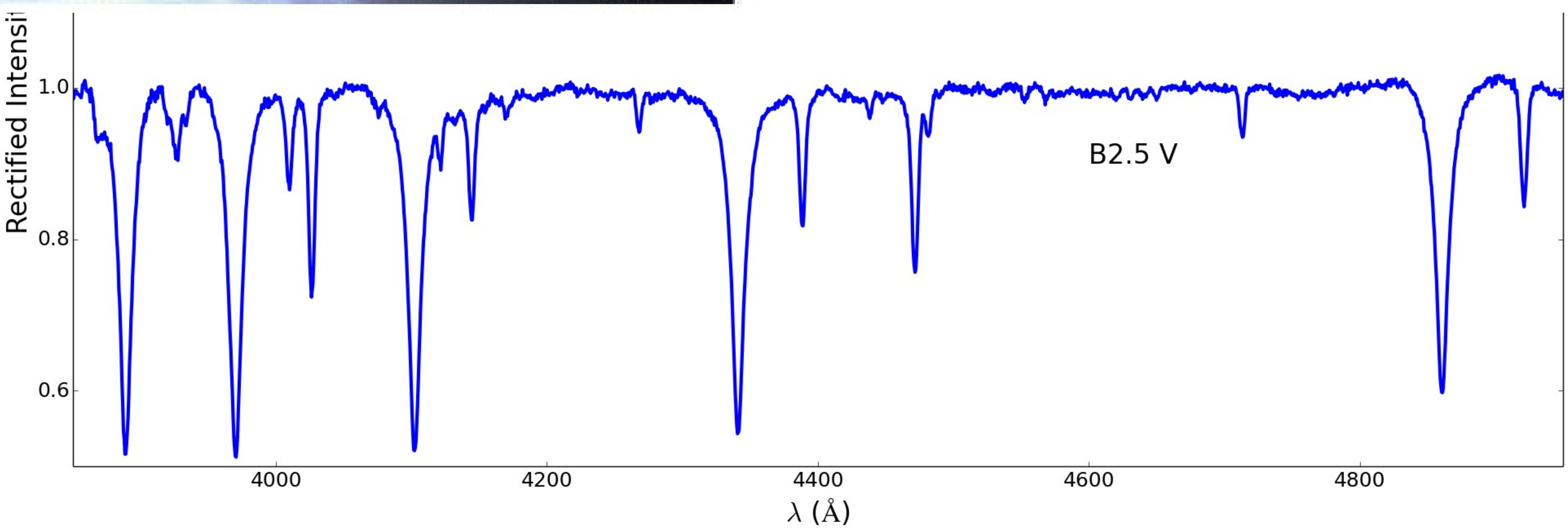




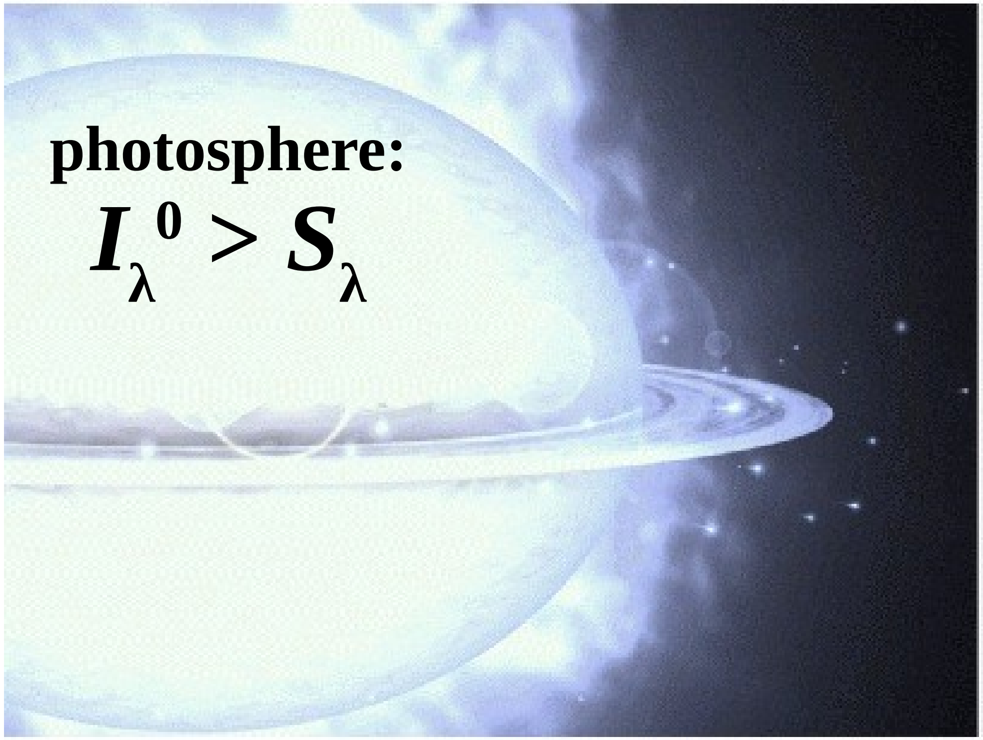
4. Emission *versus* Absorption: A Physical Approach

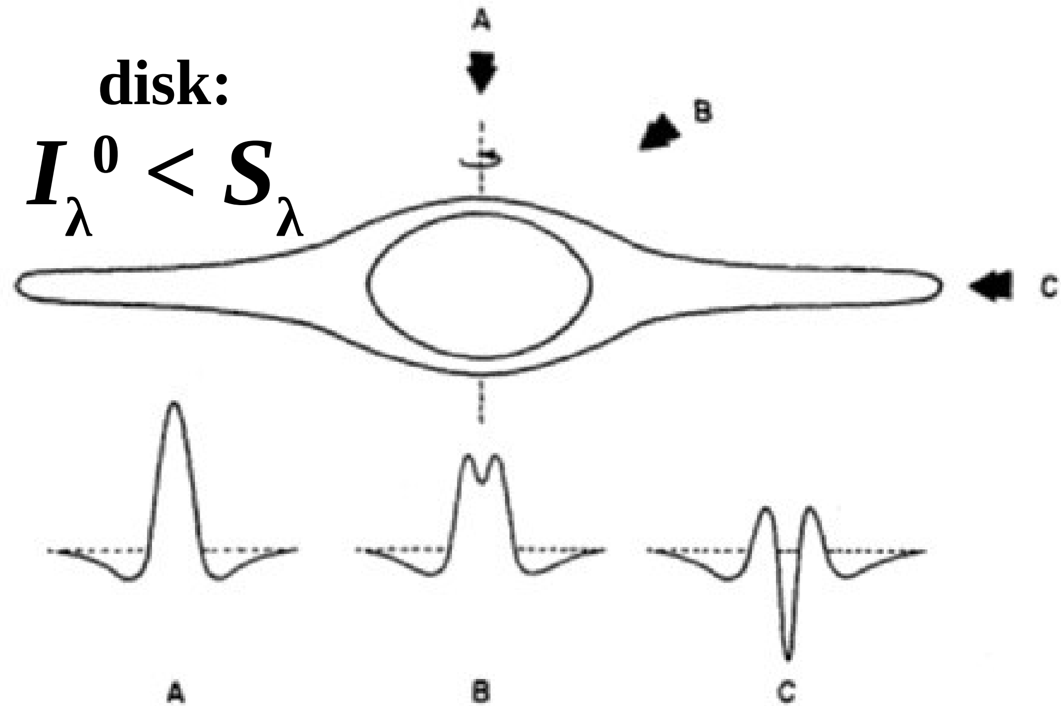




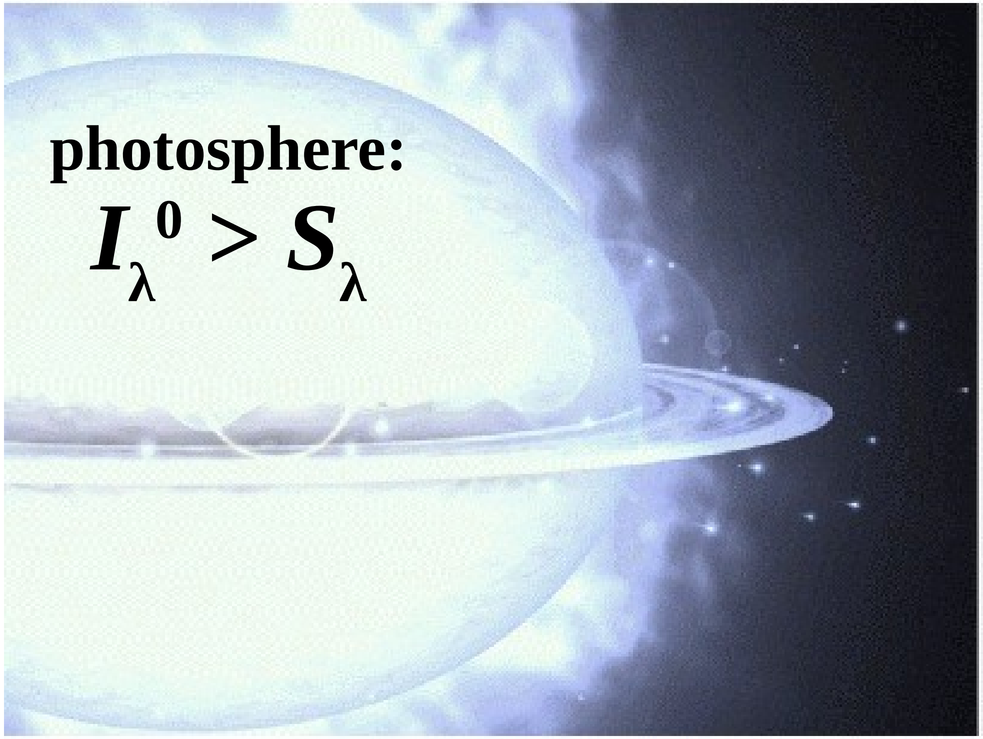


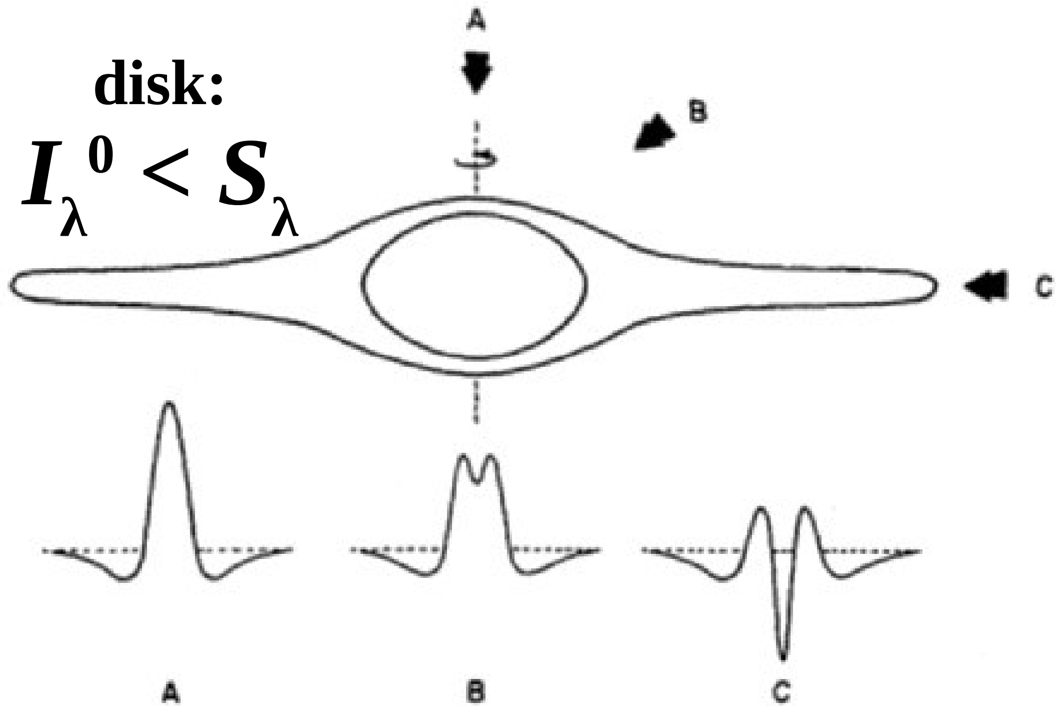
4. Emission *versus* Absorption: A Physical Approach

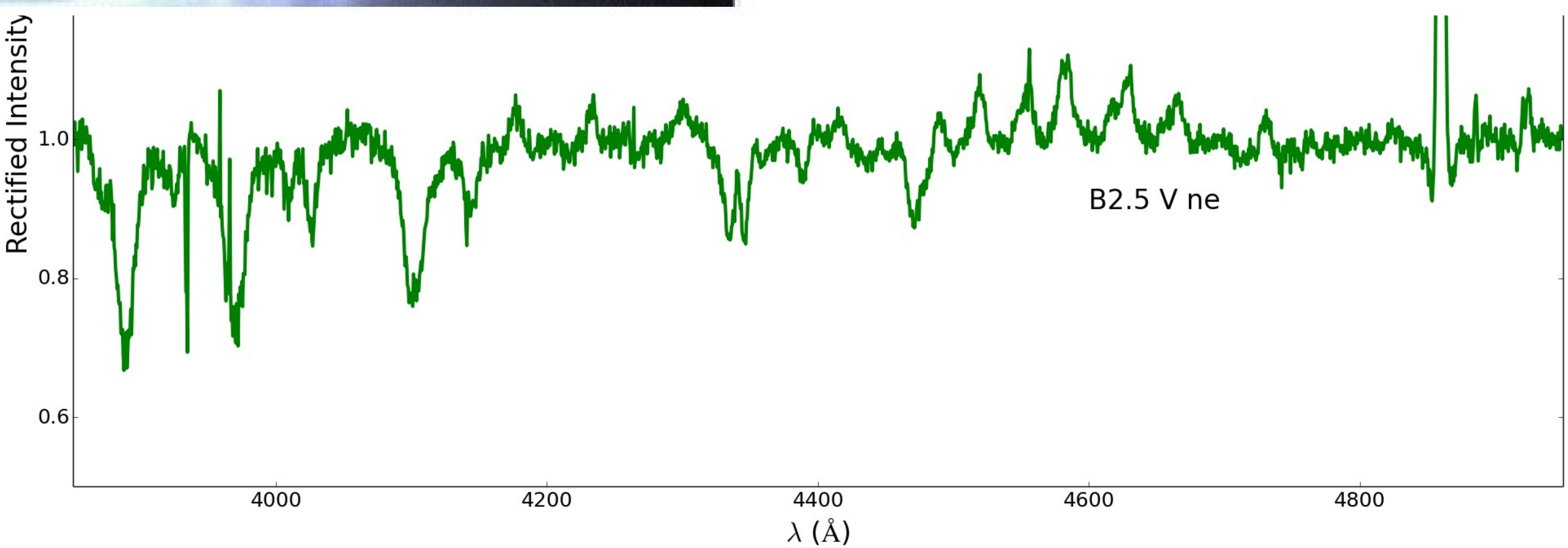




4. Emission *versus* Absorption: A Physical Approach







5. Studying Rapid Spectroscopic Variability

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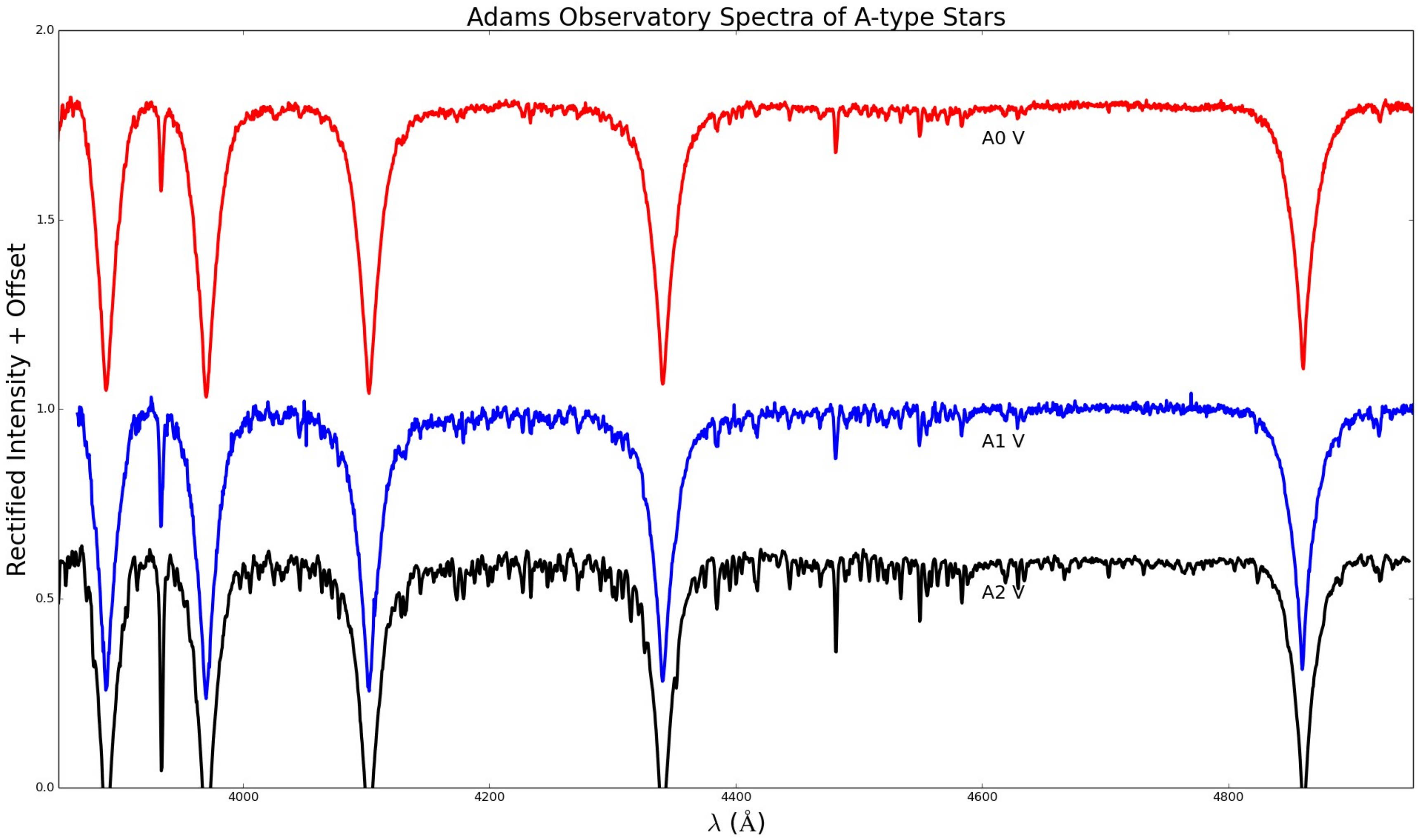
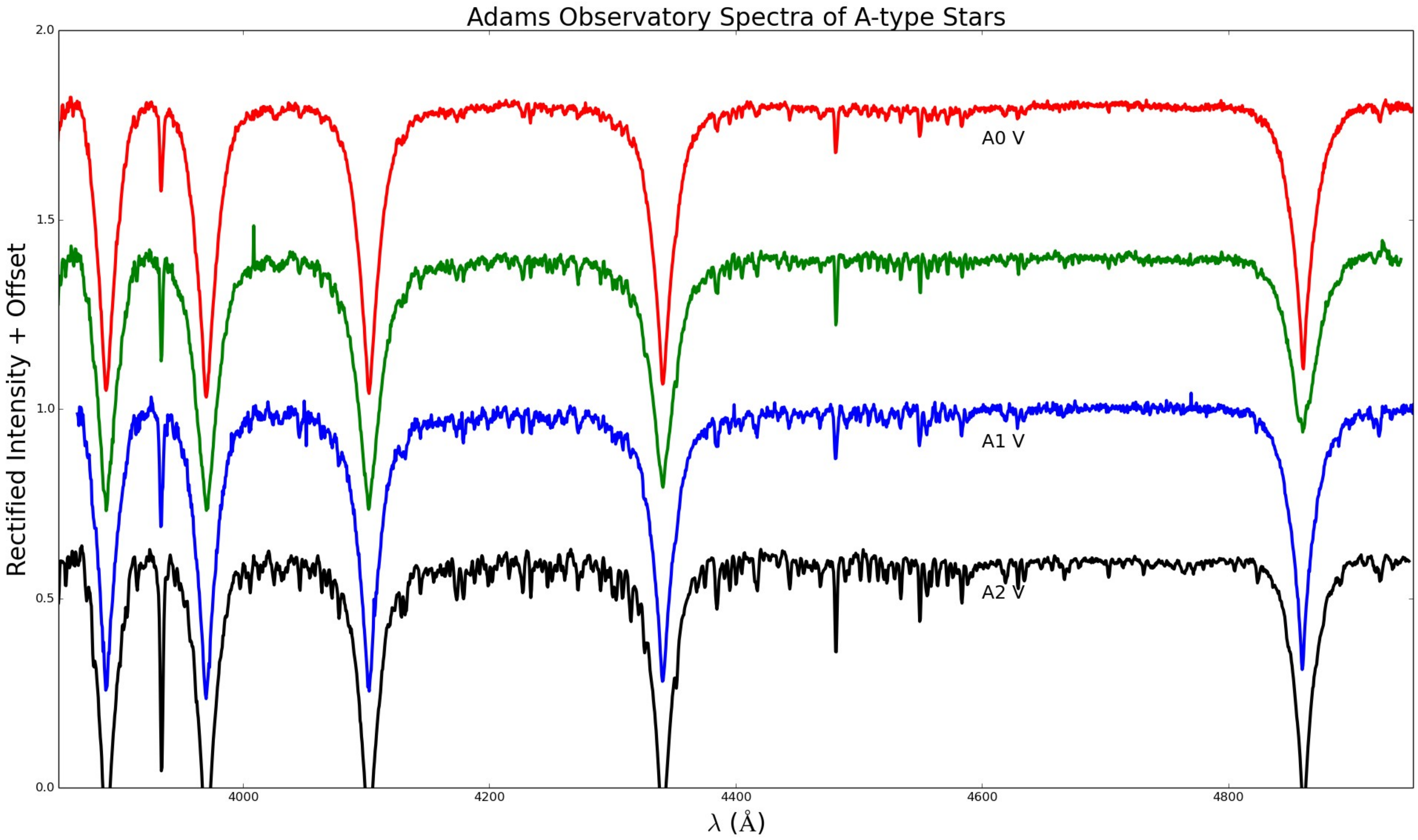
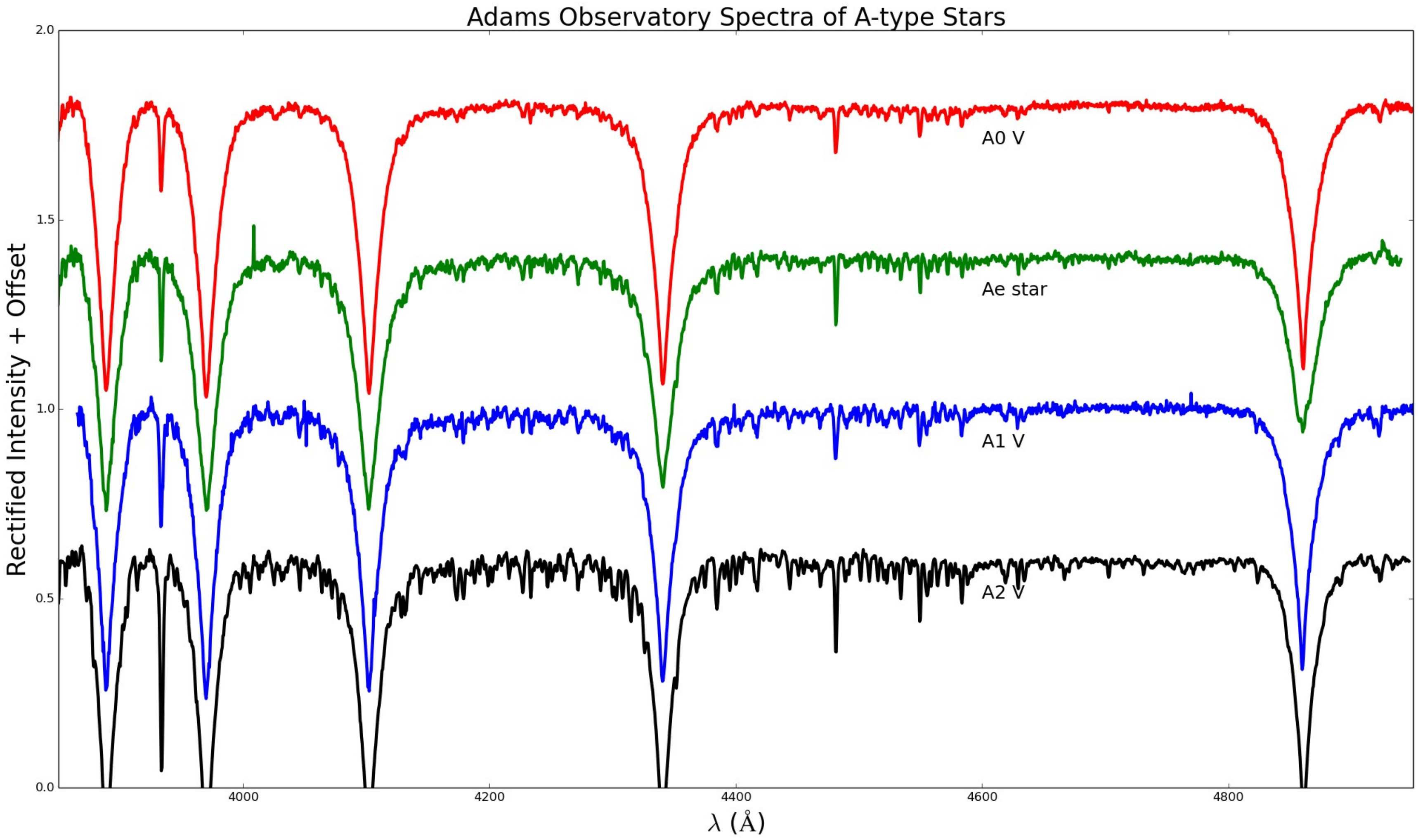


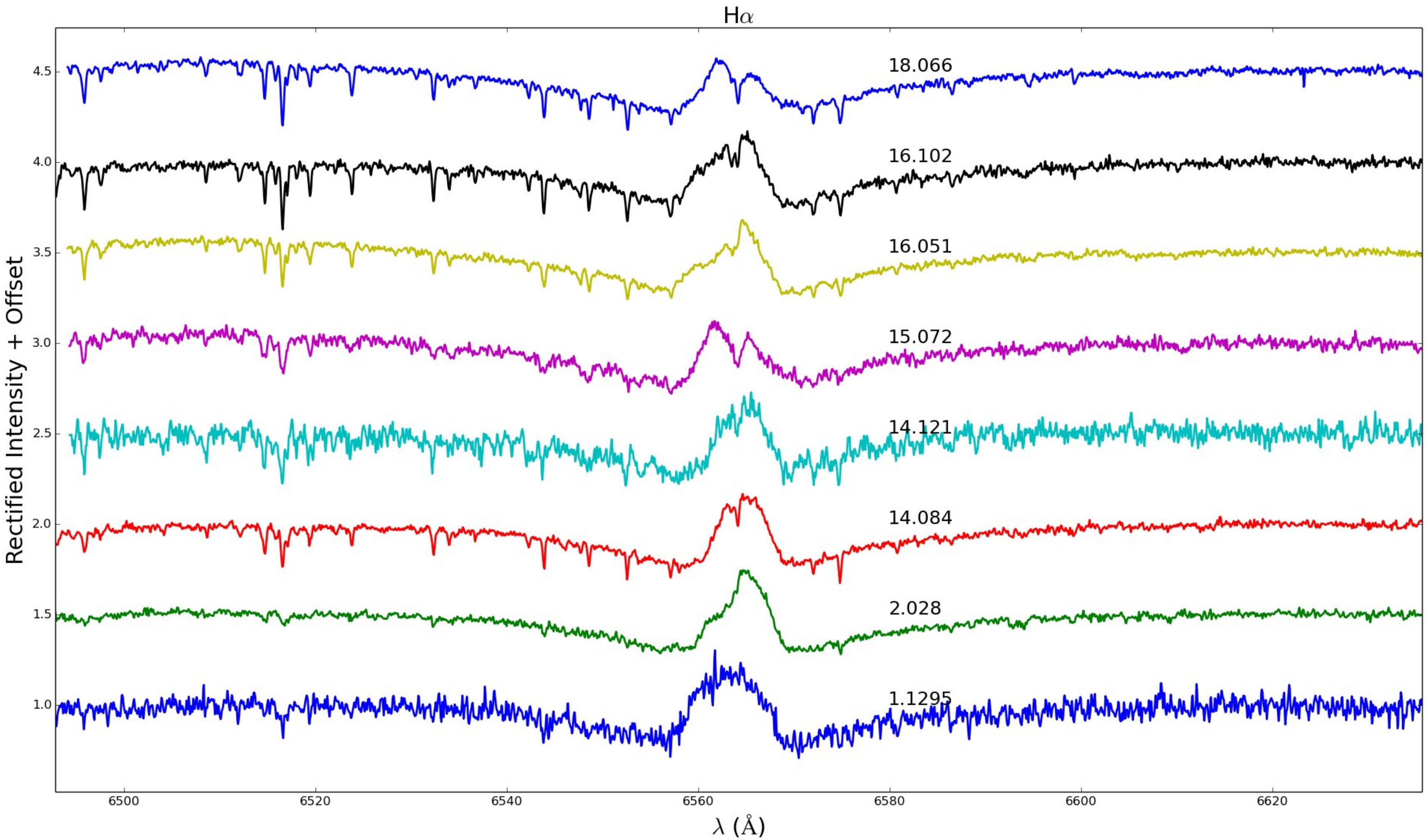
5. Studying Rapid Spectroscopic Variability



5. Studying Rapid Spectroscopic Variability



5. Studying Rapid Spectroscopic Variability



5. Studying Rapid Spectroscopic Variability

RNAAS RESEARCH NOTES OF THE AAS

HD 63021: An Ae Star with X-Ray Flux

5. Studying Rapid Spectroscopic Variability

RNAAS RESEARCH NOTES OF THE AAS

HD 63021: An Ae Star with X-Ray Flux

David G. Whelan[1], Jon Labadie-Bartz[2], S. Drew Chojnowski[3], James Daglen[4], and Ken Hudson[5]

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Figures References

+ Article information

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1. Spectroscopic Variability

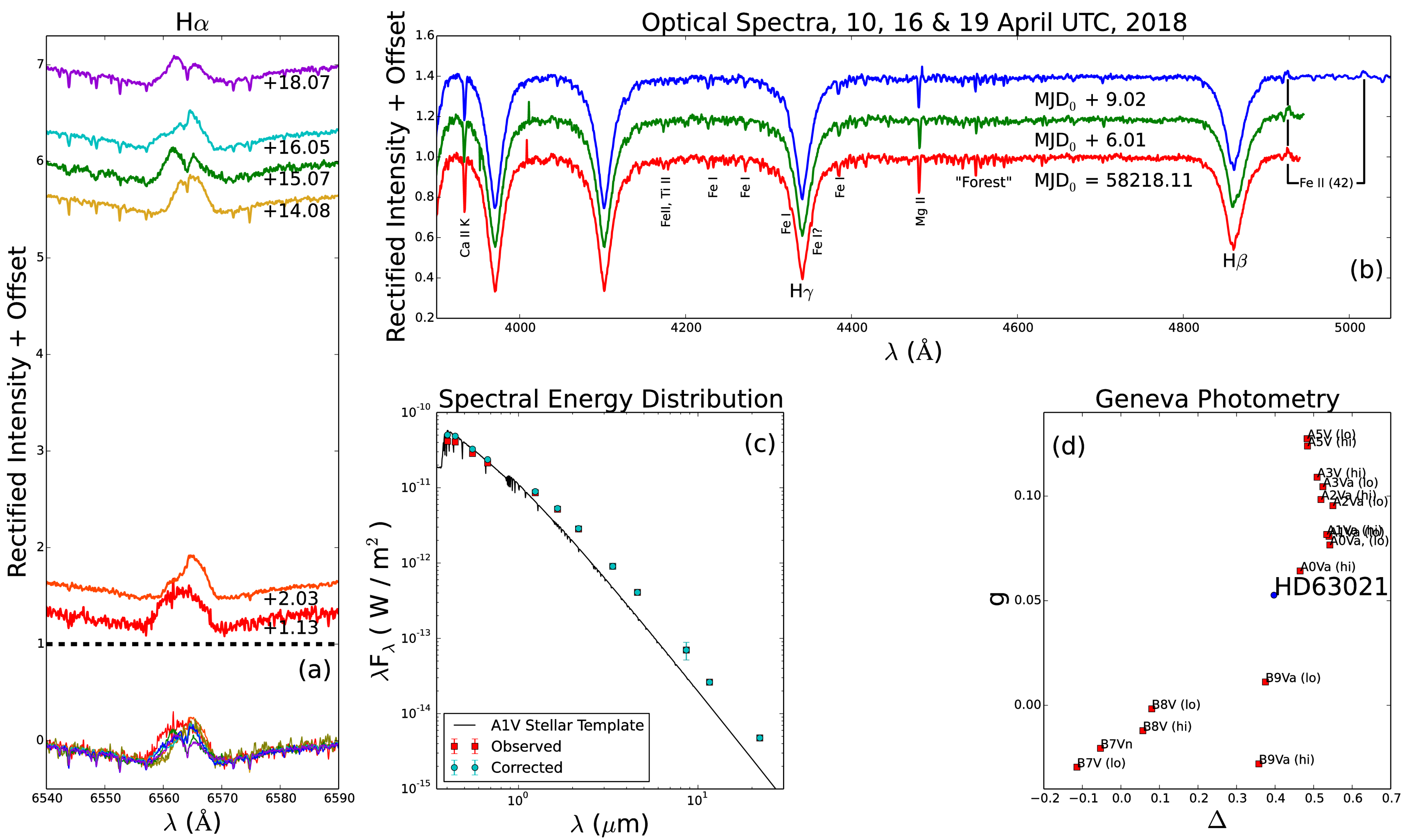
Balmer and Fe II (42) multiplet emission were discovered in a spectrum of HD 63021 on 10 April (UTC), 2018. Subsequent observations revealed variability in both photospheric absorption lines and Balmer line emission.

Figure 1(a) shows Hα observations over the course of 18 nights. The emission morphology changes on a nightly basis; additional spectra not exhibited show that emission changes perceptibly on the scale of hours.

5. Studying Rapid Spectroscopic Variability

RNAAS RESEARCH NOTES OF THE AAS

HD 63021: An Ae Star with X-Ray Flux



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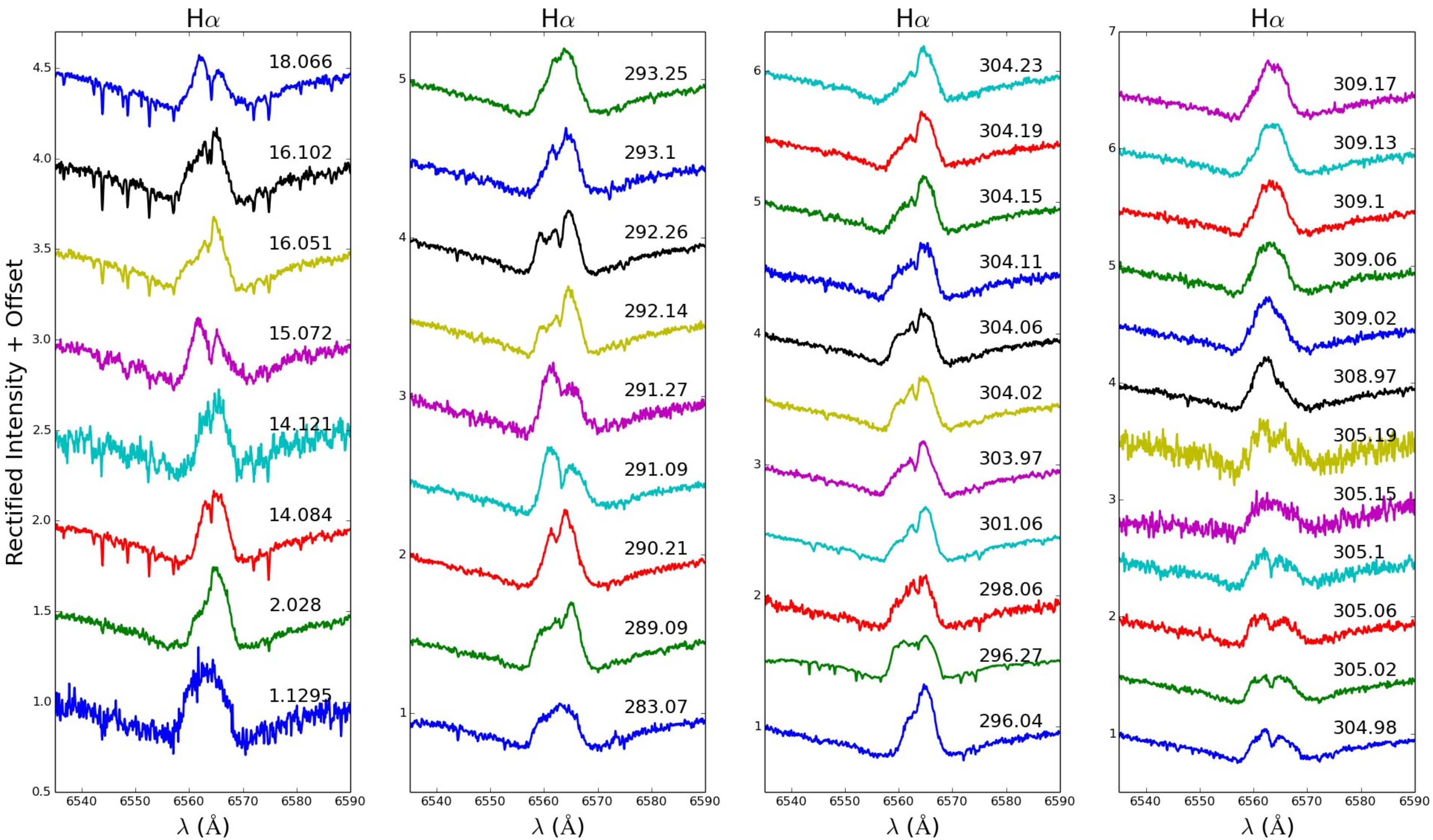


In Conclusion

In Conclusion

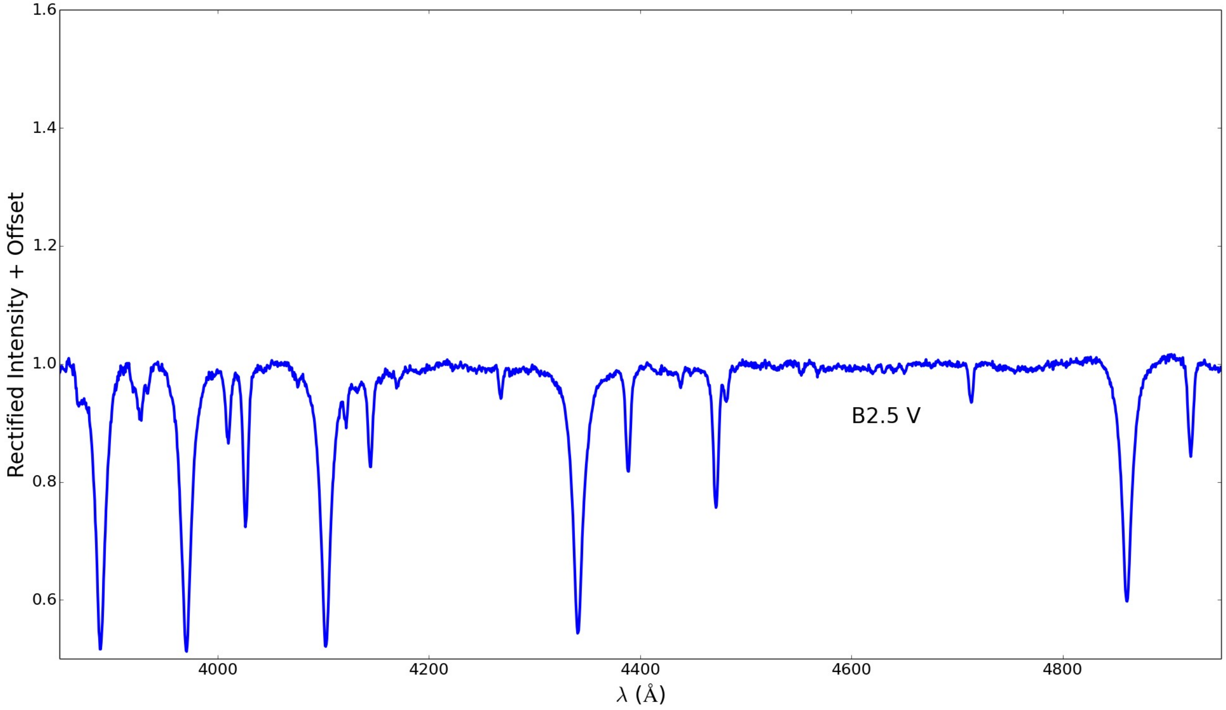
1. Physical Properties of Intermediate- and High-Mass Stars
    a. Mass, Radius, Temperature

Spec Type	Mass (M_{sol})	Radius (R_{sol})	T_{eff} (K)
A2	2.2	1.75	8,900
B3	6.3	3.5	16,500

Spec Type	Mass (M_{sol})	Radius (R_{sol})	T_{eff} (K)
B2	8.3	4.7	19,500
O9	20?	9	32,882

In Conclusion

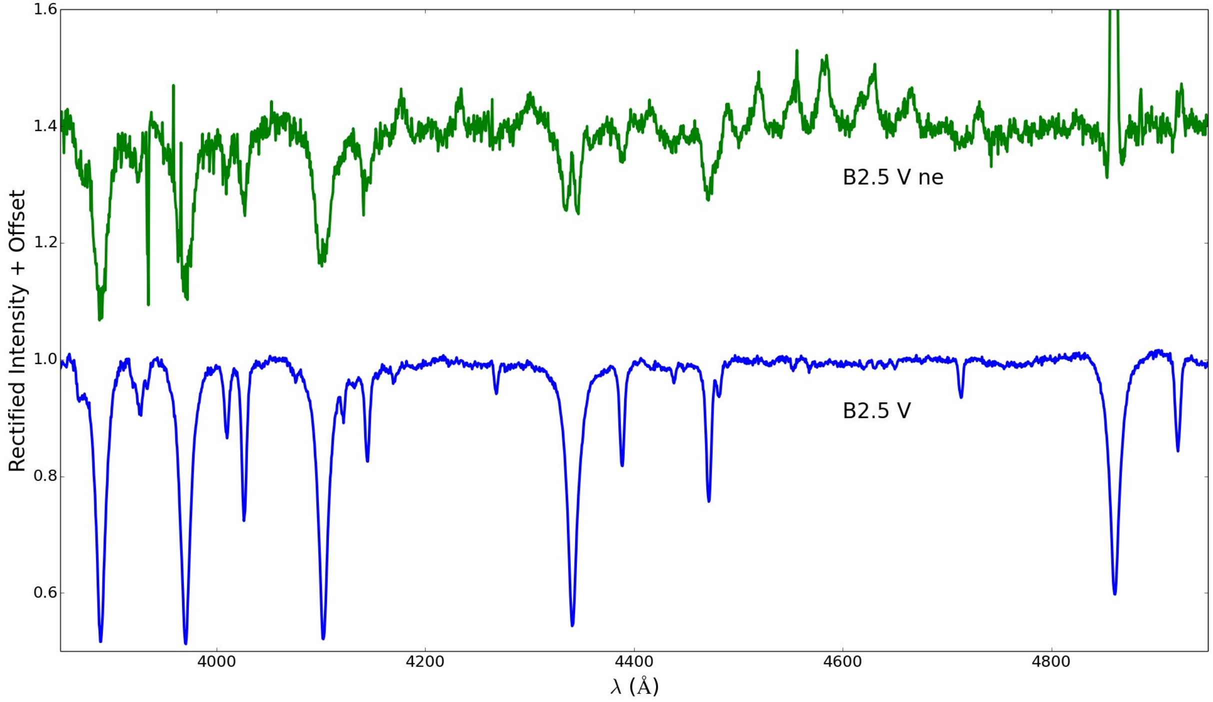
1. Physical Properties of Intermediate- and High-Mass Stars
    a. Mass, Radius, Temperature
    b. Photospheric Absorption Lines



In Conclusion

1. Physical Properties of Intermediate- and High-Mass Stars
    a. Mass, Radius, Temperature
    b. Photospheric Absorption Lines

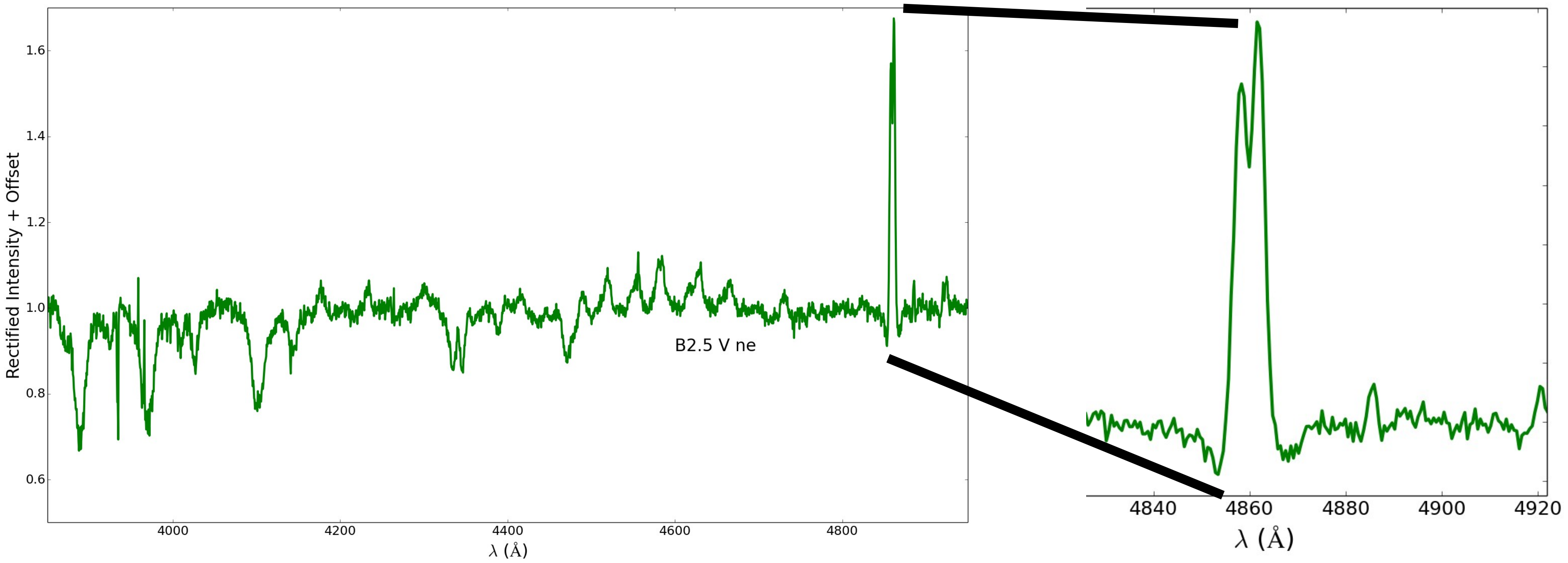
2. Observable Properties of B-type and Emission-Line B-type (Be) Stellar Spectra
    a. Hydrogen Lines
    b. Helium and Metal Lines



In Conclusion

1. Physical Properties of Intermediate- and High-Mass Stars
    a. Mass, Radius, Temperature
    b. Photospheric Absorption Lines

2. Observable Properties of B-type and Emission-Line B-type (Be) Stellar Spectra
    a. Hydrogen Lines
    b. Helium and Metal Lines
    c. Emission Signatures



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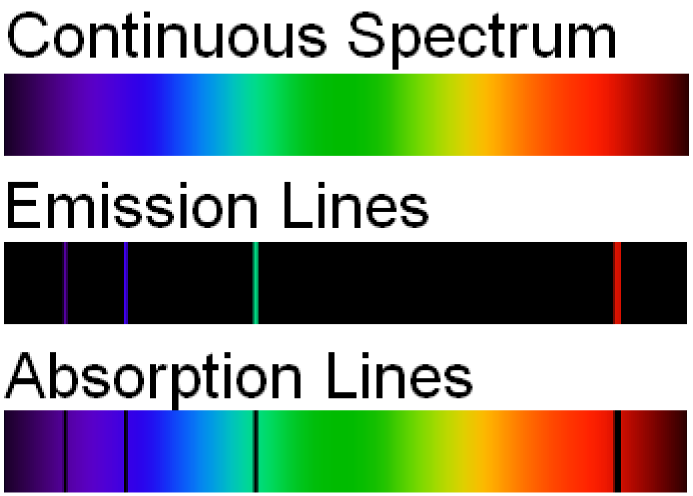
    b. Helium and Metal Lines
    c. Emission Signatures

3. Emission versus Absorption: A Qualitative Look
    a. Kirchhoff's Laws



In Conclusion

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    b. Photospheric Absorption Lines

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    a. Hydrogen Lines
    b. Helium and Metal Lines
    c. Emission Signatures

3. Emission versus Absorption: A Qualitative Look
    a. Kirchhoff's Laws

4. Emission versus Absorption: A Physical Approach
    a. Radiative Energy Transfer: I_λ^0, S_λ, I_λ

$$I_\lambda = I_\lambda^0 e^{-\tau_\lambda} + S_\lambda \left(1 - e^{-\tau_\lambda}\right)$$

In Conclusion

1. Physical Properties of Intermediate- and High-Mass Stars
   a. Mass, Radius, Temperature
   b. Photospheric Absorption Lines

2. Observable Properties of B-type and Emission-Line B-type (Be) Stellar Spectra
   a. Hydrogen Lines
   b. Helium and Metal Lines
   c. Emission Signatures

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   a. Kirchhoff's Laws

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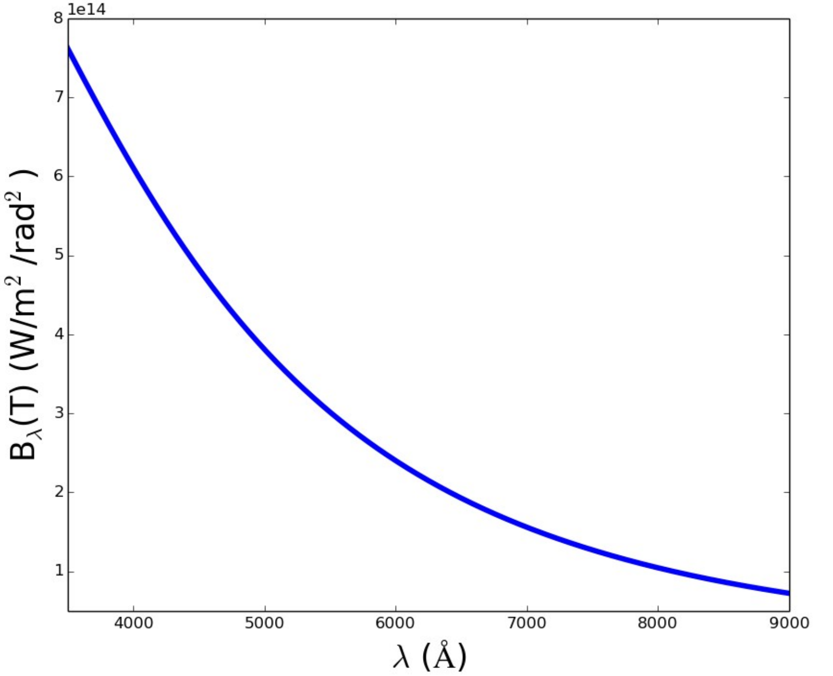
   a. Radiative Energy Transfer: I_λ^0, S_λ, I_λ
   b. High Optical Depth Limit



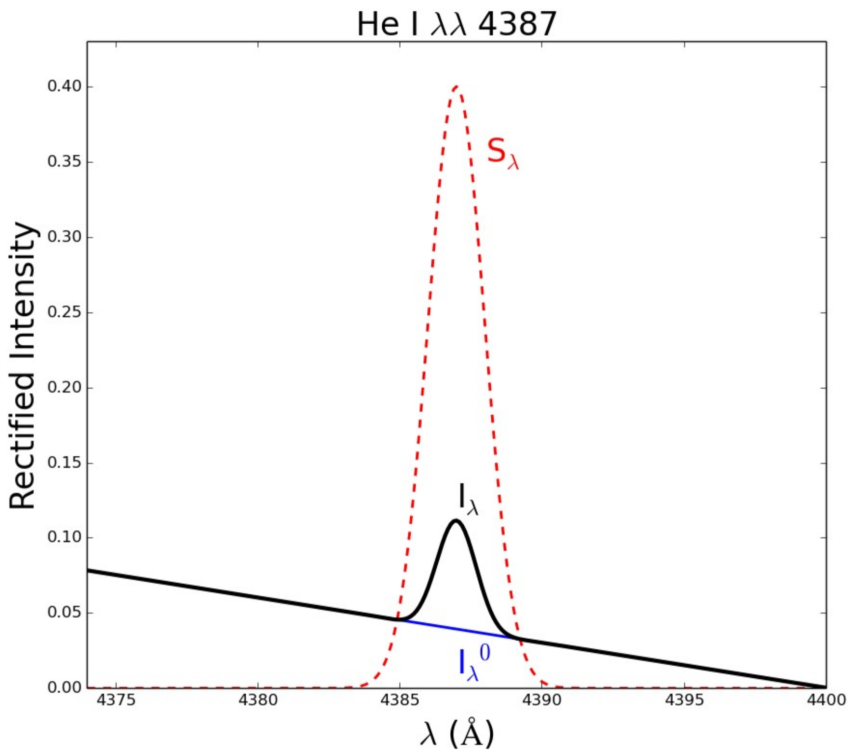
In Conclusion

1. Physical Properties of Intermediate- and High-Mass Stars
   a. Mass, Radius, Temperature
   b. Photospheric Absorption Lines

2. Observable Properties of B-type and Emission-Line B-type (Be) Stellar Spectra
   a. Hydrogen Lines
   b. Helium and Metal Lines
   c. Emission Signatures

3. Emission versus Absorption: A Qualitative Look
   a. Kirchhoff's Laws

4. Emission versus Absorption: A Physical Approach
   a. Radiative Energy Transfer: I_λ^0, S_λ, I_λ
   b. High Optical Depth Limit
   c. Formation of Spectral Lines



In Conclusion

1. Physical Properties of Intermediate- and High-Mass Stars
   a. Mass, Radius, Temperature
   b. Photospheric Absorption Lines

2. Observable Properties of B-type and Emission-Line B-type (B*e*) Stellar Spectra
   a. Hydrogen Lines
   b. Helium and Metal Lines
   c. Emission Signatures

3. Emission *versus* Absorption: A Qualitative Look
   a. Kirchhoff's Laws

4. Emission *versus* Absorption: A Ph
   a. Radiative Energy Transfer: I
   b. High Optical Depth Limit
   c. Formation of Spectral Lines

5. Rapid Spectroscopic Variability
   a. Answering New Questions...
      ...together!