The nature of the light variations of chemically peculiar stars

Jiří Krtička, Zdeněk Mikulášek

Masaryk University, Brno, Czech Republic

Juraj Zverko, Jozef Žižňovský

Astronomical Institute SAV, Tatranská Lomnica, Slovak Republic

In collaboration with. . .

- Krtička J., Mikulášek, Z., Zverko J., Zižňovský J. 2007, A&A, 470, 1089
- Mikulášek Z., Krtička J., Henry G. W., Zverko J., Žižňovský J., Bohlender D., Romanyuk I. I., Janík J., Božić H., Korčáková D., Zejda M., Iliev I. Kh., Škoda P., Šlechta M., Gráf T., Netolický M., Ceniga M. 2008, A&A, 485, 585
- Krtička J., Mikulášek Z., Henry G. W., Zverko, J. Žižňovský J., Skalický J., Zvěřina P., 2008, submitted to A&A

Hot chemically peculiar stars

- chemically peculiar $=$ CP stars
- main sequence hot stars (spectral types B, A)
- overabundance (or underabundance) of certain elements (He, Si, Mg, Fe, $\ldots$) in the atmosphere
- the chemical peculiarity affects surface layers only (the initial chemical composition of the stellar core is roughly solar one)

The cause of peculiarity

* hotter main sequence O stars have winds accelerated by the line transitions of heavier elements (C, N, O, Si, Fe, . . .)

The cause of peculiarity

* for late B stars and A stars (of the main sequence) the radiative force is not strong enough to drive a wind

The cause of peculiarity

* for late B stars and A stars (of the main sequence) the radiative force is not strong enough to drive a wind
* however: the radiative force may cause diffusion of some elements whereas other elements settle down due to the gravity force

The cause of peculiarity

- for late B stars and A stars (of the main sequence) the radiative force is not strong enough to drive a wind
- however: the radiative force may cause diffusion of some elements whereas other elements settle down due to the gravity force

radiative diffusion $\times$ gravitation settling

The cause of peculiarity

* $\ast$ for late B stars and A stars (of the main sequence) the radiative force is not strong enough to drive a wind
* $\ast$ however: the radiative force may cause diffusion of some elements whereas other elements settle down due to the gravity force

radiative diffusion $\times$ gravitation settling

$\Rightarrow$ chemically peculiar (CP) stars

(e.g., Vauclair 2003, Michaud 2005)

Some CP stars are variable

with period of order of days the observations show variability in

* apparent magnitude
* spectral line profiles
* intensity of the magnetic field (if present)

Some CP stars are variable

with period of order of days the observations show variability in

- ∗ apparent magnitude
- ∗ spectral line profiles
- ∗ intensity of the magnetic field (if present)

$\Rightarrow$ observed periodical variations can be explained if the period of the variability is a rotational one

Magnetic field variability

∗ inhomogeneous surface distribution of the magnetic field

⇒ as a results of the stellar rotation we observe surface elements with different magnetic field

⇒ mean observed magnetic field varies with rotational period

Spectroscopic variability

∗ chemical peculiarity influenced by the magnetic field

⇒ also chemical elements distributed on the surface inhomogeneously

⇒ variable equivalent width and line profile (due to the Doppler effect)

∗ Doppler mapping can be used to derive the elemental distribution (e.g., Rice et al. 1988)

Spectroscopic variability

∗ chemical peculiarity influenced by the magnetic field

⇒ also chemical elements distributed on the surface inhomogeneously

⇒ variable equivalent width and line profile (due to the Doppler effect)

∗ Doppler mapping can be used to derive the elemental distribution (e.g., Rice et al. 1988)

⇒ *what is the cause of the light variability of these stars?*

The origin of the light variability

* line blanketing + inhomogeneous elemental surface distribution (Molnar 1973)

The origin of the light variability

* line blanketing + inhomogeneous elemental surface distribution (Molnar 1973)
* bound-free transitions + inhomogeneous elemental surface distribution (Peterson 1970, Lanz et al. 1996)

The origin of the light variability

* line blanketing + inhomogeneous elemental surface distribution (Molnar 1973)
* bound-free transitions + inhomogeneous elemental surface distribution (Peterson 1970, Lanz et al. 1996)
* influence of the magnetic field on the light variability (Staude 1972, Stępień 1978, LeBlanc et al. 1994, Khan & Shulyak 2006)

The origin of the light variability

* line blanketing + inhomogeneous elemental surface distribution (Molnar 1973)
* bound-free transitions + inhomogeneous elemental surface distribution (Peterson 1970, Lanz et al. 1996)
* influence of the magnetic field on the light variability (Staude 1972, Stępień 1978, LeBlanc et al. 1994, Khan & Shulyak 2006)
* no detailed study available up to now

A test case: HD 37776

A test case: HD 37776

- V901 Ori, B2IV
- $T_{\mathrm{eff}} = 22\,000\,\mathrm{K}$, $\log g = 4.0$ (Groote & Kaufmann 1981)

A test case: HD 37776

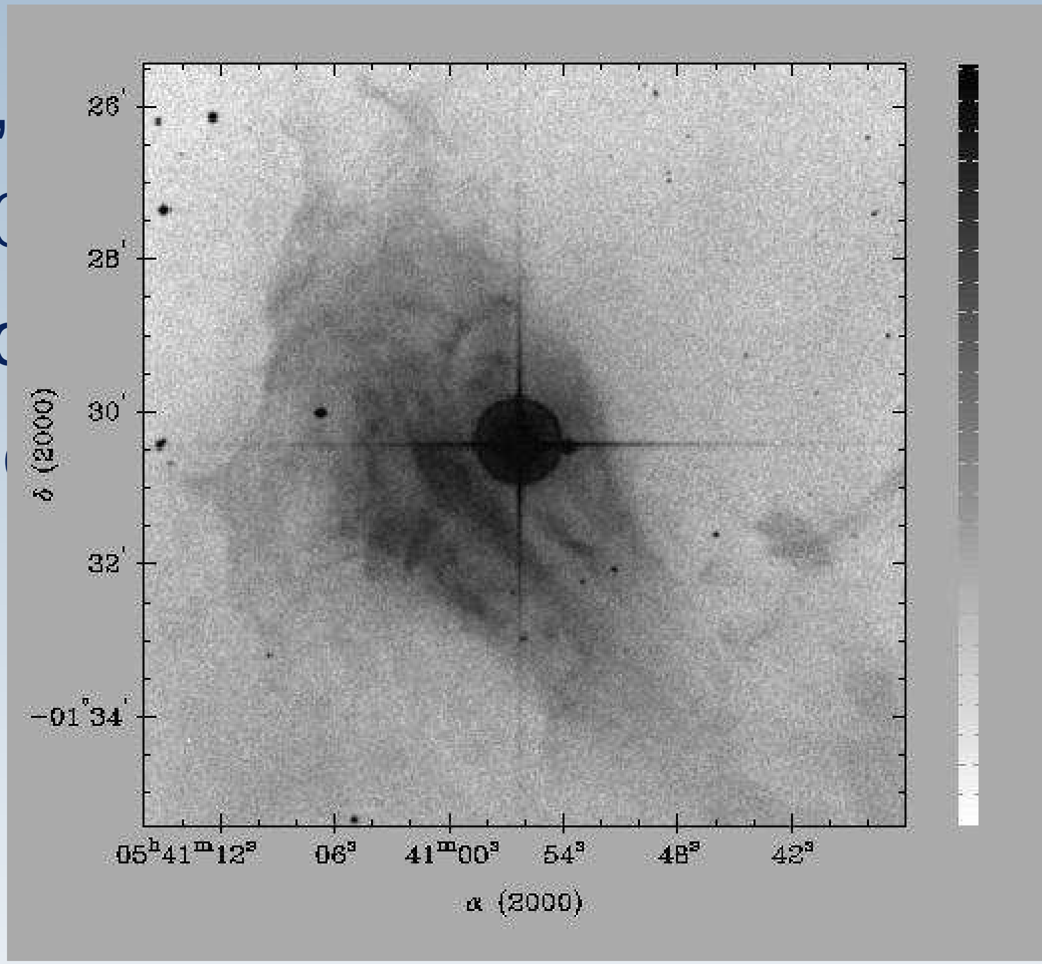
- ∗ V901 Ori, B2IV
- ∗ $T_{\text{eff}} = 22\,000\,\text{K}$, $\log g = 4.0$
- ∗ member of Ori OB1b association (e.g., Landstreet et al. 2007)

A test case: HD 37776

- V901 Ori, B2IV
- $T_{\text{eff}} = 22\,000\,\text{K}$, $\log g = 4.0$
- member of Ori OB1b association
- star resides in the nebula IC 431

A test case: HD 37776

* V901 Ori,
* $T_{\mathrm{eff}} = 22$
* member c
* star resid



A test case: HD 37776

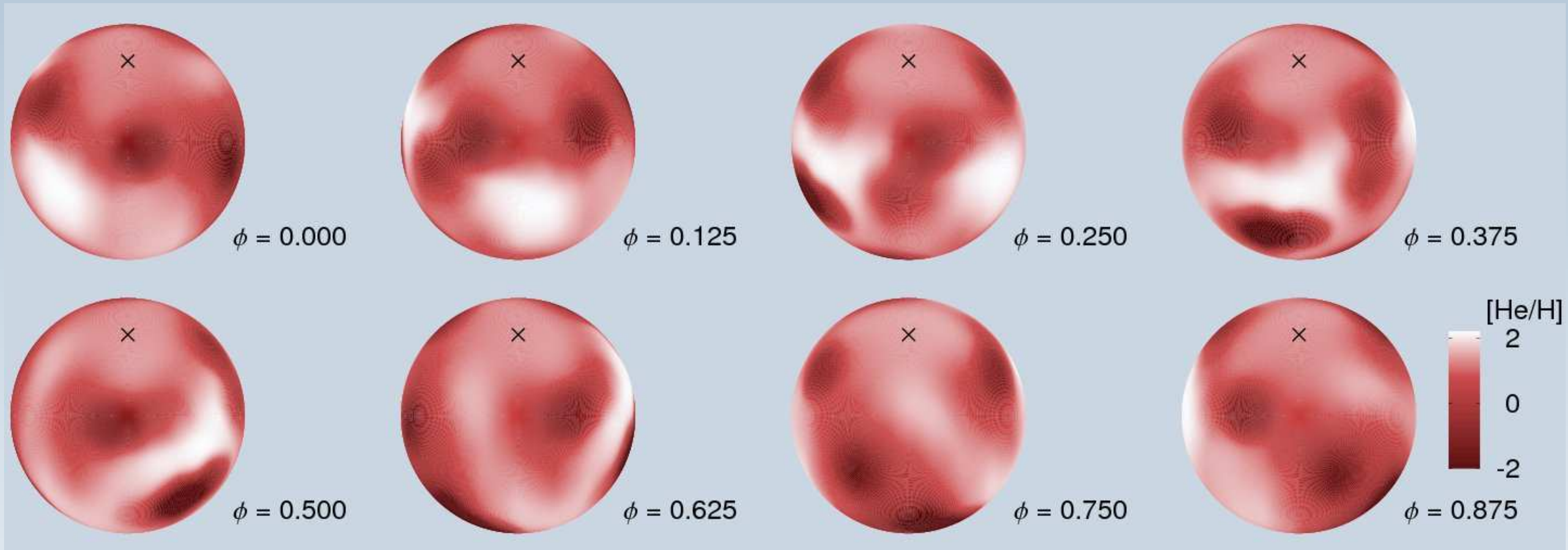
- ∗ V901 Ori, B2IV
- ∗ $T_{\rm eff} = 22\,000\,$K, $\log g = 4.0$
- ∗ member of Ori OB1b association
- ∗ helium strong star
- ∗ magnetic field with a strong quadrupolar component
  (Thompson & Landstreet 1985)

A test case: HD 37776

* V901 Ori, B2IV
* $T_{\text{eff}} = 22\,000\,\text{K}$, $\log g = 4.0$
* member of Ori OB1b association
* helium strong star
* magnetic field with a strong quadrupolar component
* period of the light, spectrum and magnetic field variations is about 1.5 days (Pedersen & Thomsen 1977)

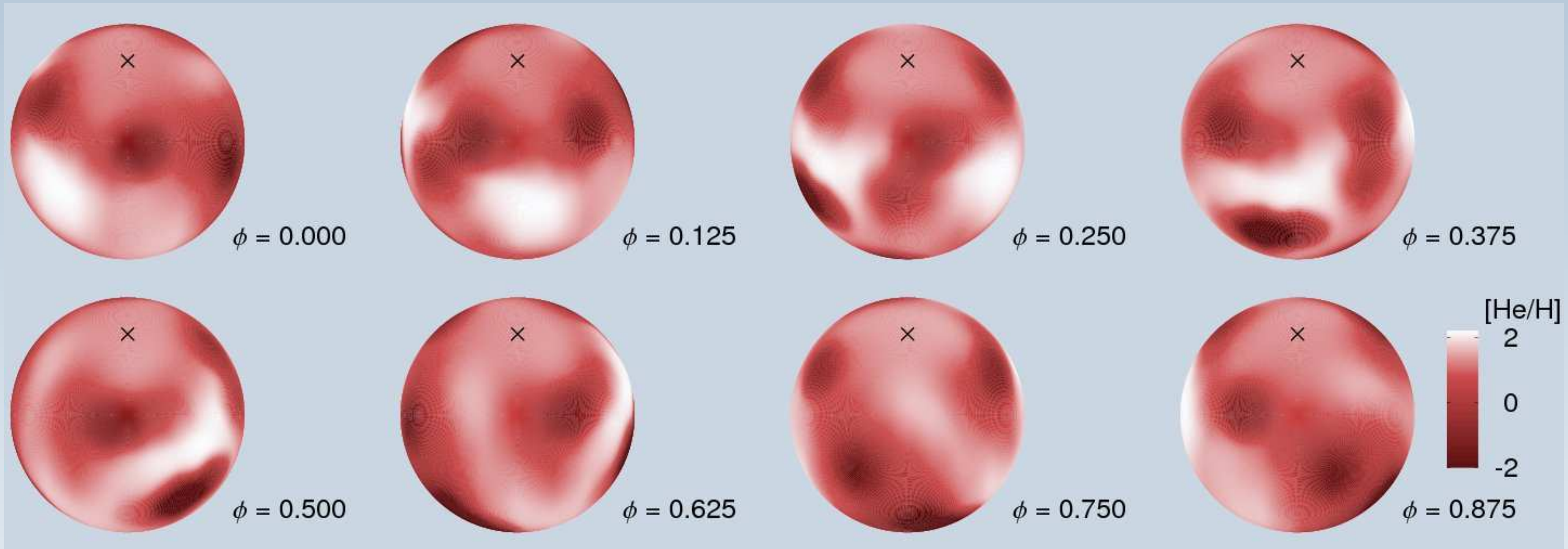
He surface distribution

(Chochlova et al. 2000)



He surface distribution

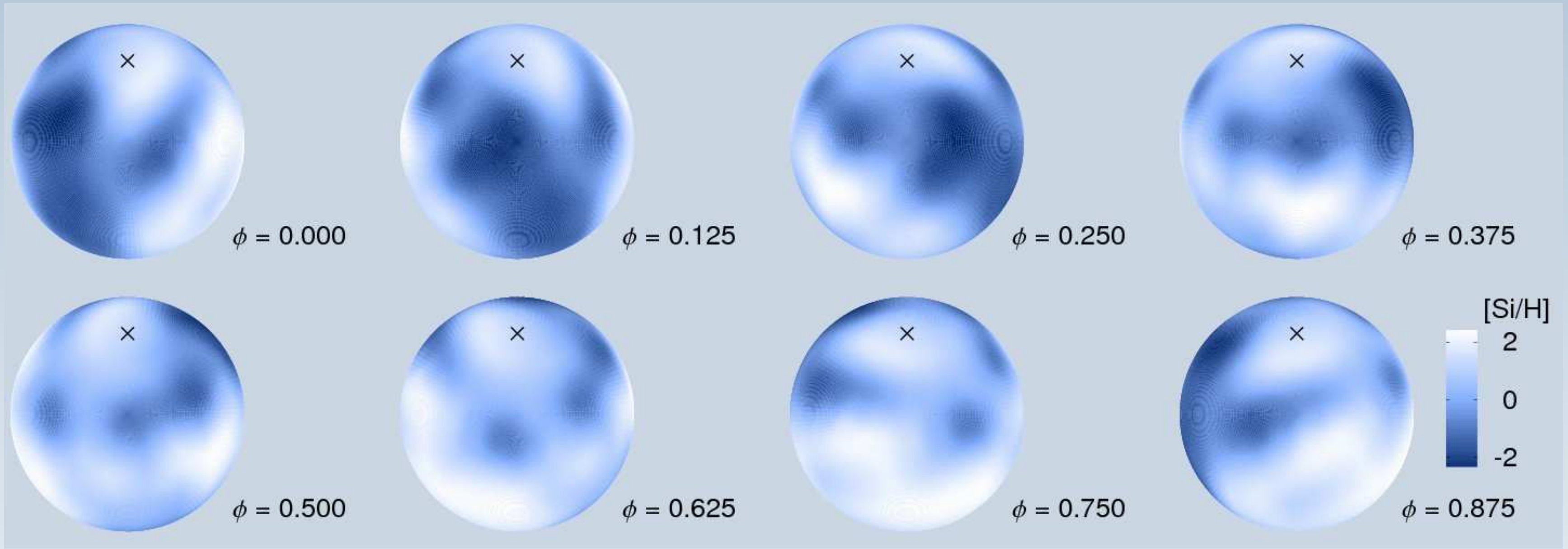
(Chochlova et al. 2000)



$\Rightarrow$ helium lines strongest for the phase $\phi \approx 0.25$

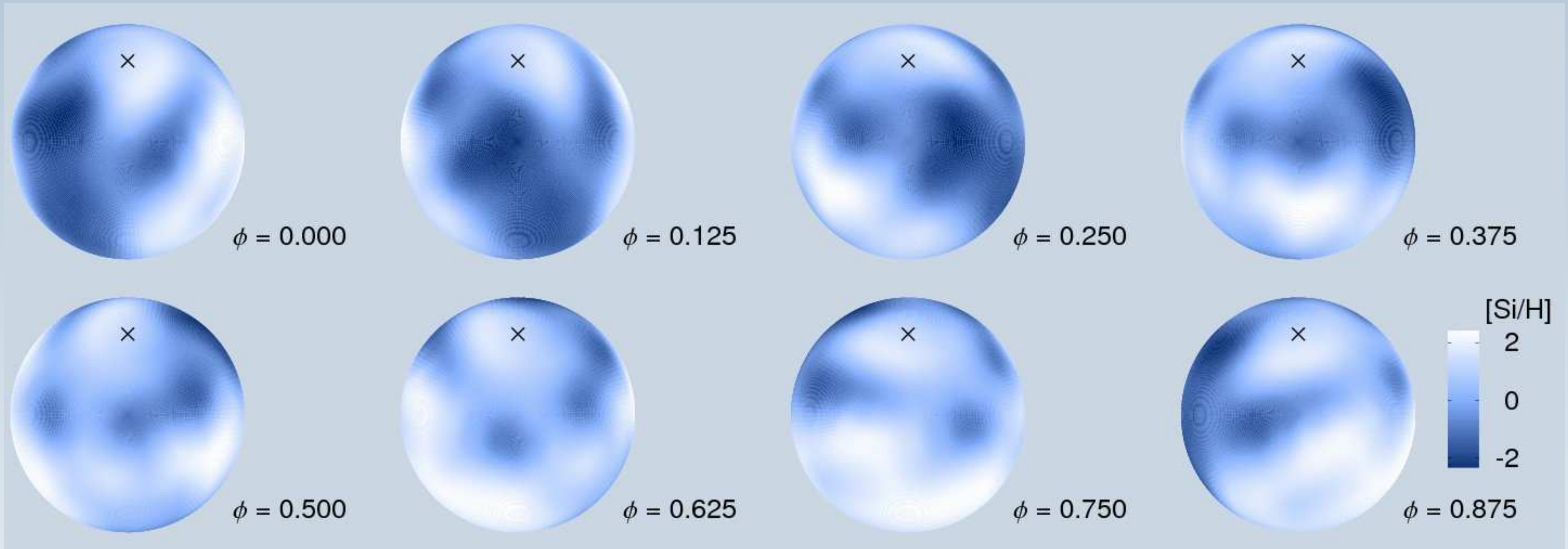
Si surface distribution

(Chochlova et al. 2000)



Si surface distribution

(Chochlova et al. 2000)



$\Rightarrow$ silicon lines strongest for the phase $\phi \approx 0.75$

Other elements: O, Fe

(Chochlova et al. 2000)

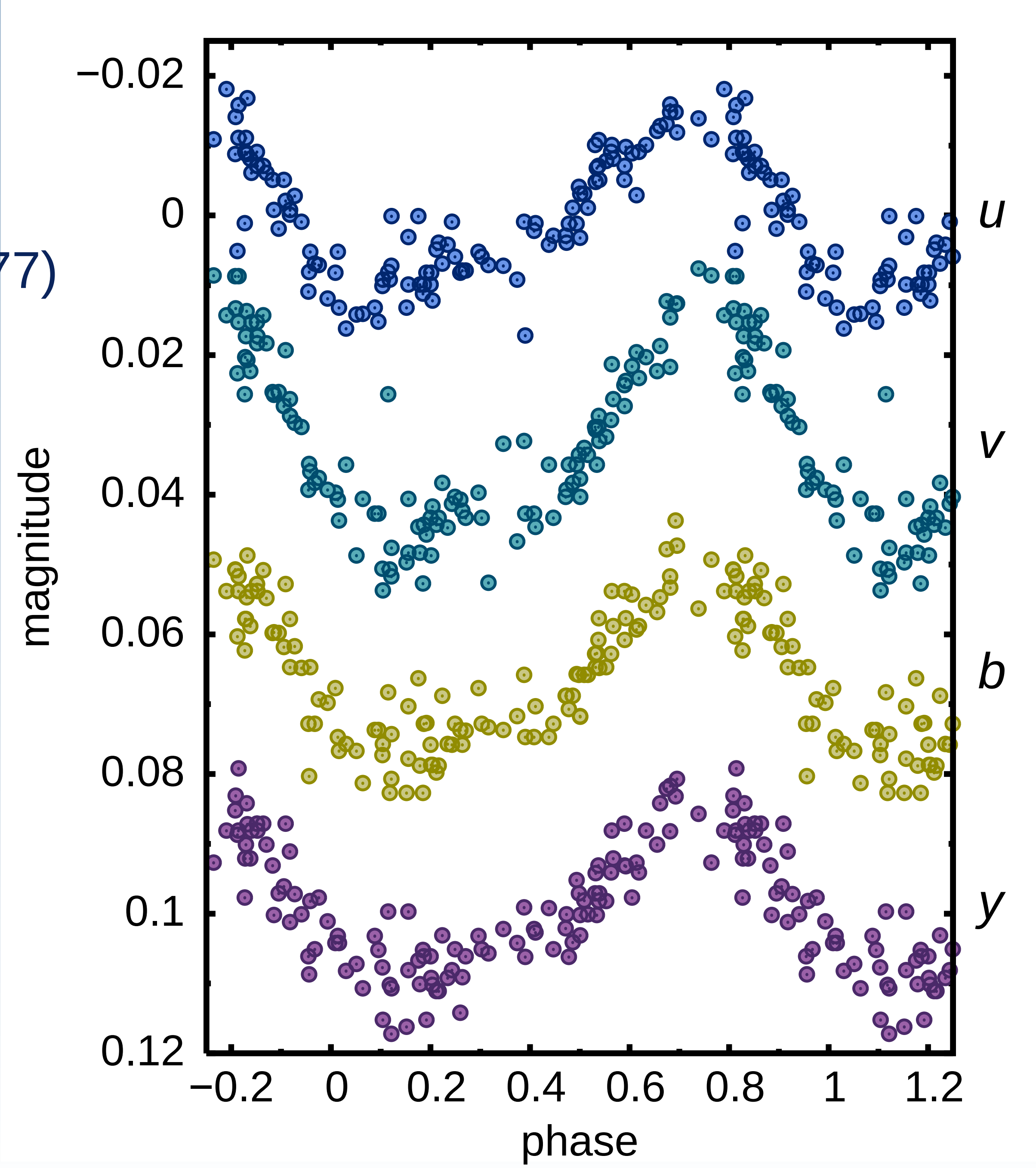
- inhomogeneous surface distribution of oxygen and iron
- the abundance of these elements much lower than the solar one

uvby variations

Adelman (1997)

Adelman & Pyper (1985)

Pedersen & Thomsen (1977)



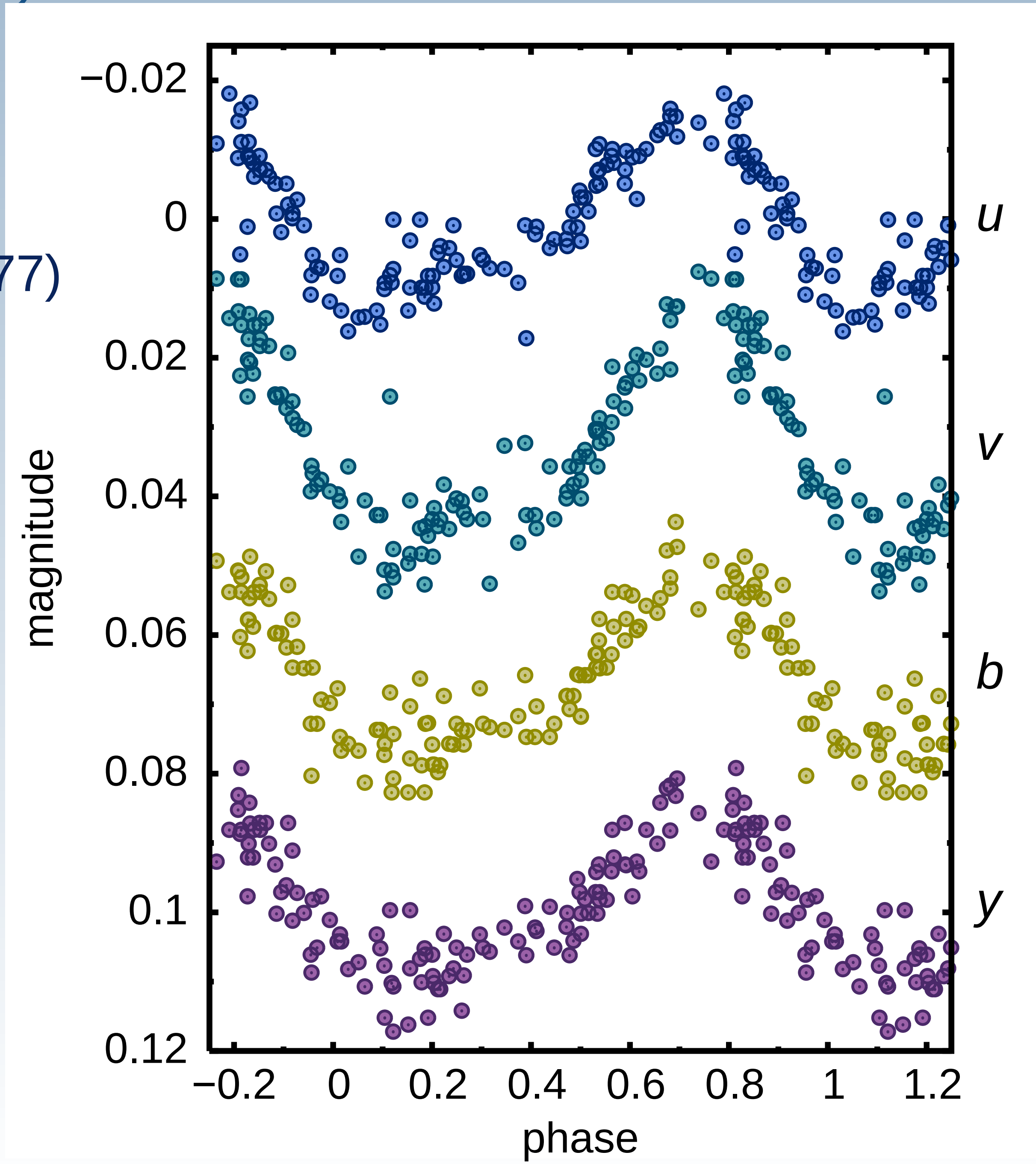
uvby variations

Adelman (1997)

Adelman & Pyper (1985)

Pedersen & Thomsen (1977)

⇒ simulation of the light variations



Model atmospheres

* calculation of model atmospheres using the code TLUSTY (Lanz & Hubeny 2007)
* LTE plane-parallel model atmospheres
* inclusion of light elements only

Calculation of the spectrum

* spectrum synthesis using the code SYNSPEC (Hubeny 1988)
* inclusion of the same elements as for the model atmosphere calculation
* input model atmosphere taken from the code TLUSTY

The grid

* constant $T_{\rm eff}$, $\log g$, variable composition

Y = [He/H]		-6	-5	-4	-3	-2	-1	0	1	2	3
	-3	●	●	●	●	●	●	●	●	●	●
	-2	●	●	●	●	●	●	●	●	●	●
	-1	●	●	●	●	●	●	●	●	●	●
Z = [Si/H]	0	●	●	●	●	●	●	●	●	●	●
	1	●	●	●	●	●	●	●	●	●	●
	2	●	●	●	●	●	●	●	●	●	●
	2.5	●	●	●	●	●	●	●	●	●	●
	3	●	●	●	●	●	●	●	●	●	●

The grid

* constant $T_{\rm eff}$, $\log g$, variable composition
* for each chemical composition from the grid

The grid

* constant T_{eff}, $\log g$, variable composition
* for each chemical composition from the grid
  * we calculate model atmosphere

The grid

- ∗ constant T_{eff}, $\log g$, variable composition
- ∗ for each chemical composition from the grid
  - ⋆ we calculate model atmosphere
  - ⋆ we calculate the spectrum $H(\lambda, Y, Z)$

The grid

- constant $T_{\rm eff}$, $\log g$, variable composition
- for each chemical composition from the grid
  - we calculate model atmosphere
  - we calculate the spectrum $H(\lambda, Y, Z)$
  - we calculate the flux $H_c(Y, Z)$ in each colour $c = u, v, b, y$

u, v, b, y **magnitudes**

* division of the visible star's surface into 90 × 360 surface elements

u, v, b, y **magnitudes**

* division of the visible star's surface into 90×360 surface elements
* for each phase ϕ we know the abundance of He and Si in each surface element (with coordinates Ω)

u, v, b, y **magnitudes**

- division of the visible star's surface into 90×360 surface elements
- for each phase ϕ we know the abundance of He and Si in each surface element (with coordinates Ω)
- we know the emergent intensity $I_c(\theta,\Omega)$ from each surface element in the direction θ

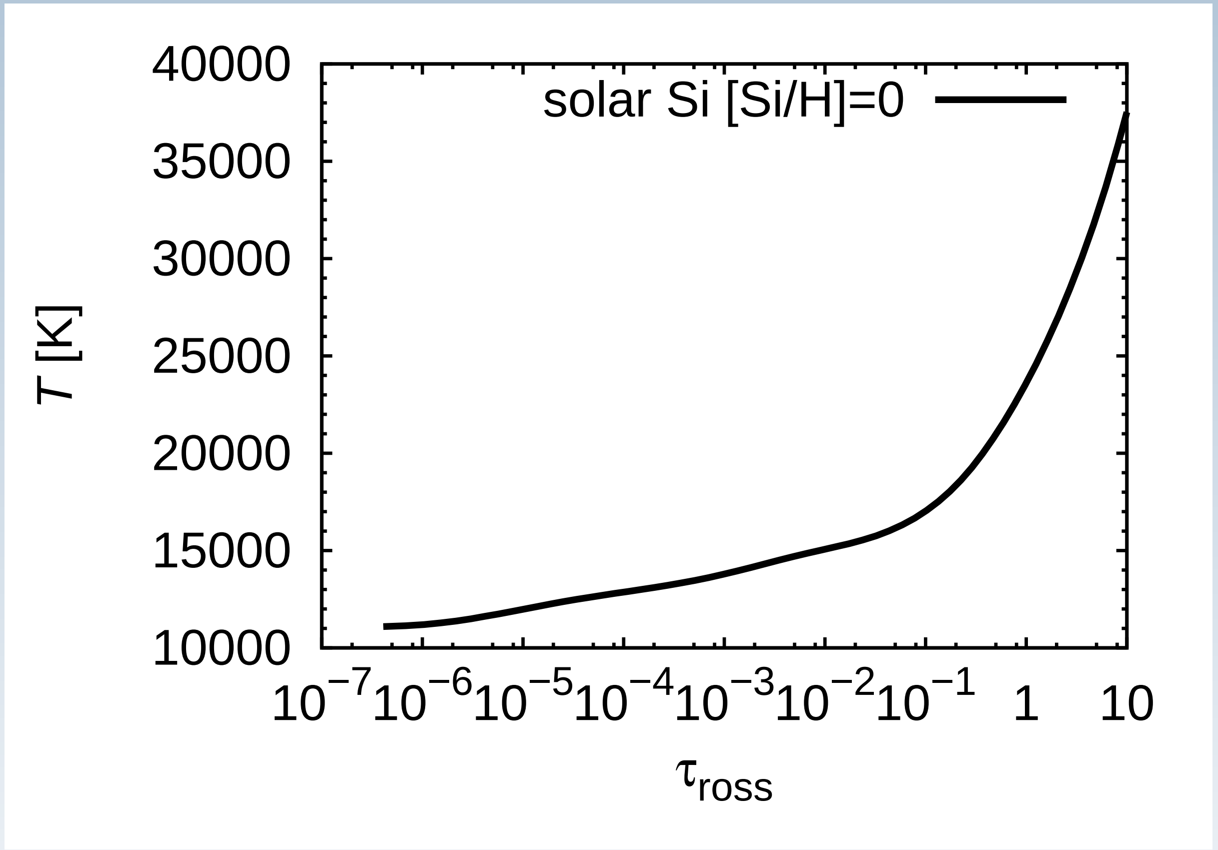
u, v, b, y magnitudes

- $\ast$ division of the visible star's surface into 90×360 surface elements
- $\ast$ for each phase ϕ we know the abundance of He and Si in each surface element (with coordinates Ω)
- $\ast$ we know the emergent intensity $I_c(\theta,\Omega)$ from each surface element in the direction θ

$\Rightarrow$ calculation of the phase-dependent flux and the u, v, b, y magnitude

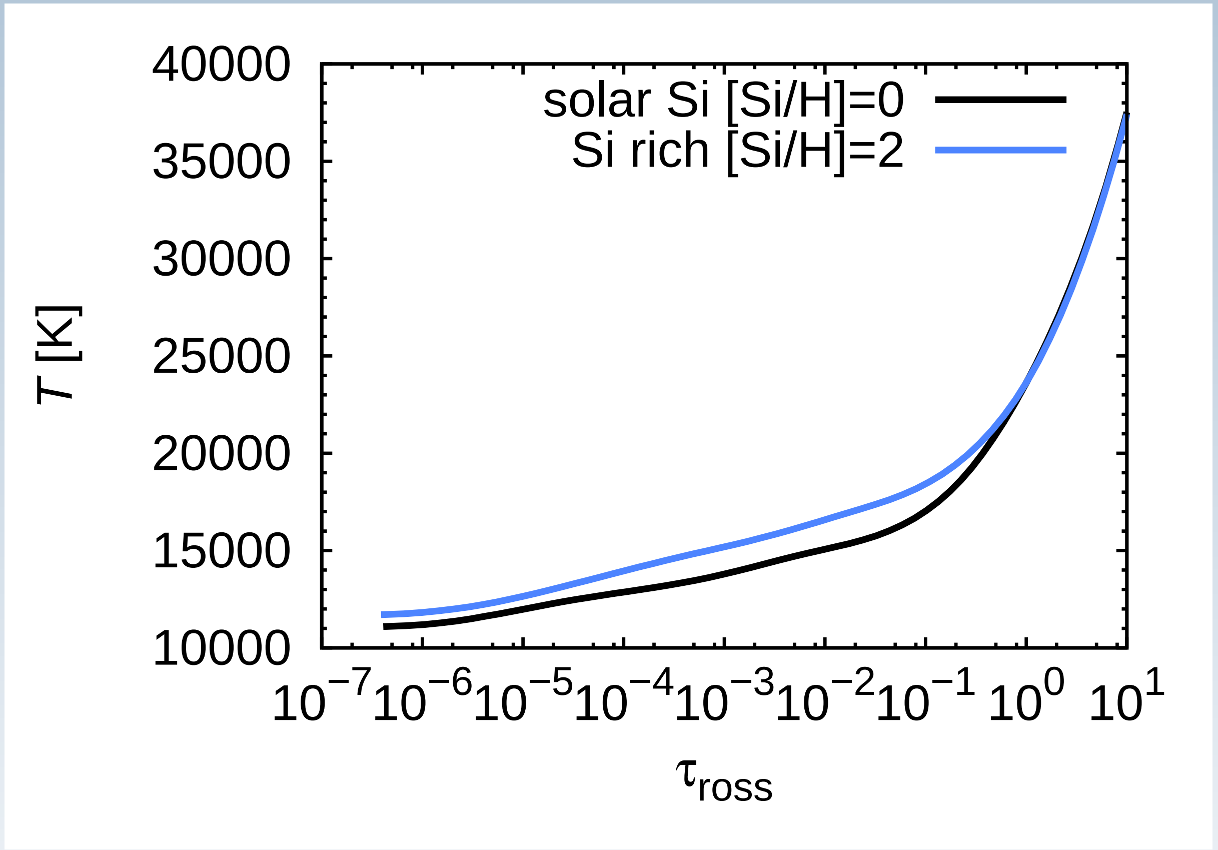
Si abundance variations

* the temperature



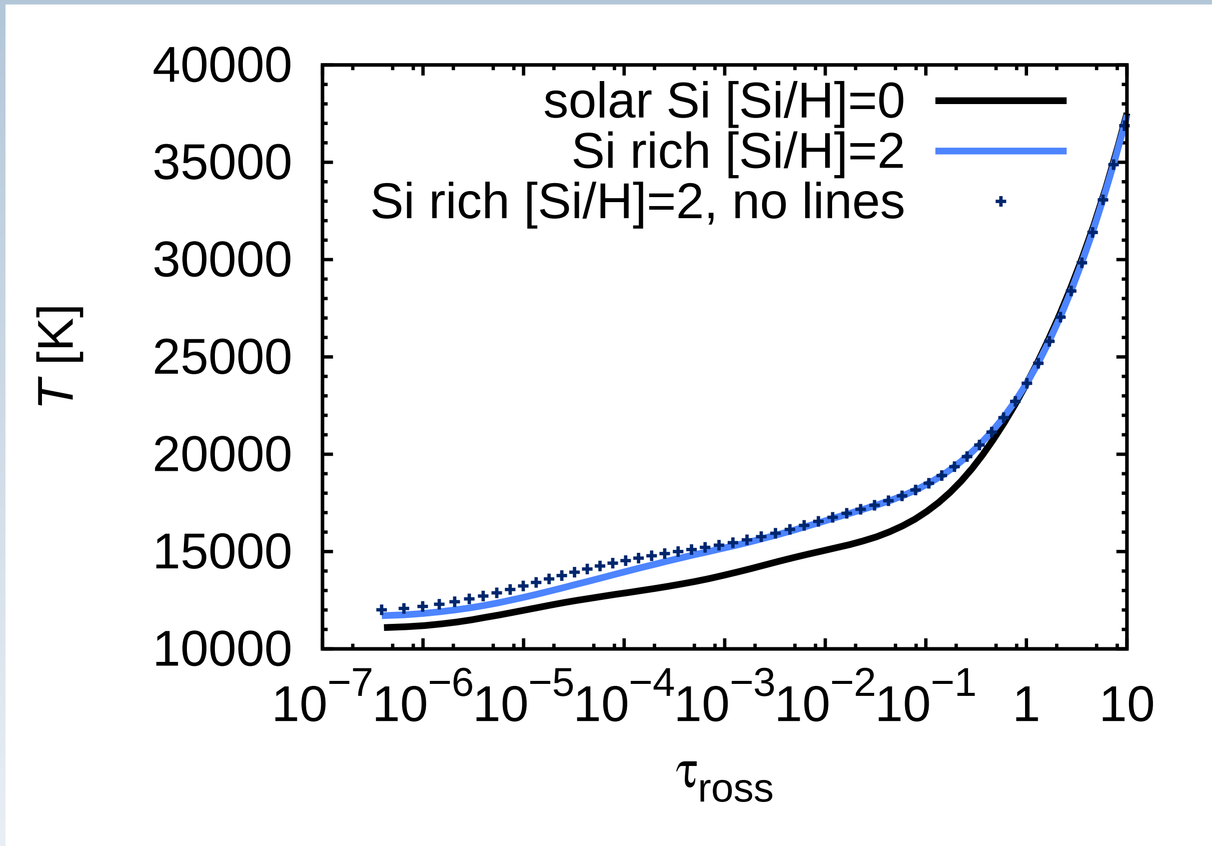
Si abundance variations

* the temperature



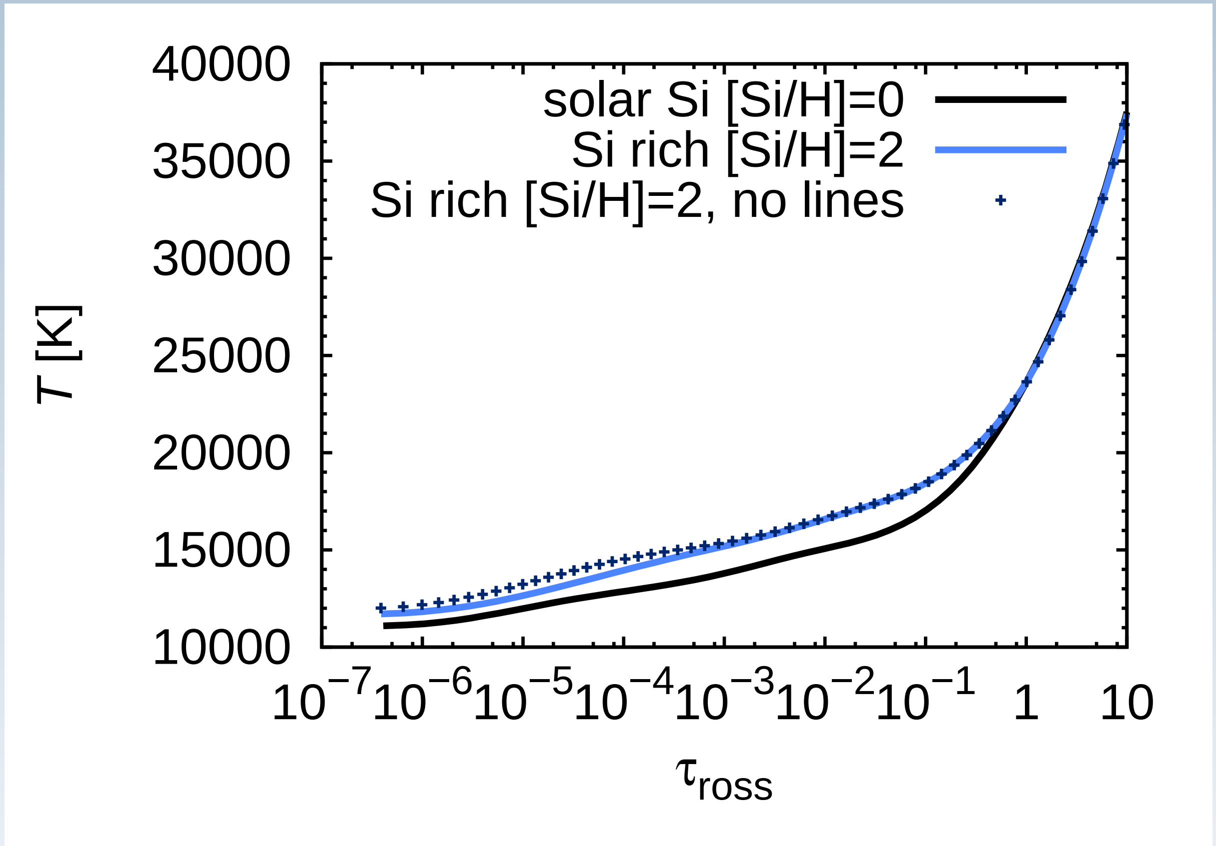
Si abundance variations

* the temperature



Si abundance variations

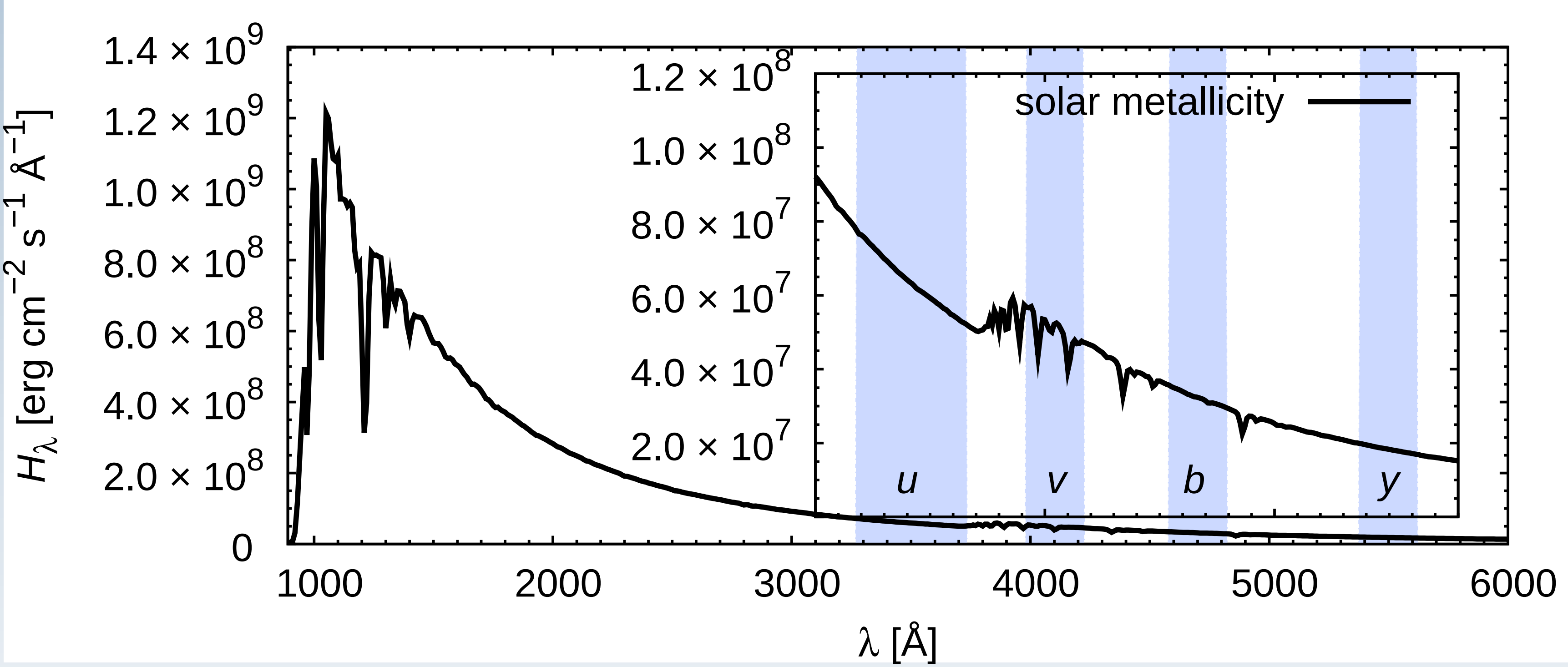
* the temperature



$\Rightarrow$ bound-free processes dominate silicon opacity

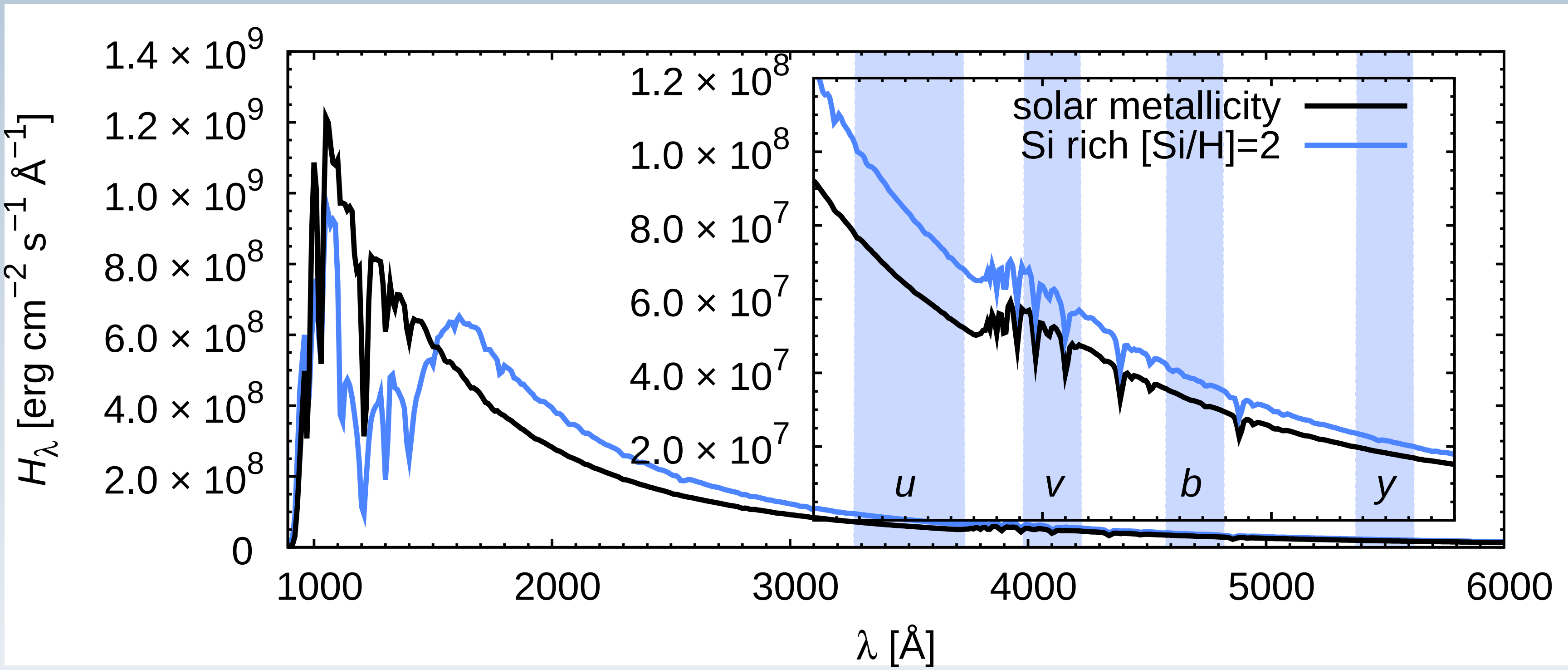
Si abundance variations

* the emergent flux



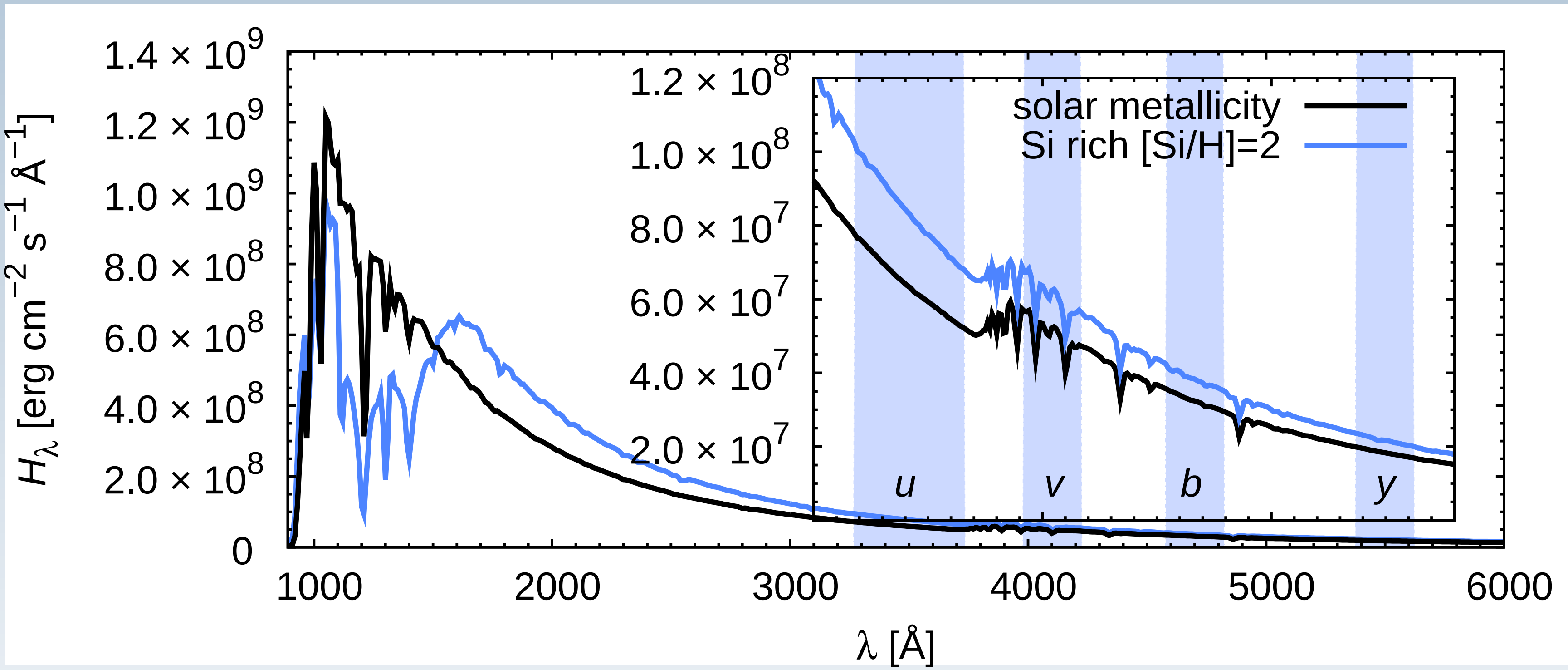
Si abundance variations

∗ the emergent flux



Si abundance variations

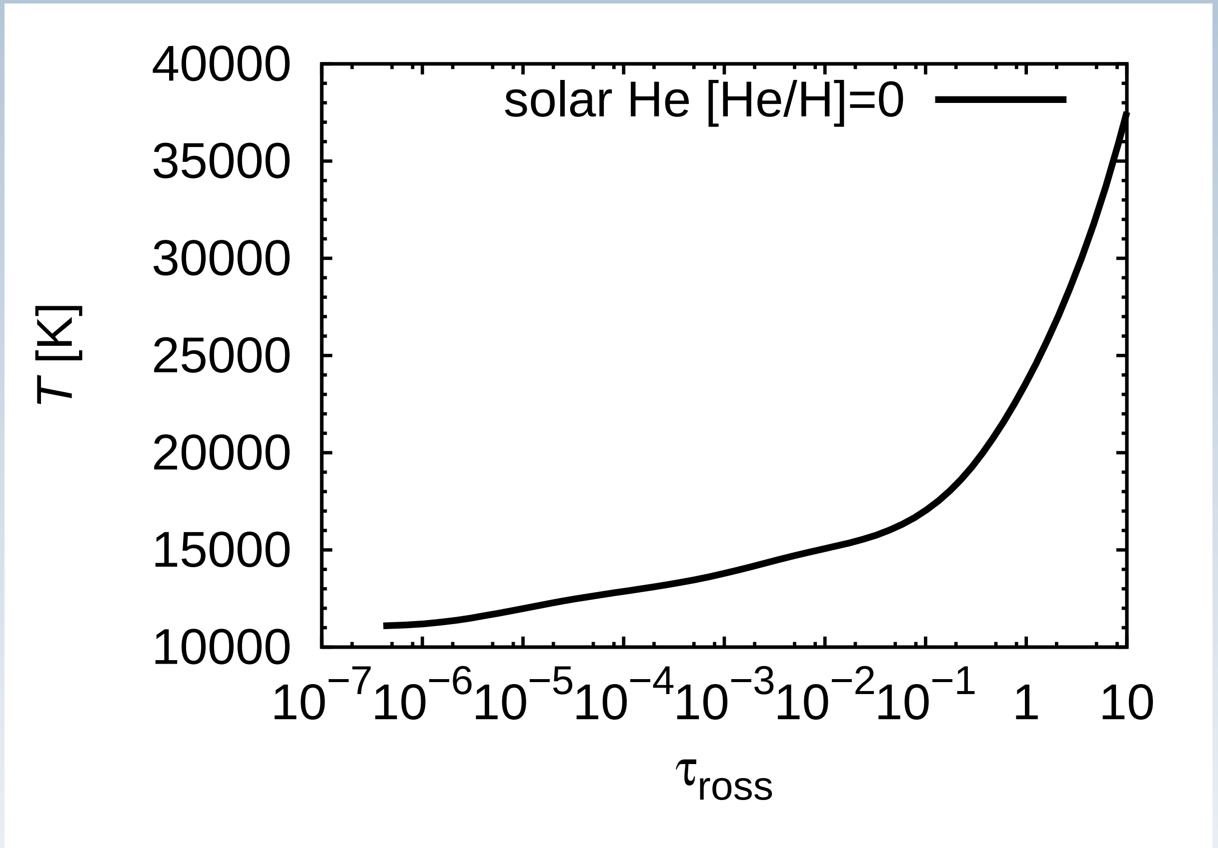
* the emergent flux



⇒ Si-rich spots are brighter

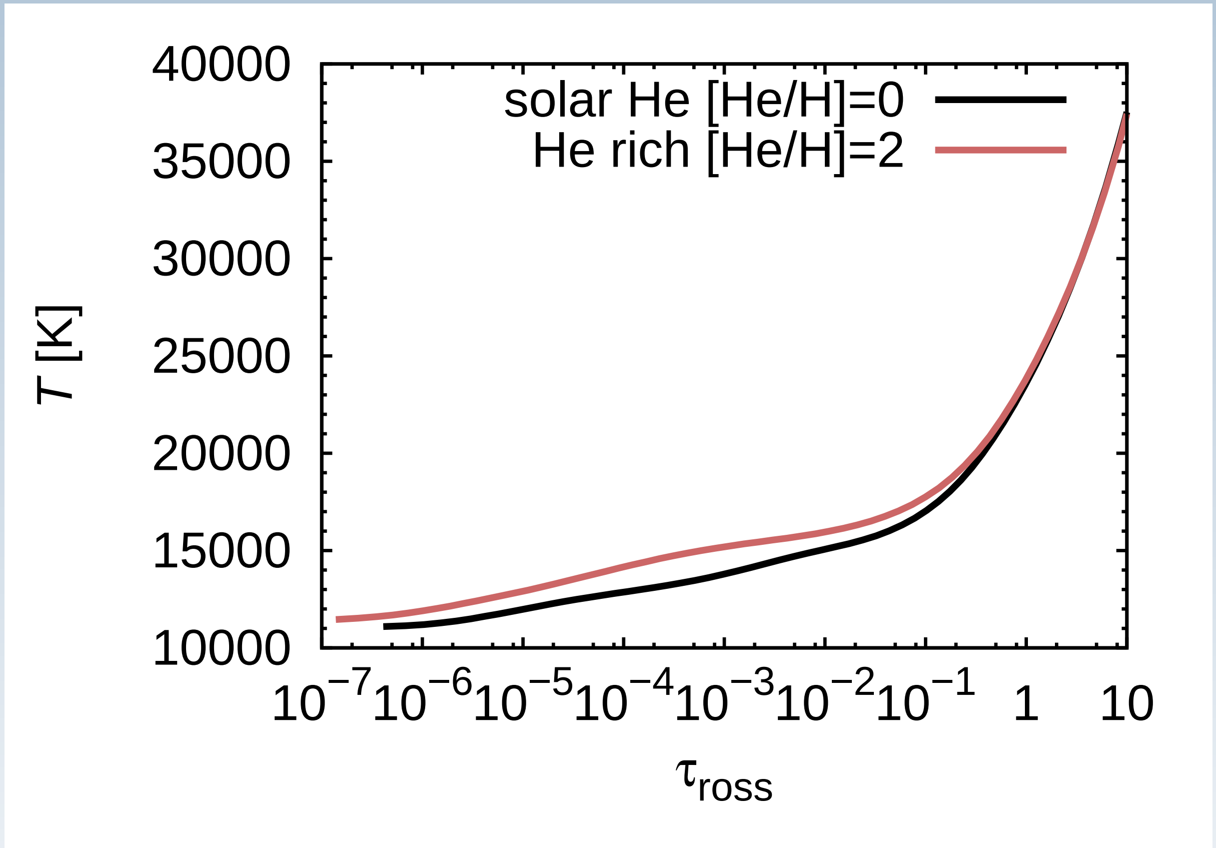
He abundance variations

* the temperature



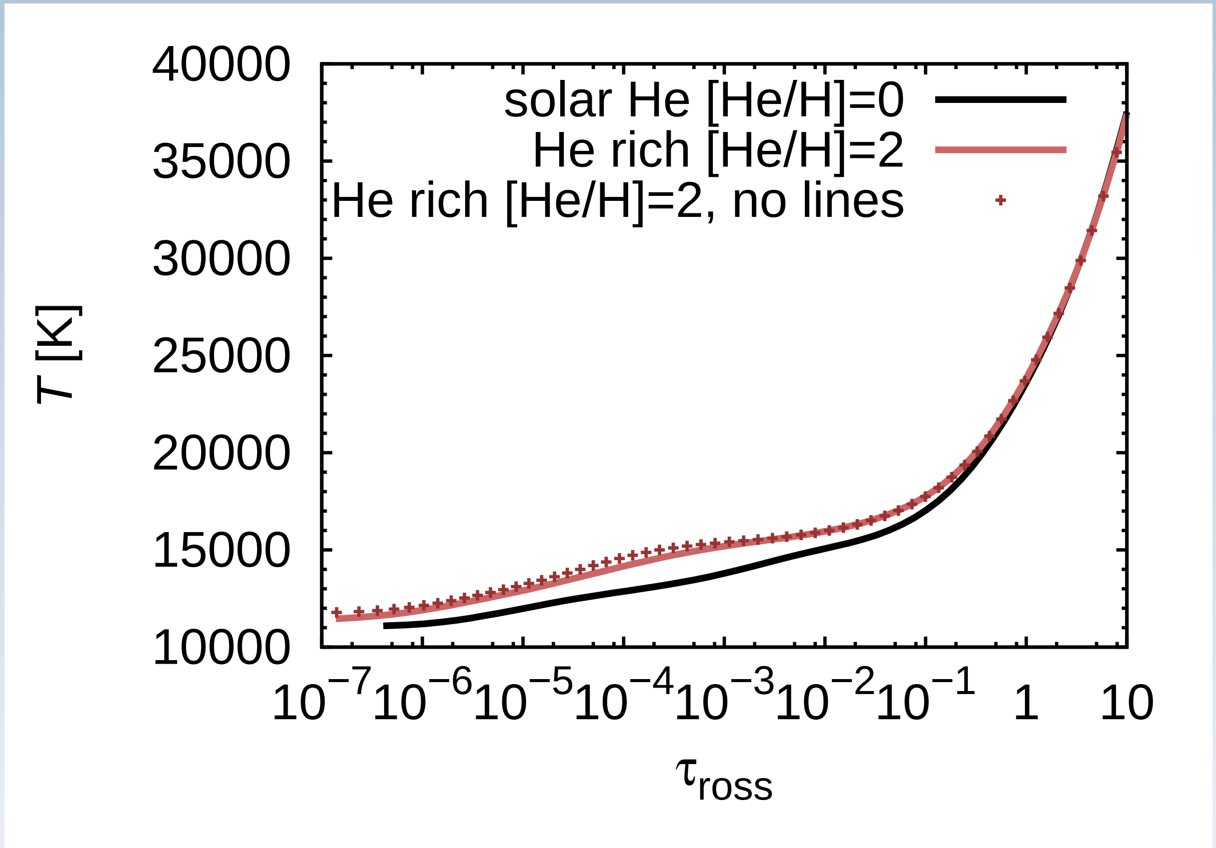
He abundance variations

* the temperature



He abundance variations

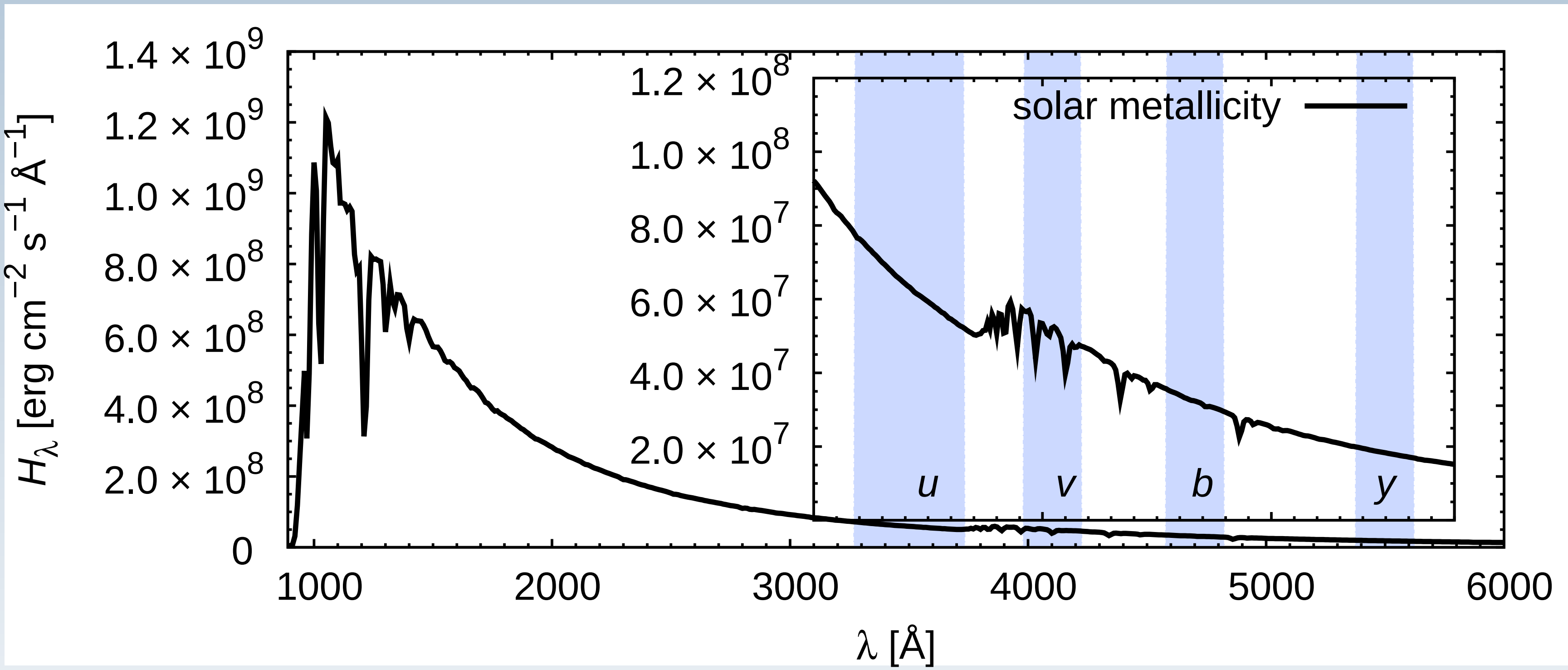
* the temperature



⇒ bound-free transitions dominate He opacity

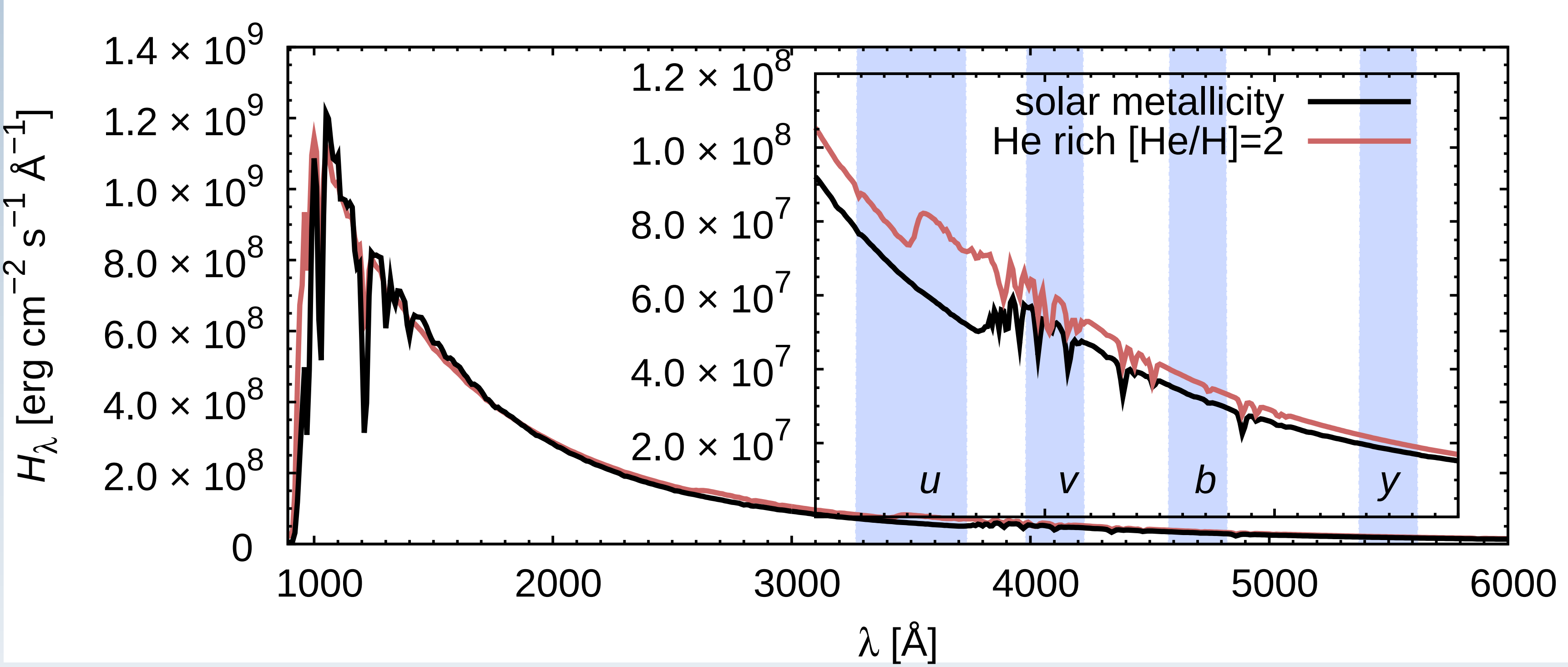
He abundance variations

* the emergent flux



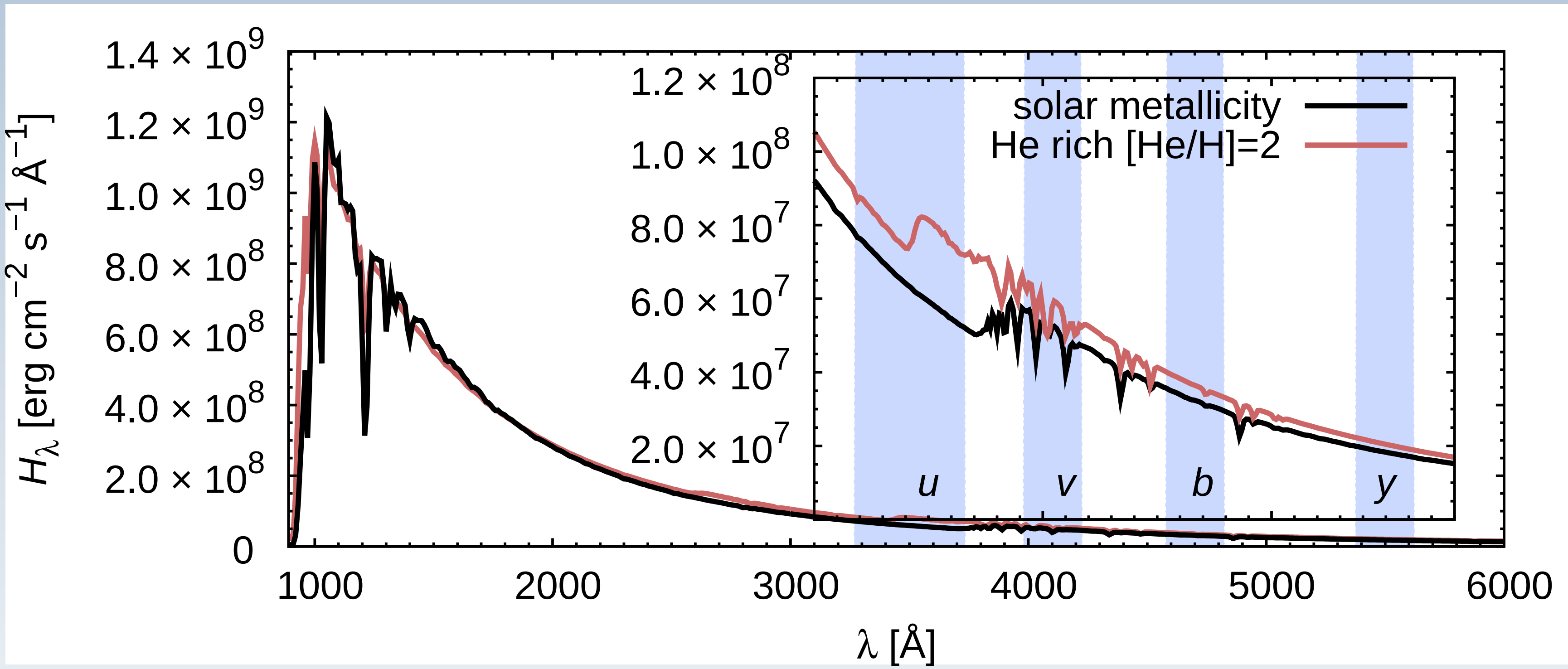
He abundance variations

- the emergent flux



He abundance variations

- the emergent flux



⇒ He-rich spots are brighter

The light variability due to He

* He rich spots are brighter

The light variability due to He

- He rich spots are brighter
- He rich spots visible for $\phi \approx 0.2$

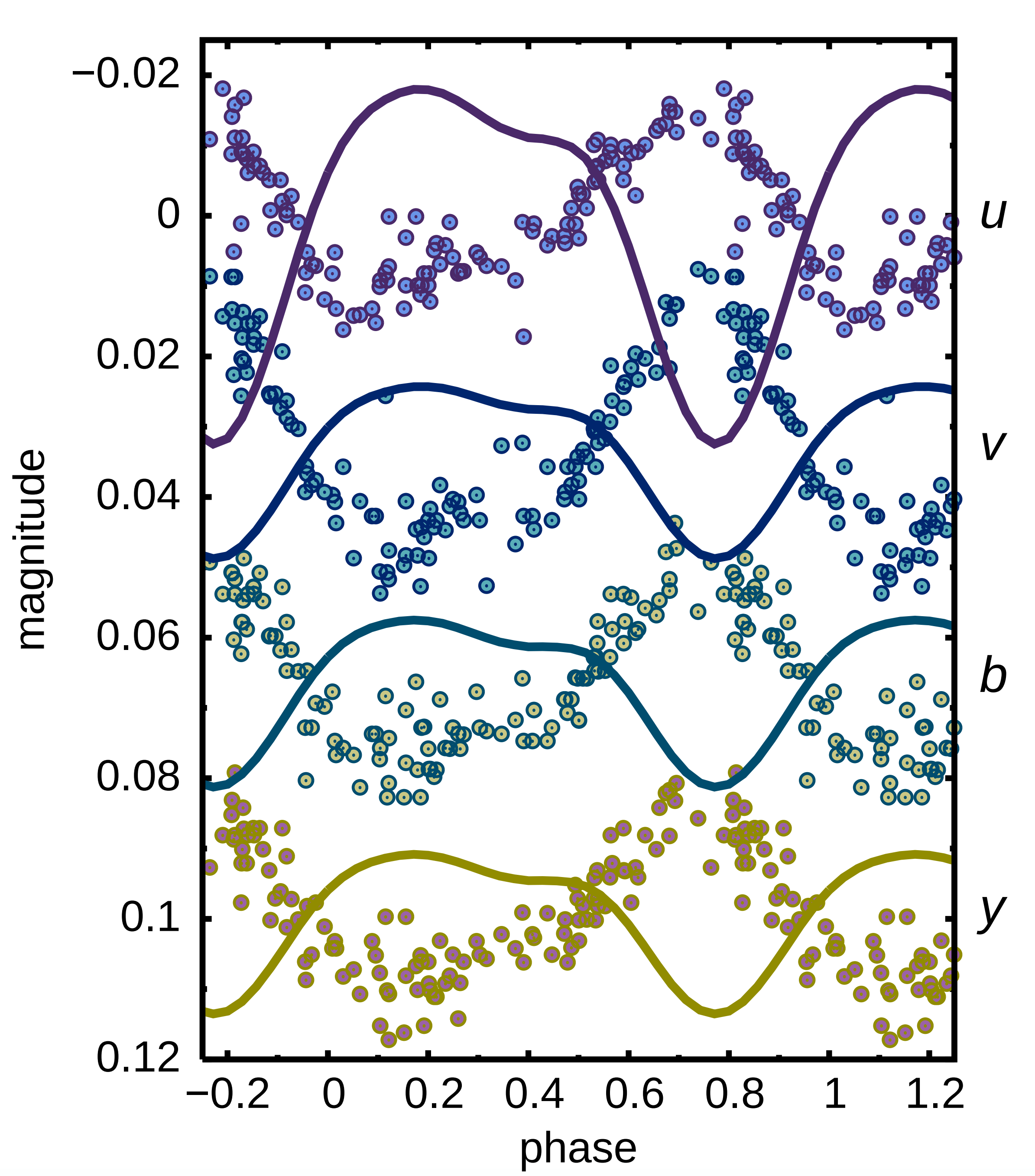
The light variability due to He

* He rich spots are brighter
* He rich spots visible for $\phi \approx 0.2$
* theory: star is brighter for $\phi \approx 0.2$

The light variability due to He

* He rich spots are brighter
* He rich spots visible for $\phi \approx 0.2$
* theory: star is brighter for $\phi \approx 0.2$
* observation: star is brighter for $\phi \approx 0.75$

The light variability due to He



The light variability due to Si

* Si rich spots are brighter

The light variability due to Si

- Si rich spots are brighter
- Si rich spots visible for $\phi \approx 0.75$

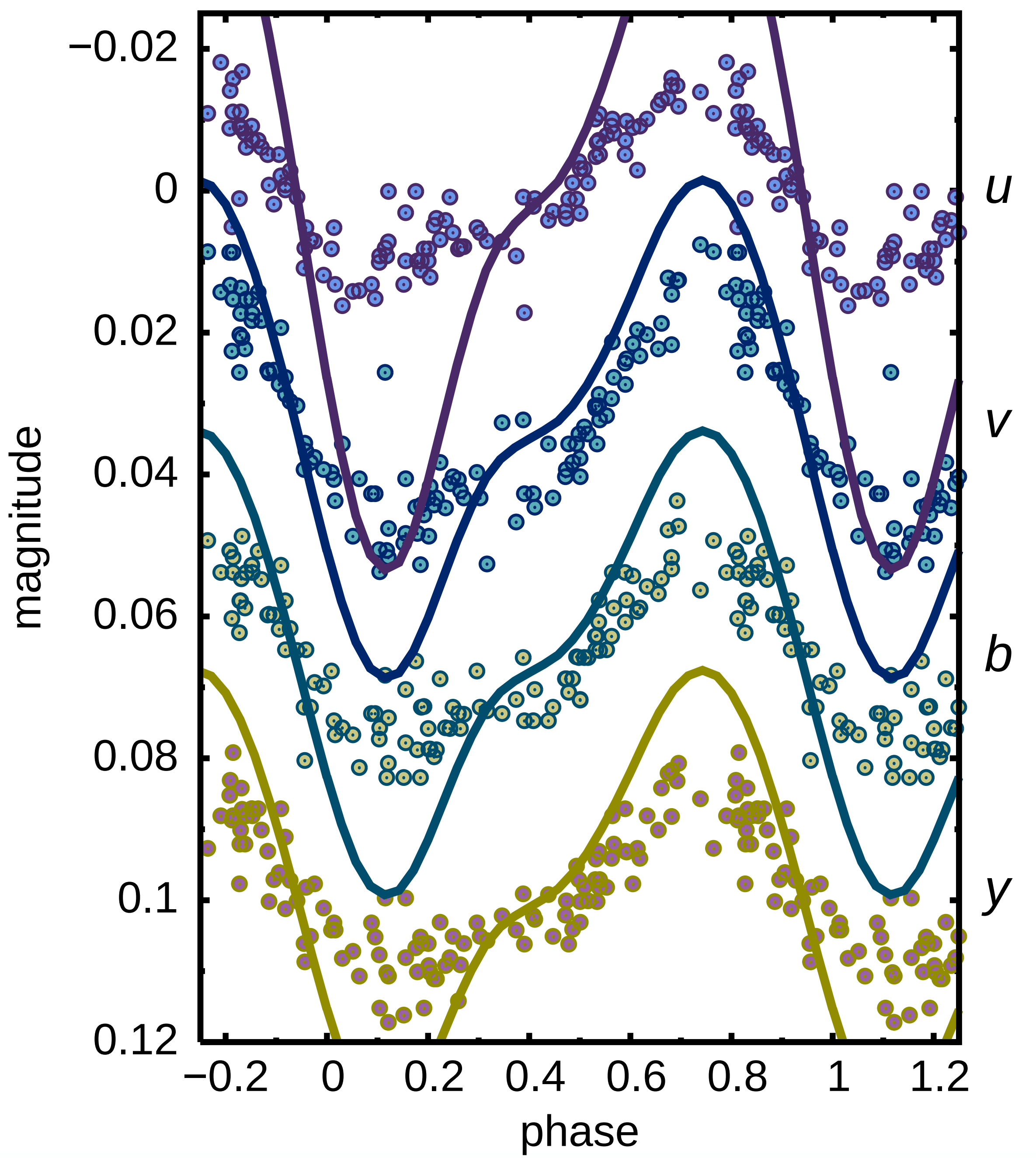
The light variability due to Si

* Si rich spots are brighter
* Si rich spots visible for $\phi \approx 0.75$
* theory: star is brighter for $\phi \approx 0.75$

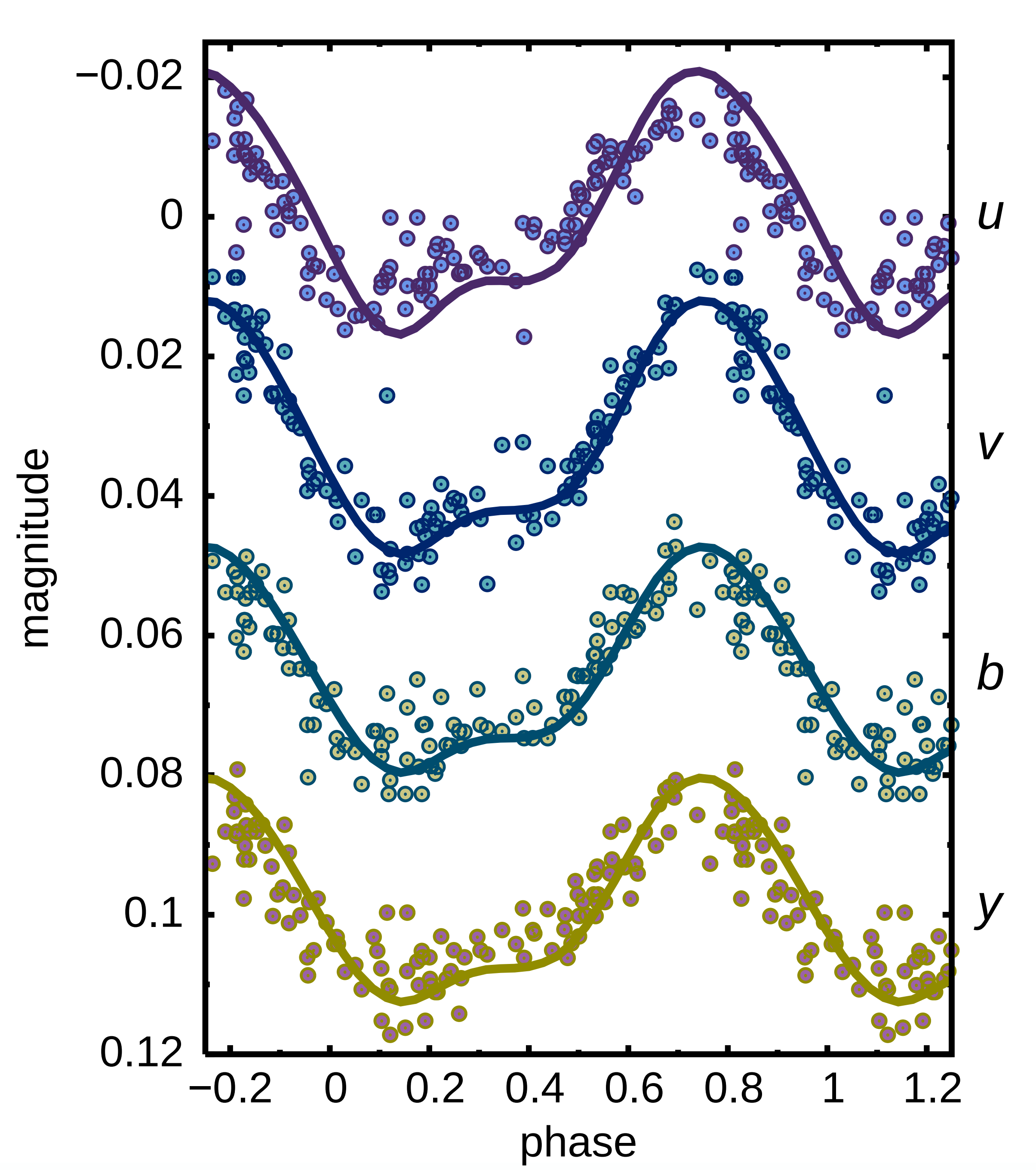
The light variability due to Si

- Si rich spots are brighter
- Si rich spots visible for $\phi \approx 0.75$
- theory: star is brighter for $\phi \approx 0.75$
- observation: star is brighter for $\phi \approx 0.75$

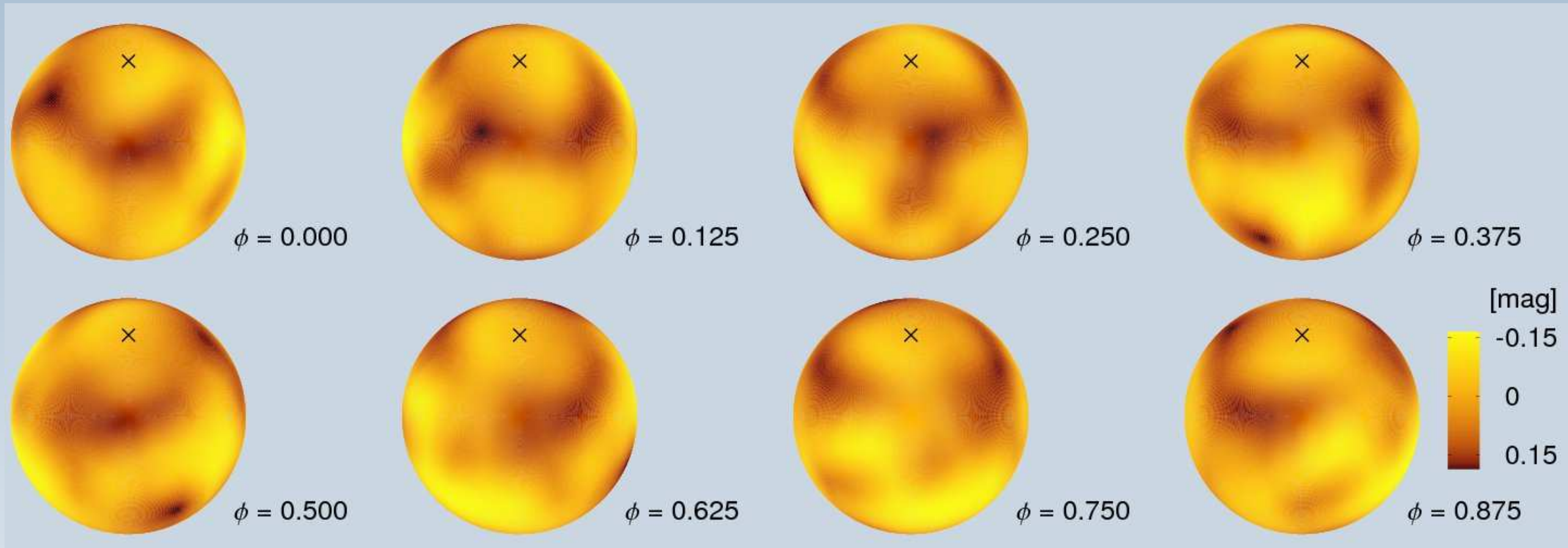
The light variability due to Si



The light variability due to He+Si

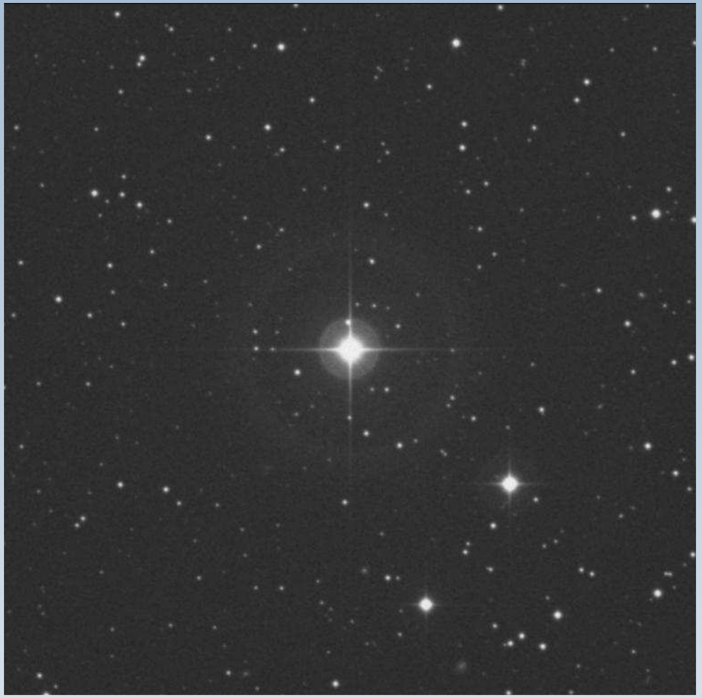


Visible surface in *u* colour



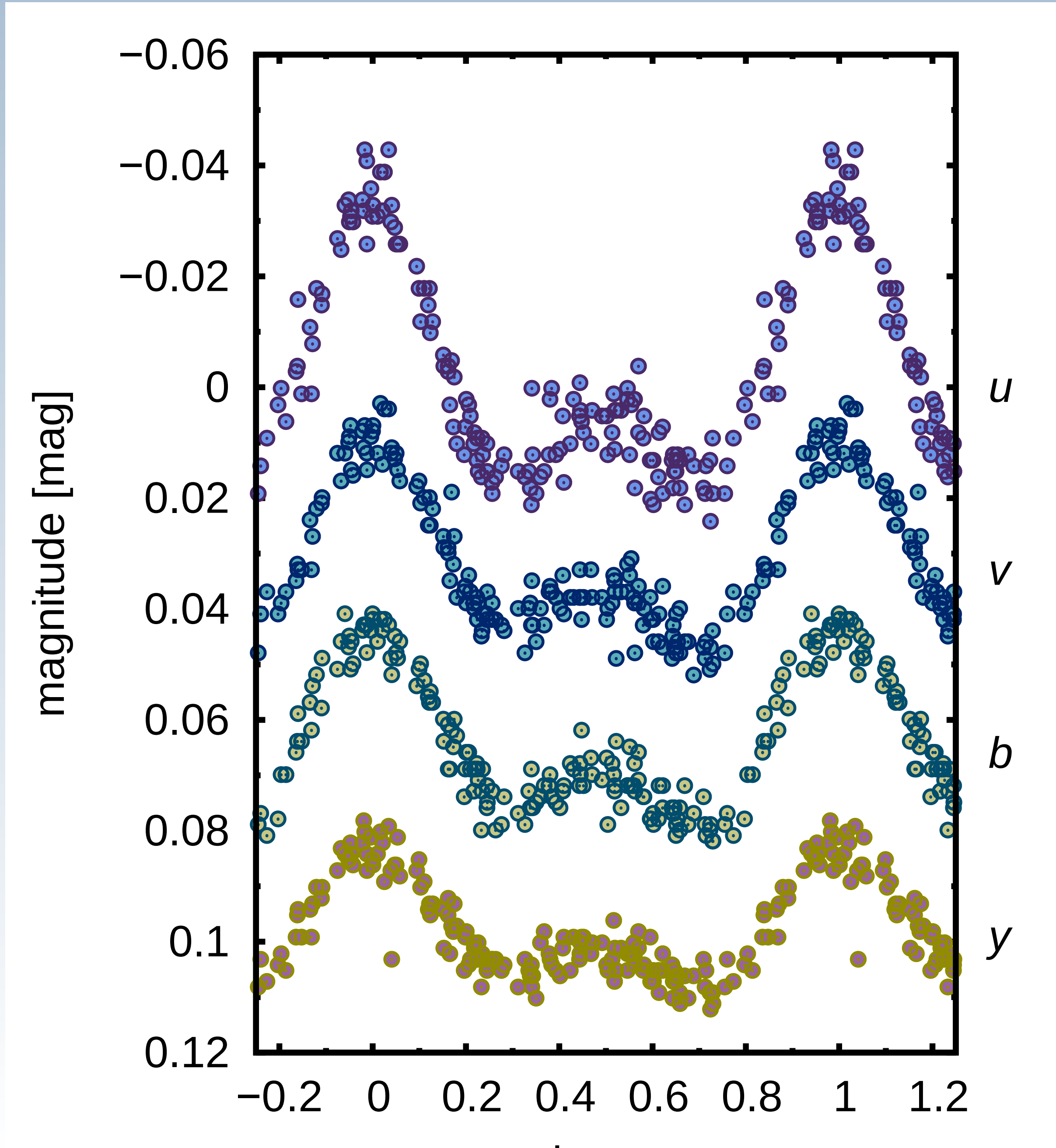
Another test: HR 7224

- HD 177410, EE Dra
- spectral type B9.5 IIIp
- helium-weak silicon star
- $T_{\text{eff}} = 14\,500\,$K, $\log g = 4.2$ (Lehmann et al. 2006)



HR 7224: observed variations

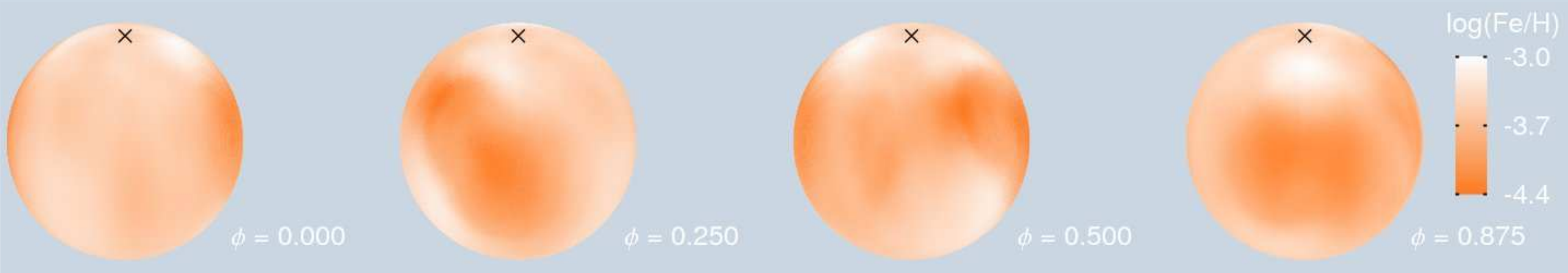
Adelman (1997)



HR 7224: surface distribution

silicon

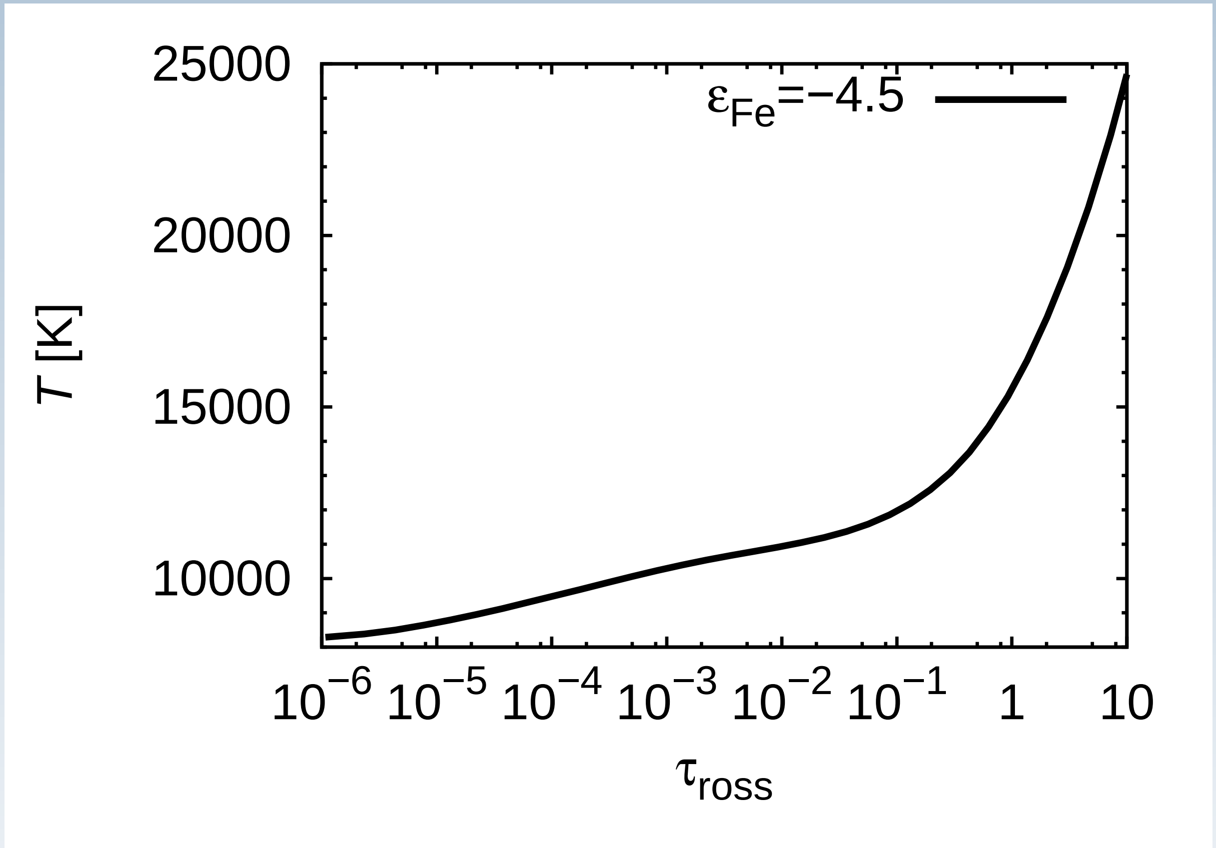
iron



(Lehmann et al. 2007)

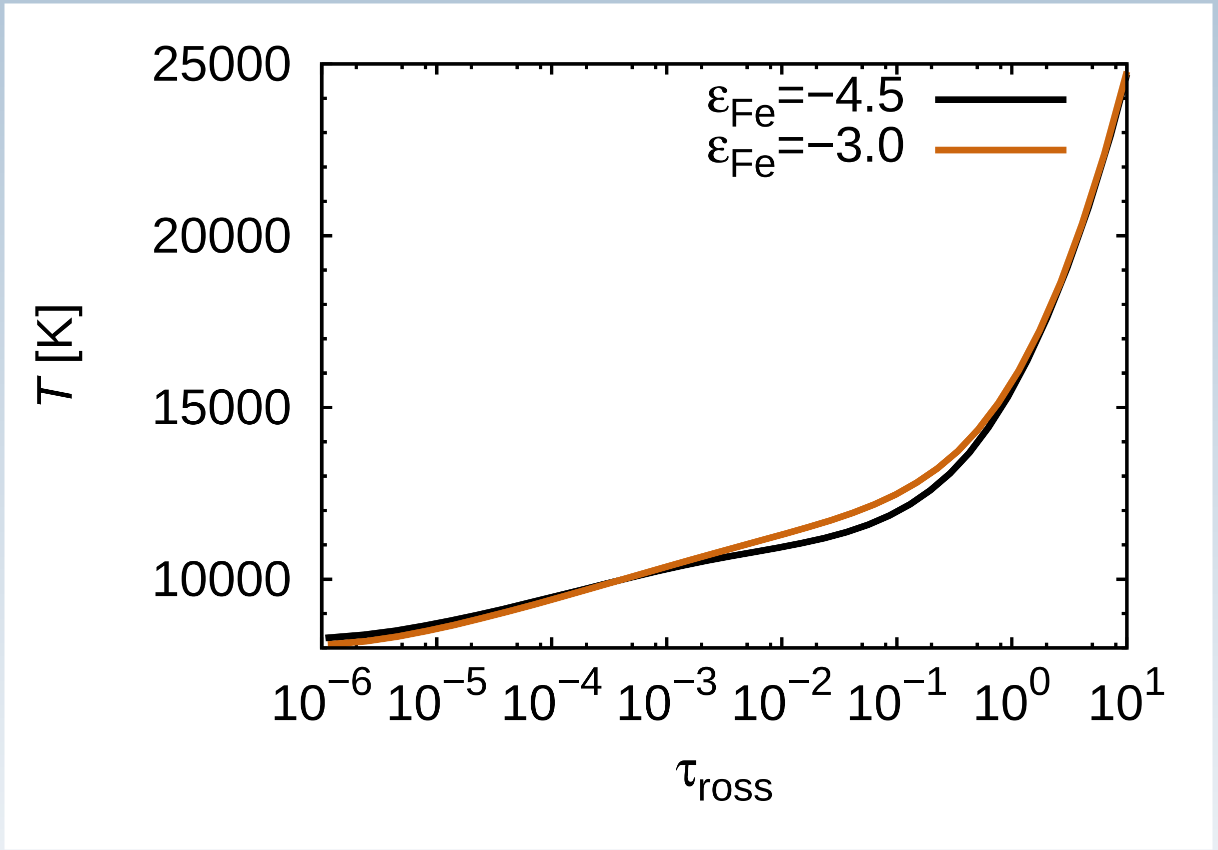
Fe abundance variations

* the temperature



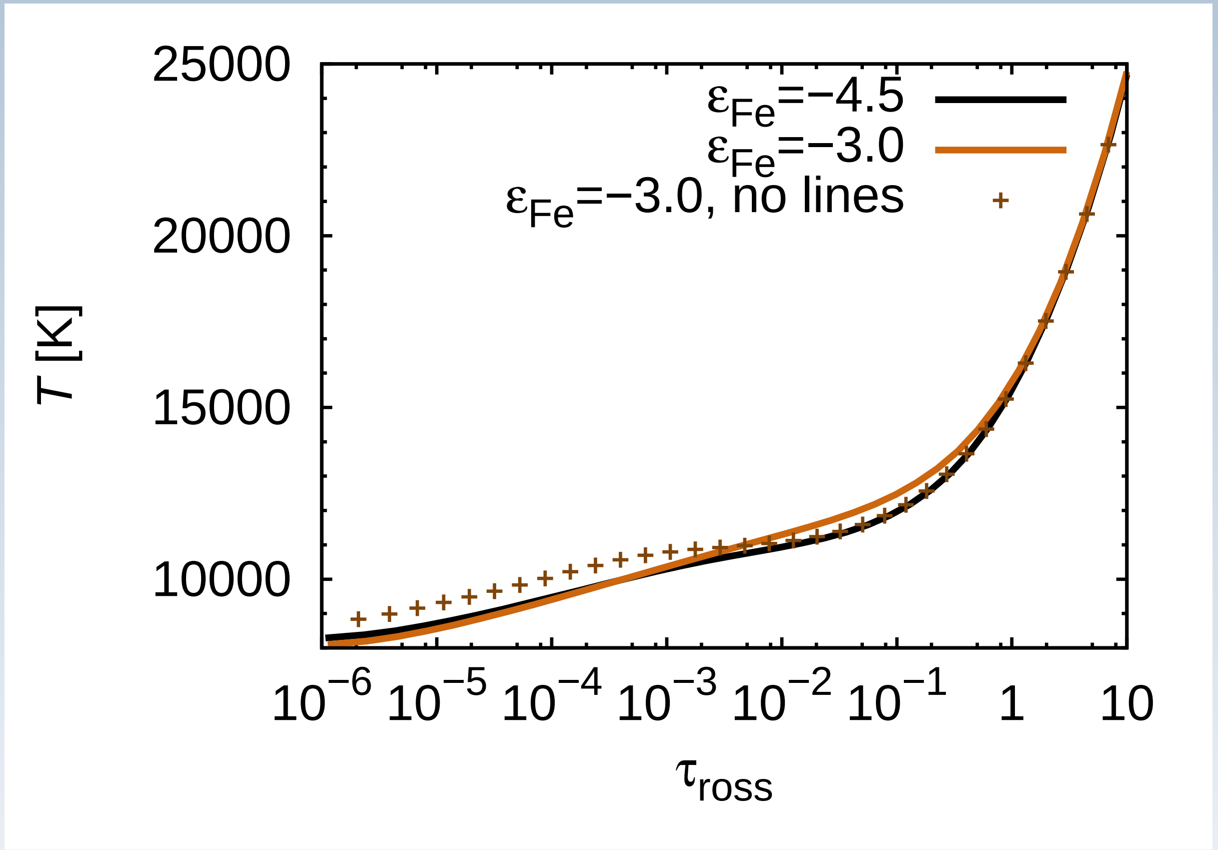
Fe abundance variations

* the temperature



Fe abundance variations

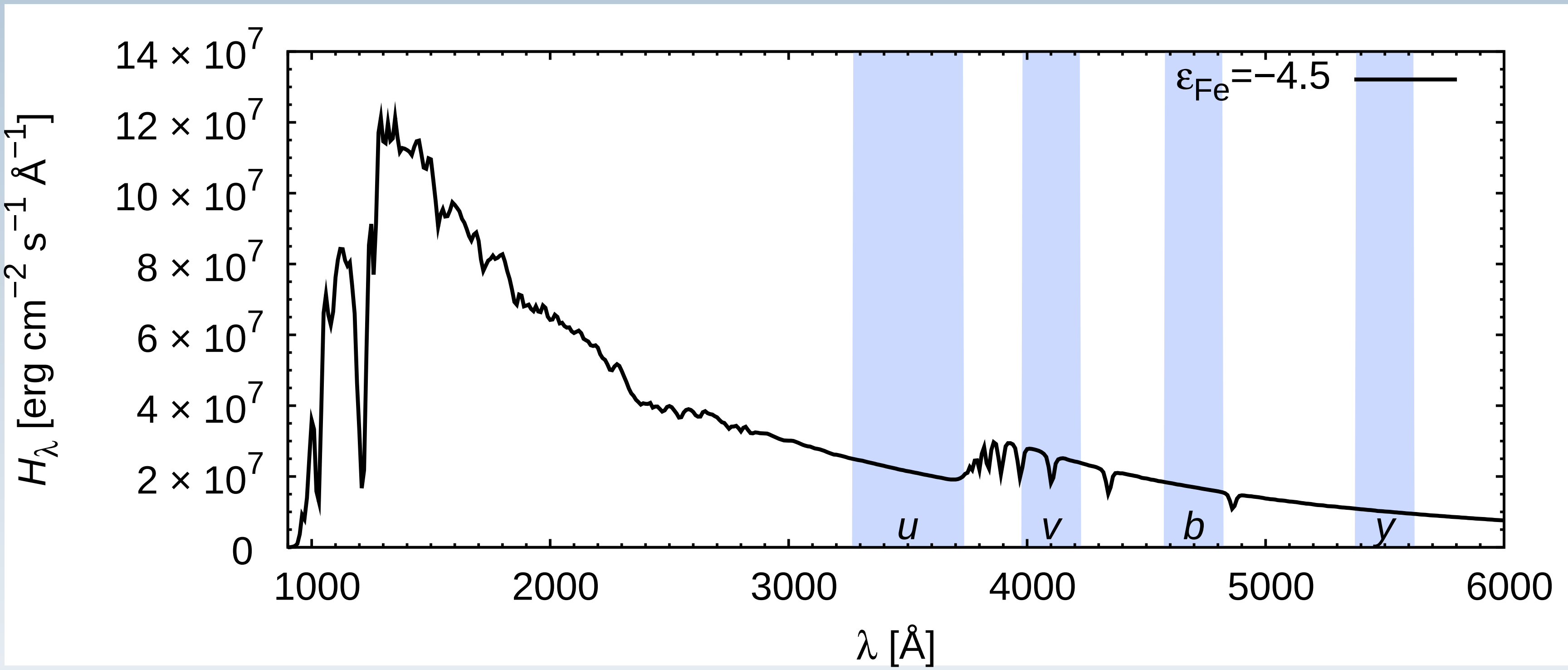
* the temperature



⇒ line transitions dominate the opacity due to Fe

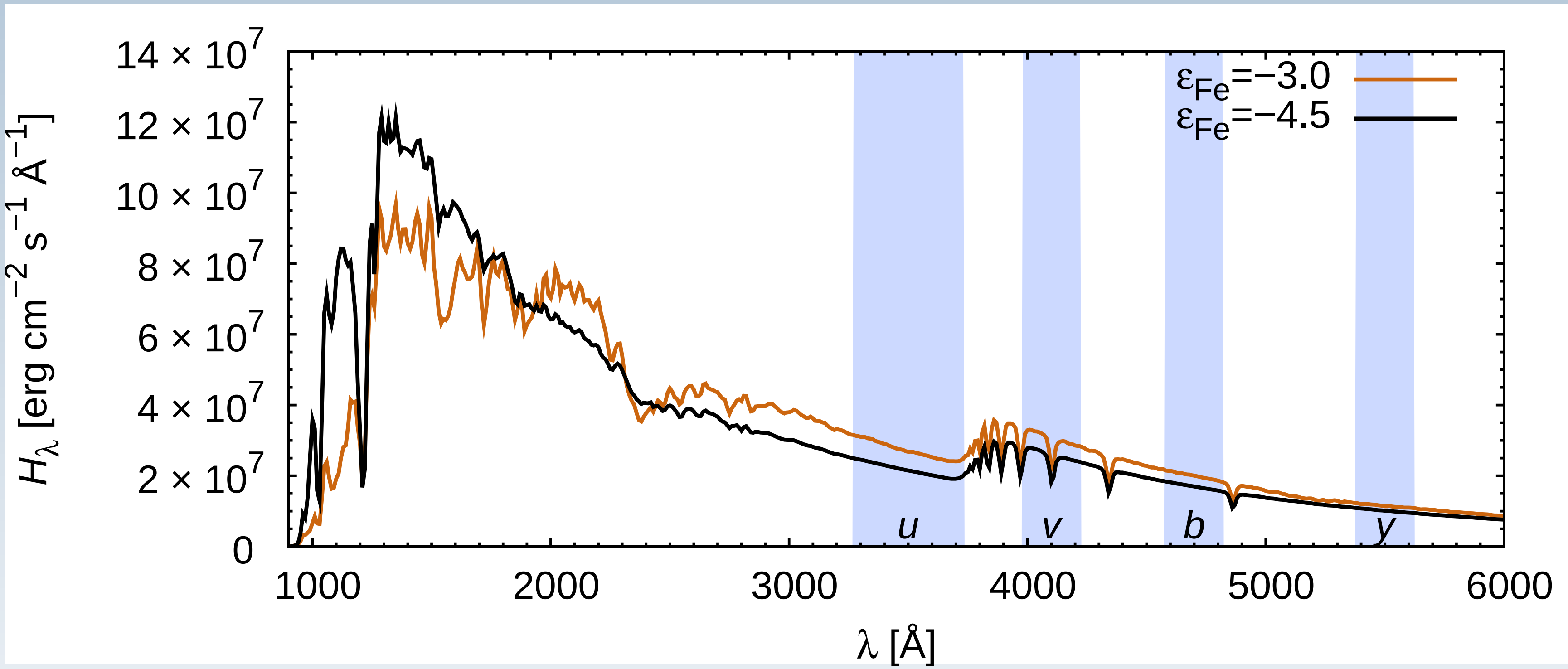
Fe abundance variations

- the emergent flux



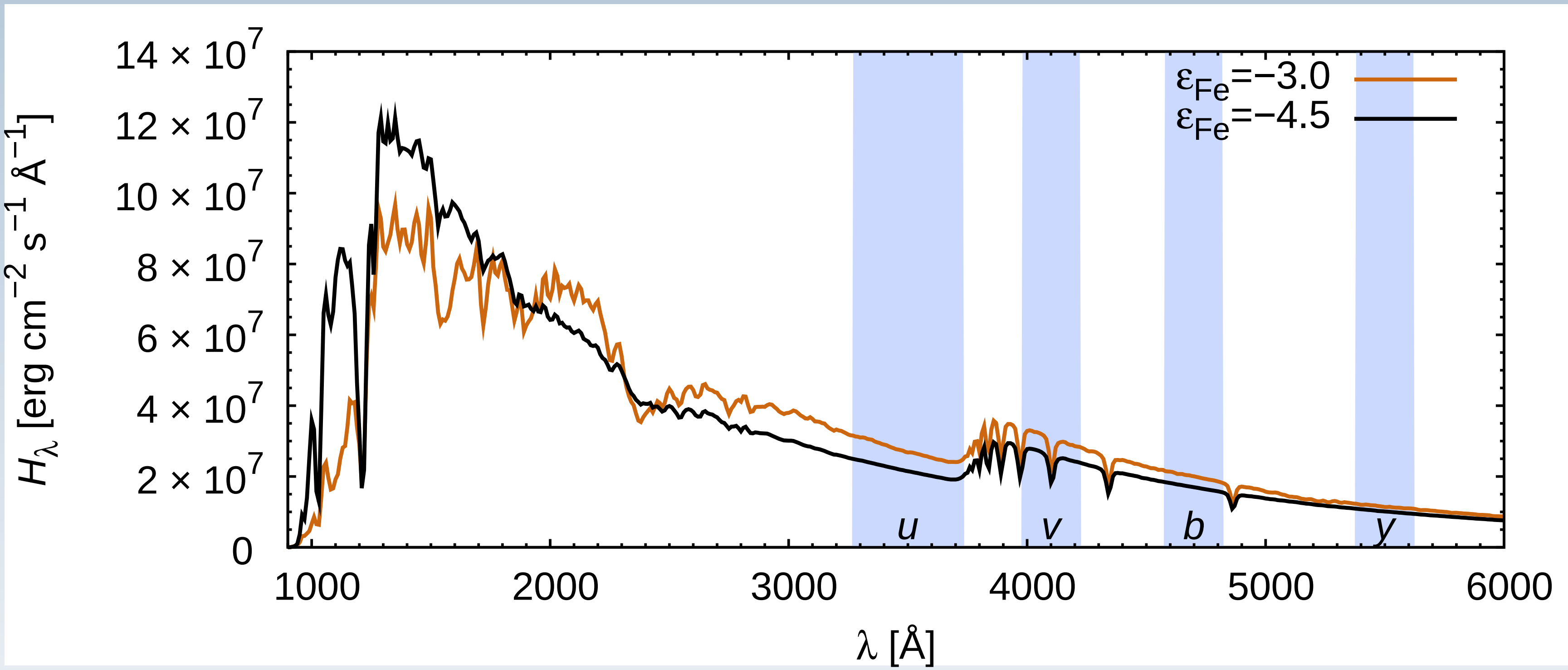
Fe abundance variations

* the emergent flux



Fe abundance variations

* the emergent flux



⇒ Fe-rich spots are brighter

Light variations due to Si+Fe

- silicon rich spot visible for the phase $\phi \approx 0$

Light variations due to Si+Fe

- ∗ silicon rich spot visible for the phase $\phi \approx 0$
  - ⋆ silicon rich spot brighter in the visible

Light variations due to Si+Fe

* silicon rich spot visible for the phase $\phi \approx 0$
  * silicon rich spot brighter in the visible
* iron rich spot visible for the phase $\phi \approx 0$

Light variations due to Si+Fe

- silicon rich spot visible for the phase $\phi \approx 0$
  - silicon rich spot brighter in the visible
- iron rich spot visible for the phase $\phi \approx 0$
  - iron rich spot brighter in the visible

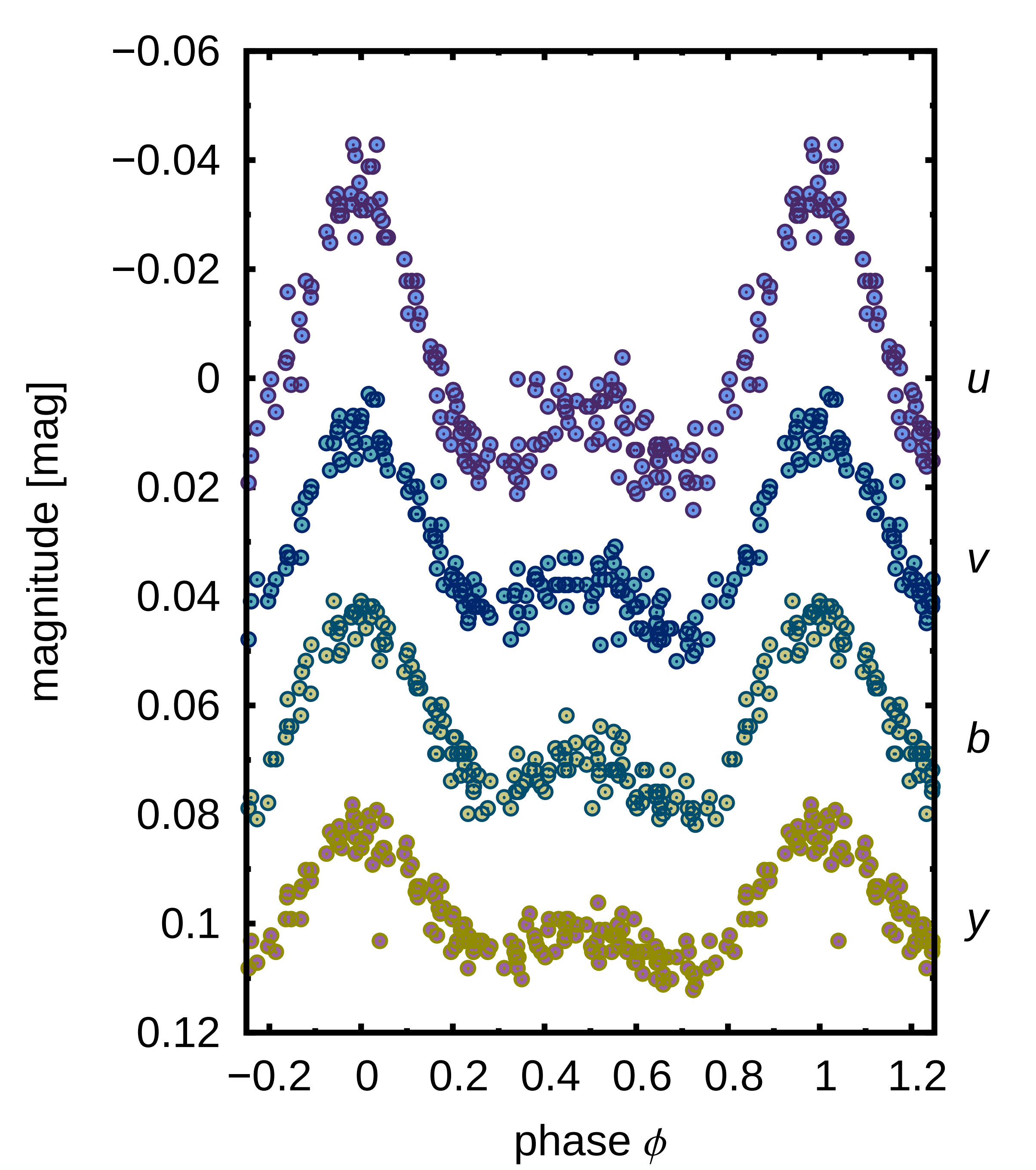
Light variations due to Si+Fe

- silicon rich spot visible for the phase $\phi \approx 0$
  - silicon rich spot brighter in the visible
- iron rich spot visible for the phase $\phi \approx 0$
  - iron rich spot brighter in the visible
- prediction: light maximum occurs for the phase $\phi \approx 0$

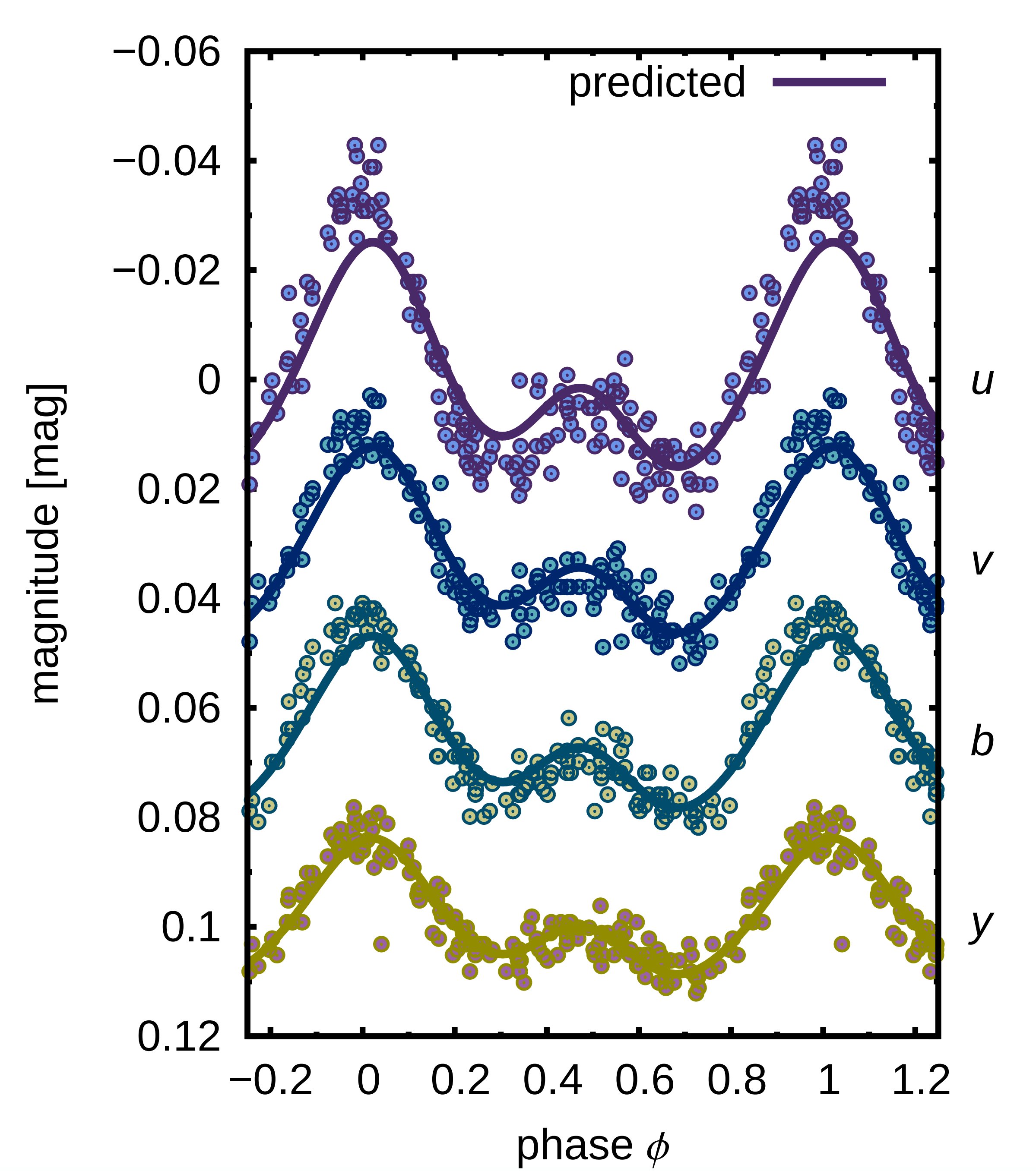
Light variations due to Si+Fe

- silicon rich spot visible for the phase $\phi \approx 0$
  - silicon rich spot brighter in the visible
- iron rich spot visible for the phase $\phi \approx 0$
  - iron rich spot brighter in the visible
- prediction: light maximum occurs for the phase $\phi \approx 0$
- observation: light maximum occurs for the phase $\phi \approx 0$

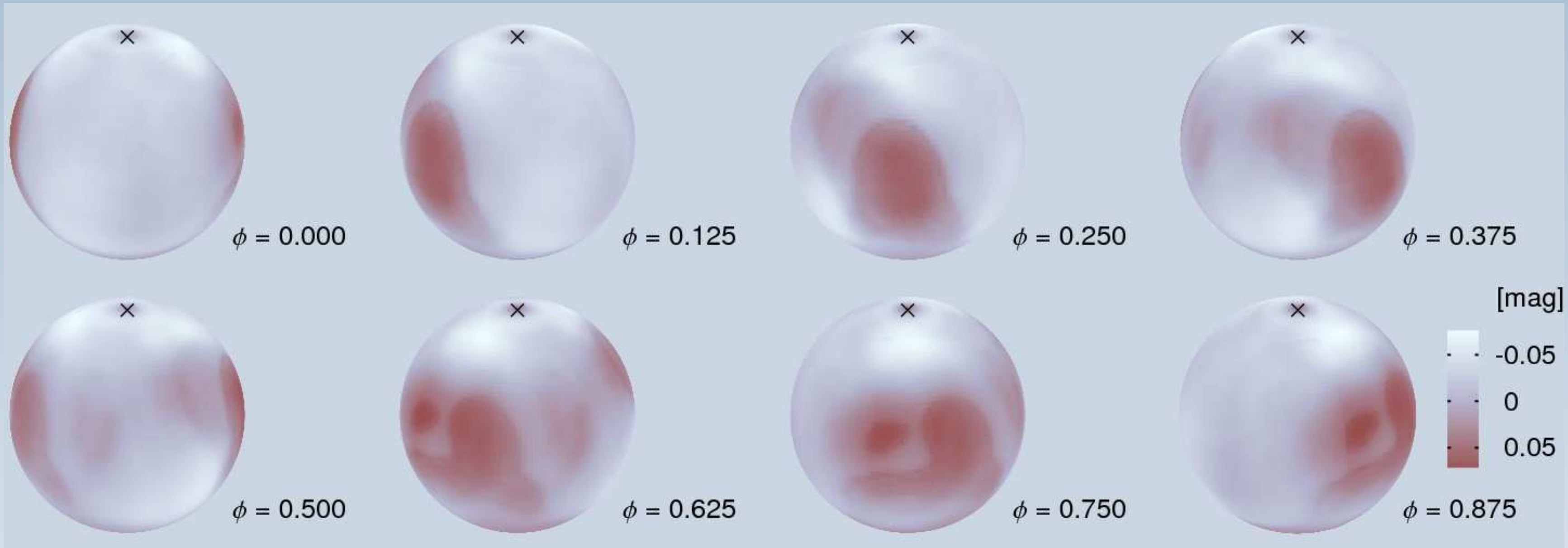
Light variations due to Si+Fe



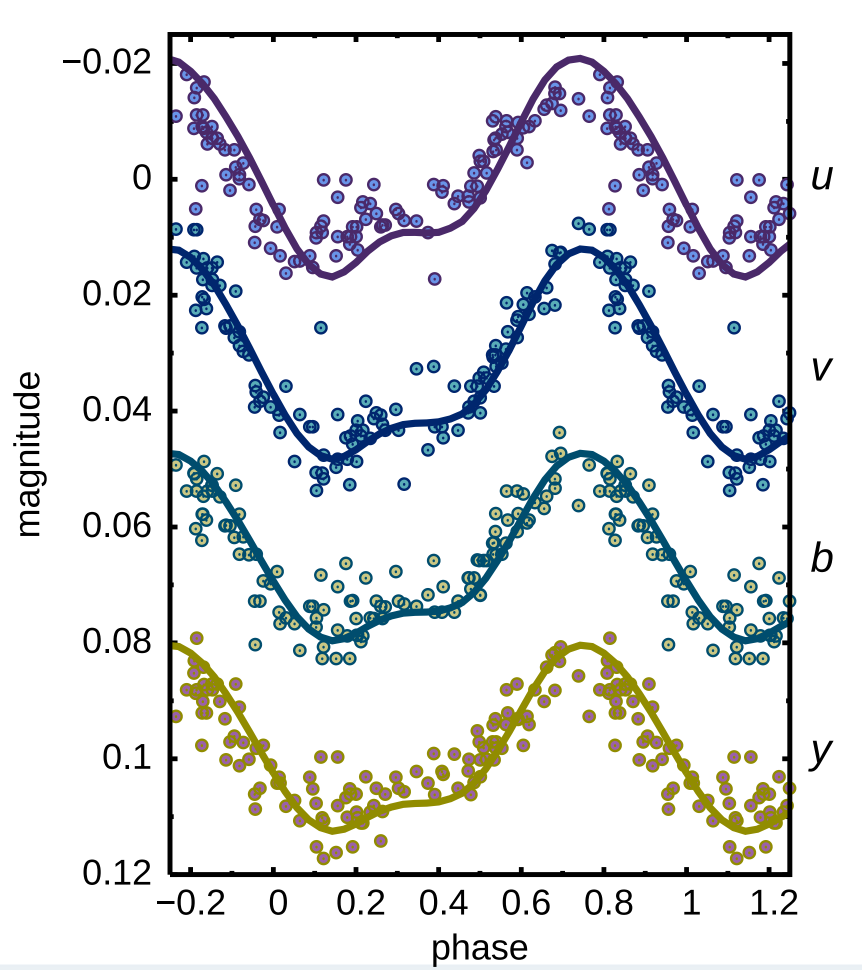
Light variations due to Si+Fe

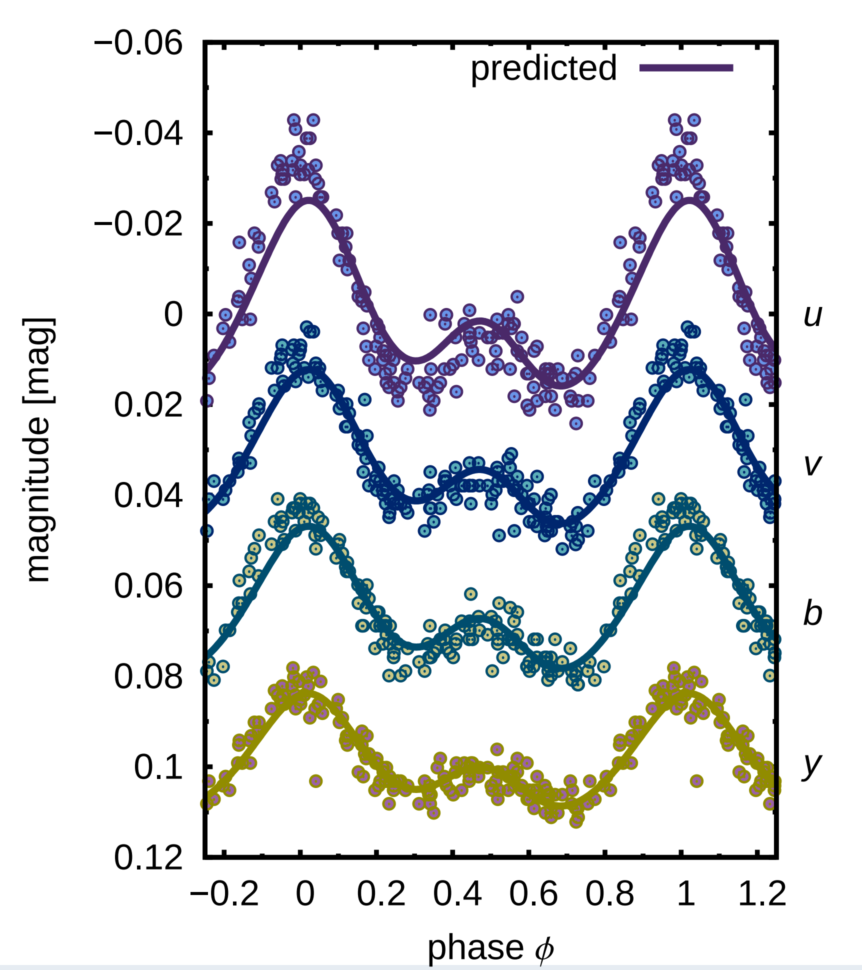


Visible surface in *u* colour



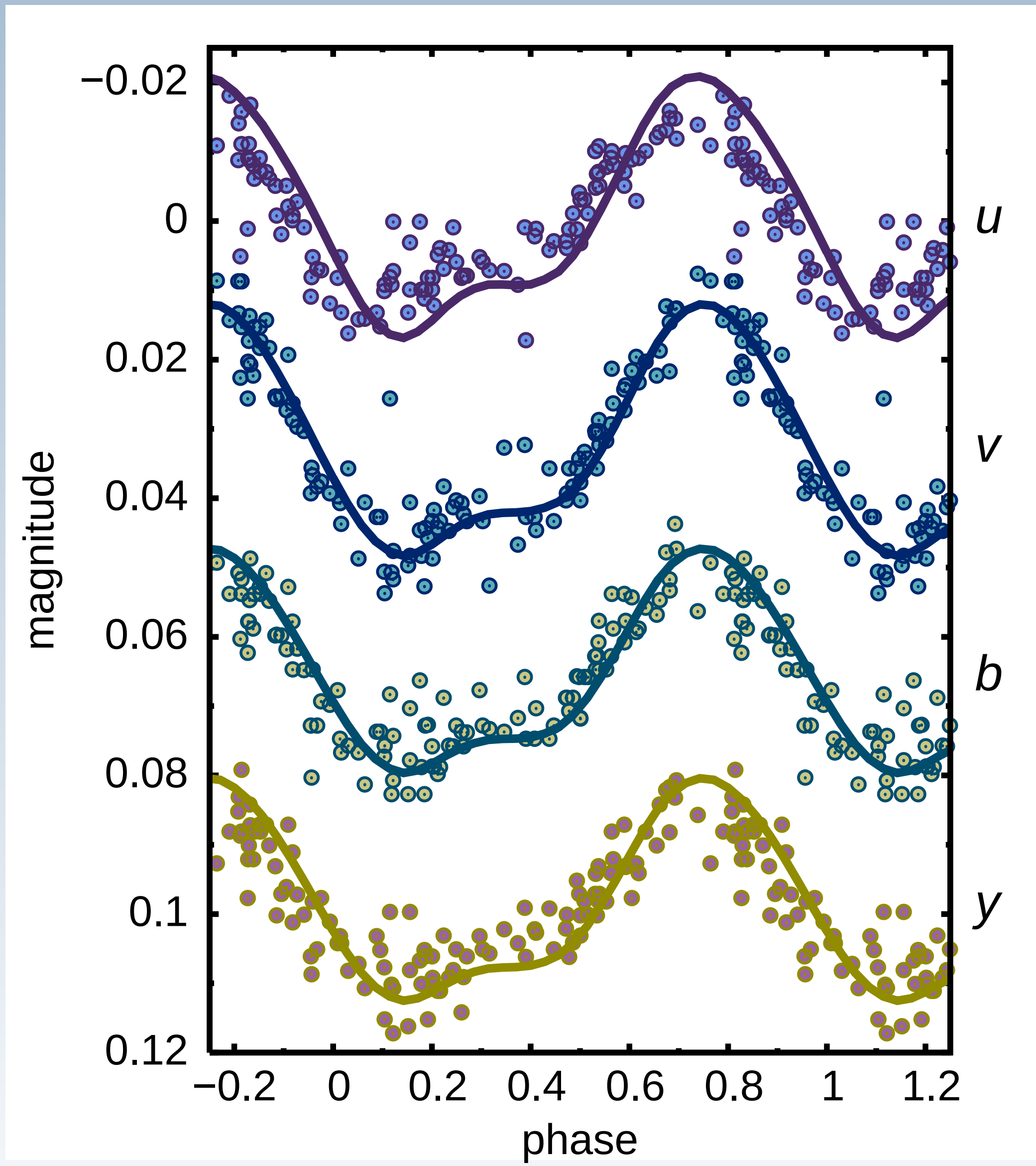
Other stars. . .



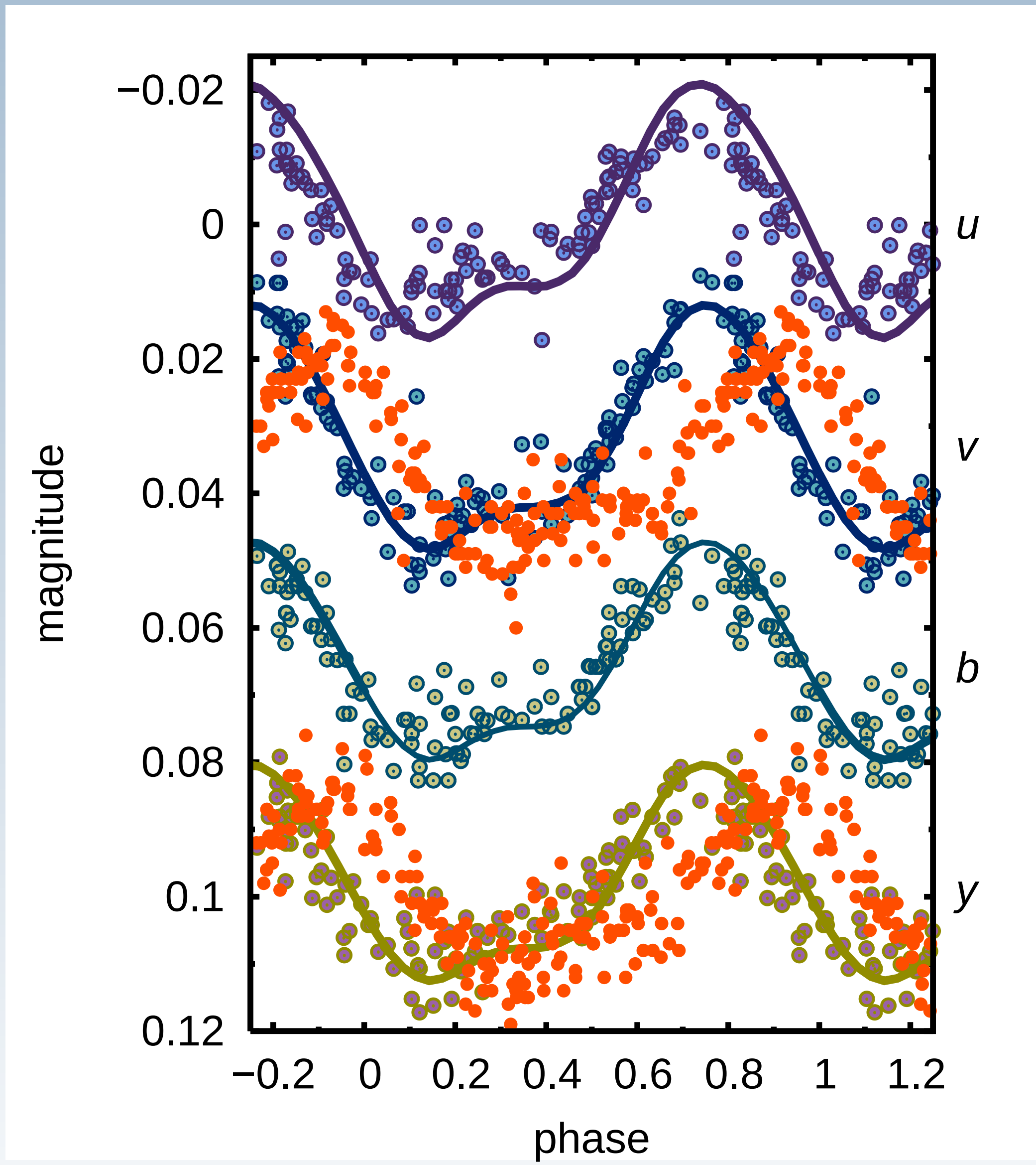


∗ important likely also for other CP stars

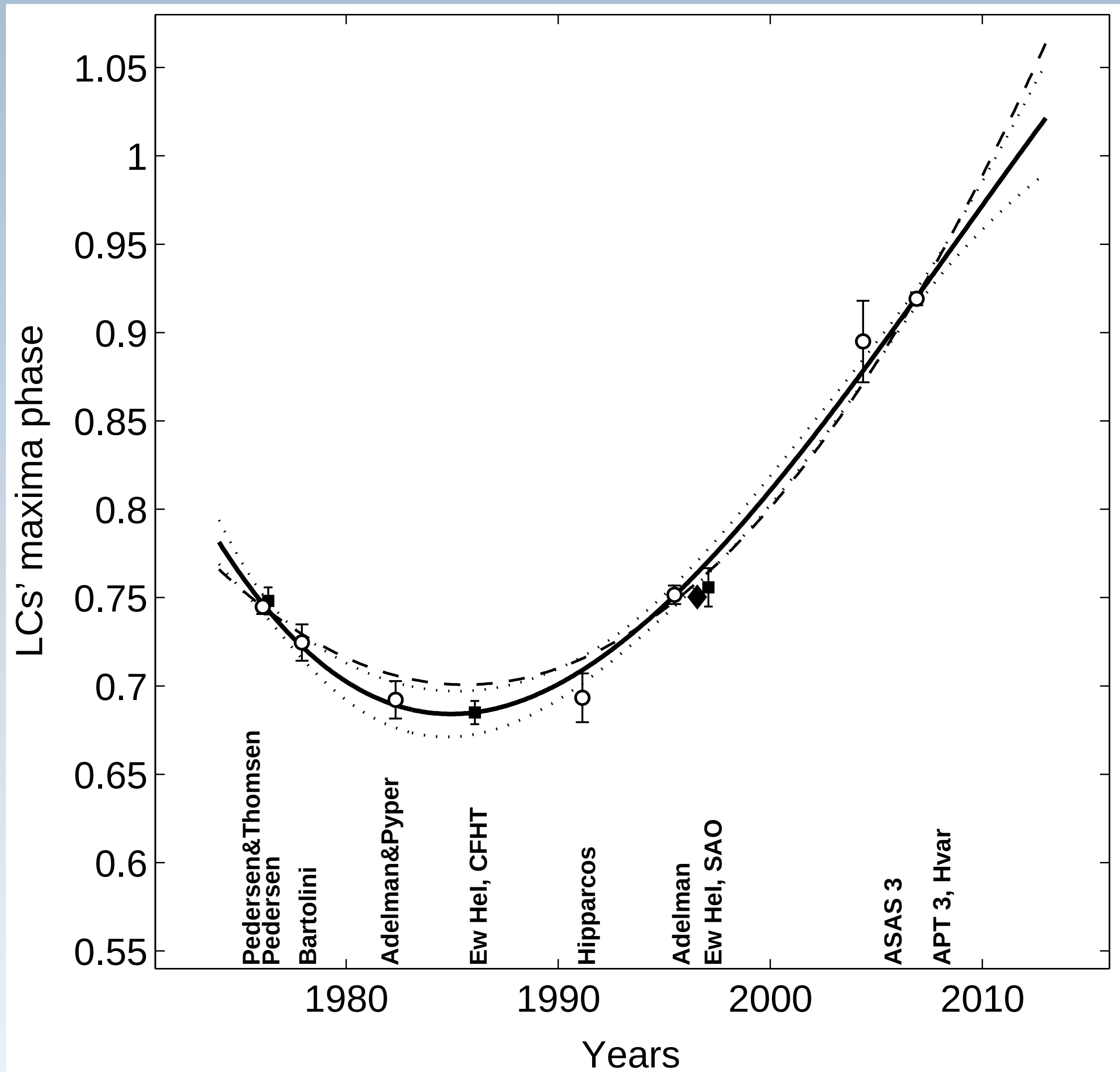
HD 37776: A closer look



HD 37776: new observations



HD 37776: O–C diagram



* period change $\dot{P}/P = 4.1 \pm 0.2 \times 10^{-6}$ year^{-1}

Interpretation

- light-time effect (binarity)

Interpretation

- light-time effect (binarity)
  - observations with 2m telescope in Ondřejov: unlikely

Interpretation

- light-time effect (binarity)
  - observations with 2m telescope in Ondřejov: unlikely
- precession

Interpretation

- light-time effect (binarity)
  - observations with 2m telescope in Ondřejov: unlikely
- precession
  - observed change too large

Interpretation

- light-time effect (binarity)
  - observations with 2m telescope in Ondřejov: unlikely
- precession
  - observed change too large
- evolutionary change

Interpretation

- light-time effect (binarity)
  - observations with 2m telescope in Ondřejov: unlikely
- precession
  - observed change too large
- evolutionary change
  - unlikely

Interpretation

- light-time effect (binarity)
  - observations with 2m telescope in Ondřejov: unlikely
- precession
  - observed change too large
- evolutionary change
  - unlikely
- angular momentum loss

Angular momentum loss

* the star has a stellar wind with $\dot{M} \approx 10^{-9}\,\mathrm{M}_\odot\,\mathrm{year}^{-1}$
* the star has a strong surface magnetic field $B \approx 20\,\mathrm{kG}$ (Khokhlova et al. 2000)

$\Rightarrow$ momentum loss due the magnetically confined stellar wind

Angular momentum loss

* period change

$$\frac{\dot{P}}{P} = -\frac{\dot{J}}{J} = -\frac{\dot{J}}{\eta\, M\, R^2\, \Omega}$$

- ⋆ $\dot{J}$ angular momentum loss per unit of time
- ⋆ $J = \eta\, M\, R^2\, \Omega$ stellar angular momentum
- ⋆ $\eta = 0.05$ is a dimensionless constant
- ⋆ $\Omega = 2\pi / P$

Angular momentum loss

* period change

$$\frac{\dot{P}}{P} = -\frac{\dot{J}}{J} = -\frac{\dot{J}}{\eta M R^2 \Omega}$$

* the loss of angular momentum

$$\dot{J} = \xi \dot{M} r_{\rm cor}^2 \Omega$$

  - ξ geometric factor
  - $\dot{M}$ the wind mass-loss rate
  - $r_{\rm cor}$ the radius of the effective corotation

Angular momentum loss

* period change

$$\frac{\dot{P}}{P} = -\frac{\dot{J}}{J} = -\frac{\dot{J}}{\eta\, M\, R^2\, \Omega}$$

* the loss of angular momentum

$$\dot{J} = \xi\, \dot{M}\, r_{\mathrm{cor}}^2\, \Omega$$

* r_{cor} according to MHD models (udDoula & Owocki 2002)

Angular momentum loss

* period change

$$\frac{\dot{P}}{P} = -\frac{\dot{J}}{J} = -\frac{\dot{J}}{\eta\, M\, R^2\, \Omega}$$

* the loss of angular momentum

$$\dot{J} = \xi\, \dot{M}\, r_{\rm cor}^2\, \Omega$$

* $r_{\rm cor}$ according to MHD models
* prediction: $\dot{P}/P = 2 \times 10^{-6}$ year^{-1}
* observation: $\dot{P}/P = 4.1 \pm 0.2 \times 10^{-6}$ year^{-1}

Conclusions

- the light variability of HD 37776 & HR 7224 is due to
  - inhomogeneous surface distribution of silicon and helium or iron
  - flux redistribution from UV to the visible
  - stellar rotation

Conclusions

- the light variability of HD 37776 & HR 7224 is due to
  - inhomogeneous surface distribution of silicon and helium or iron
  - flux redistribution from UV to the visible
  - stellar rotation
- the flux redistribution due to bound-free (ionization) and bound-bound (line) transitions is likely important also for the light variability of other CP stars

Conclusions

- the light variability of HD 37776 & HR 7224 is due to
  - inhomogeneous surface distribution of silicon and helium or iron
  - flux redistribution from UV to the visible
  - stellar rotation
- mCP stars are laboratories for testing model stellar atmospheres and MHD simulations