# Observations of light elements in massive stars

An *external* review by
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# Massive Stars

- Despite that
  - Only 3 stars out of 1000 have a mass > 8 $M_{sun}$
  - Only 14% of the mass of all stars is found in massive stars (M > 8 $M_{sun}$)
- Massive stars are important because they inject into the ISM in shortest time (3 – 30 Myr) large amounts of
  - Radiation
  - Mass
  - Mechanical energy

# Massive Stars

- … and drive the (chemical) evolution of galaxies and the Universe.

- Therefore massive stars are intensively studied:
  - Surface abundances
  - Mass loss by stellar winds and its link to the surface
  - Rotational velocities
  - Pulsations
  - Surface magnetic fields
  - Massive star populations
  - …

# Massive Stars

- In the context of this conference:
  - Accurate galaxy evolution models require a detailed understanding of the internal and core properties of massive stars.
  - The consideration of rotation in stellar evolution models predicts significant effects on the evolutionary tracks and surface abundances of massive stars.
  - And are probed by light element(s).

# Observations

- In hot massive stars observations of light elements reduce to the observation of Boron
- Beryllium and Lithium have no observable transitions
- Boron transitions are all in the satellite UV, i.e., below the atmospheric cut-off at 300nm
- STIS (+COS) @ HST is and will be the only observational resource in the future (after a 5 year forced hiatus)

# Observations

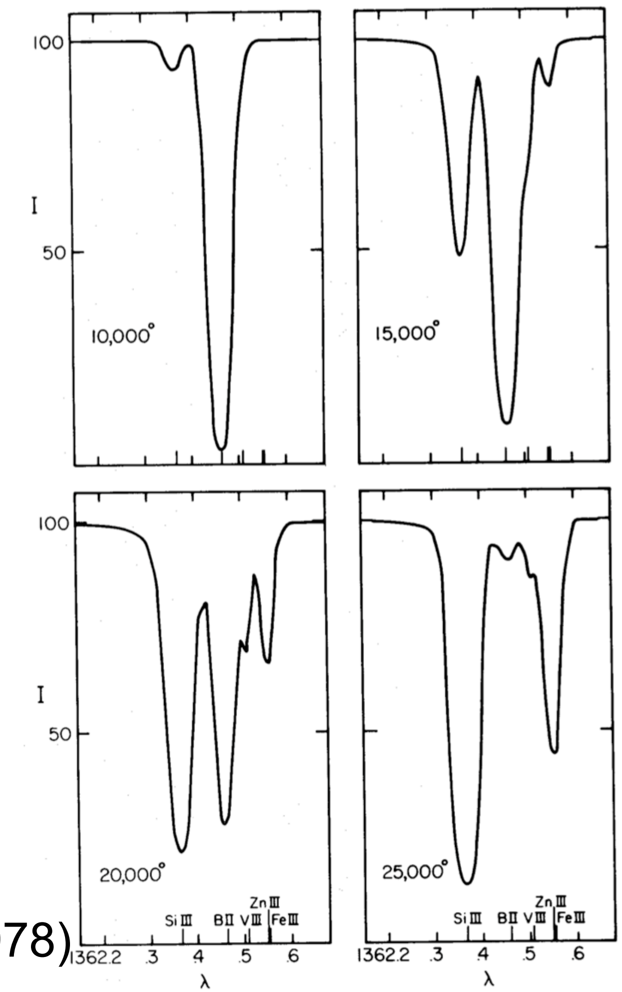
- B II λ1362 resonance line
  - Boesgaard & Heacox (1978) using Copernicus data to derive abundances of 16 'normal' A and B stars
  - Venn, Lambert, & Lemke (1996) using IUE data of 6 B and A sub/giants and supergiants
  - Cunha et al. (1997) using GHRS on HST to observe 4 B stars in Orion

# Observations

- B III λ2066 resonance doublet line
  - Proffitt et al. (1999) using high SNR GHRS spectra to determine Boron abundances and $^{11}B/^{10}B$ isotope ratios for 3 B stars
  - Proffitt & Quigley (2001) determine Boron abundance for 45 early-type B stars from IUE high-resolution archive spectra
  - Venn et al. (2002) determine 4 Boron upper limits from 7 B-type MS stars using STIS@HST
  - Mendel et al. (2006) observe 7 B-type MS stars using STIS@HST and find most of them Boron depleted

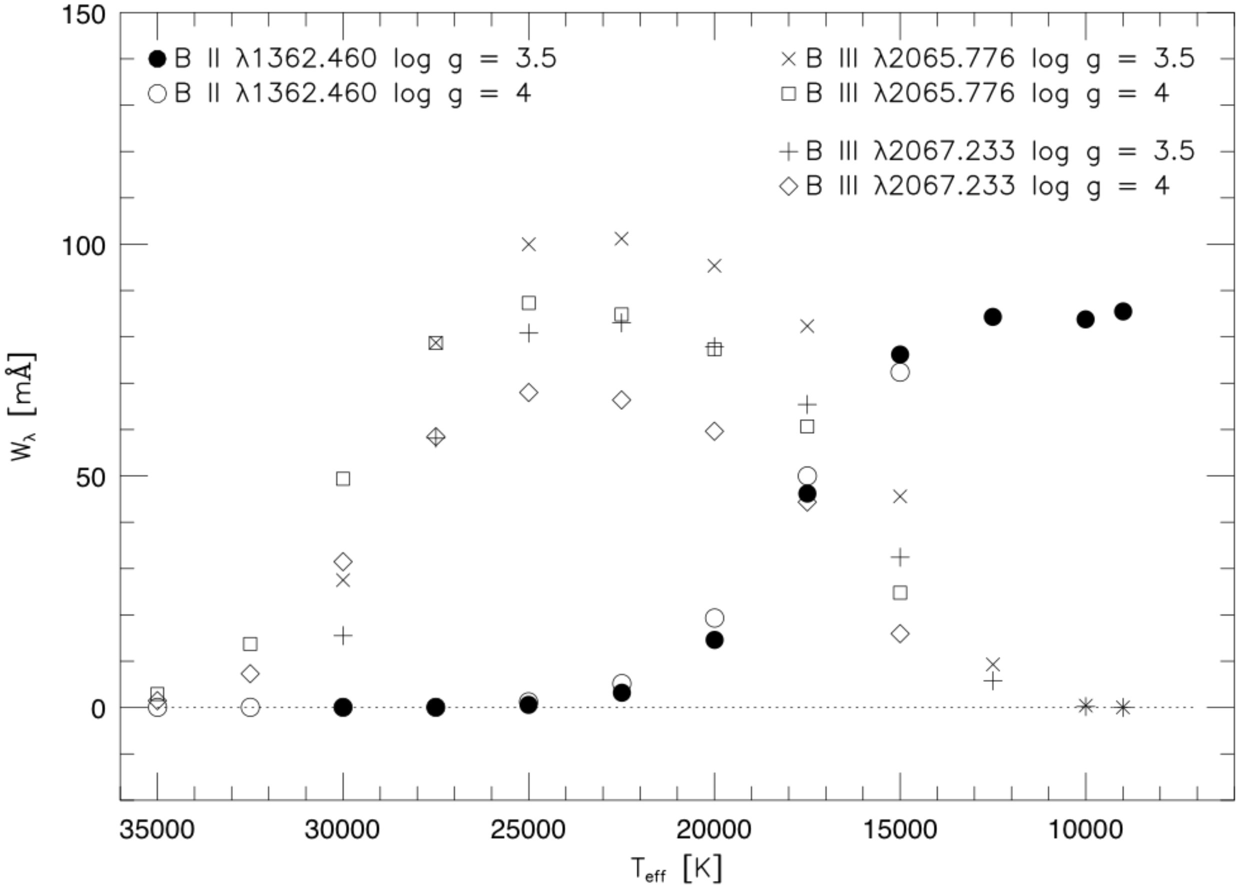
# Observation

- B II λ1362 line
  - Synthetic spectra for non-rotating star and log ε (B)=2
  - Blended with SiIII, NiII, VII, ZnIII, and FeIII
  - BIII dominant ionization stage above 18kK
  - Sensitive to NLTE corrections



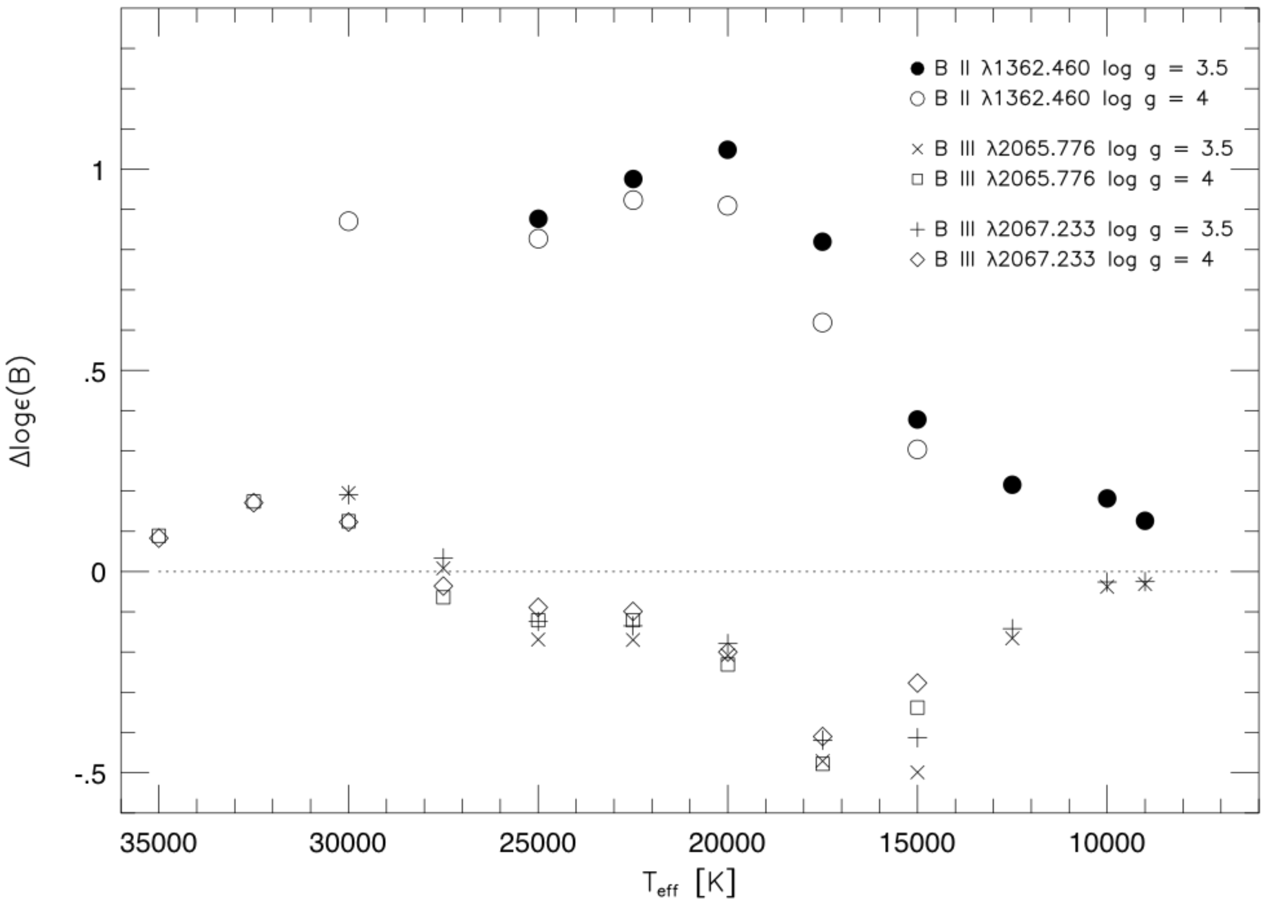

Boesgaard & Heacox (1978)

# Observation



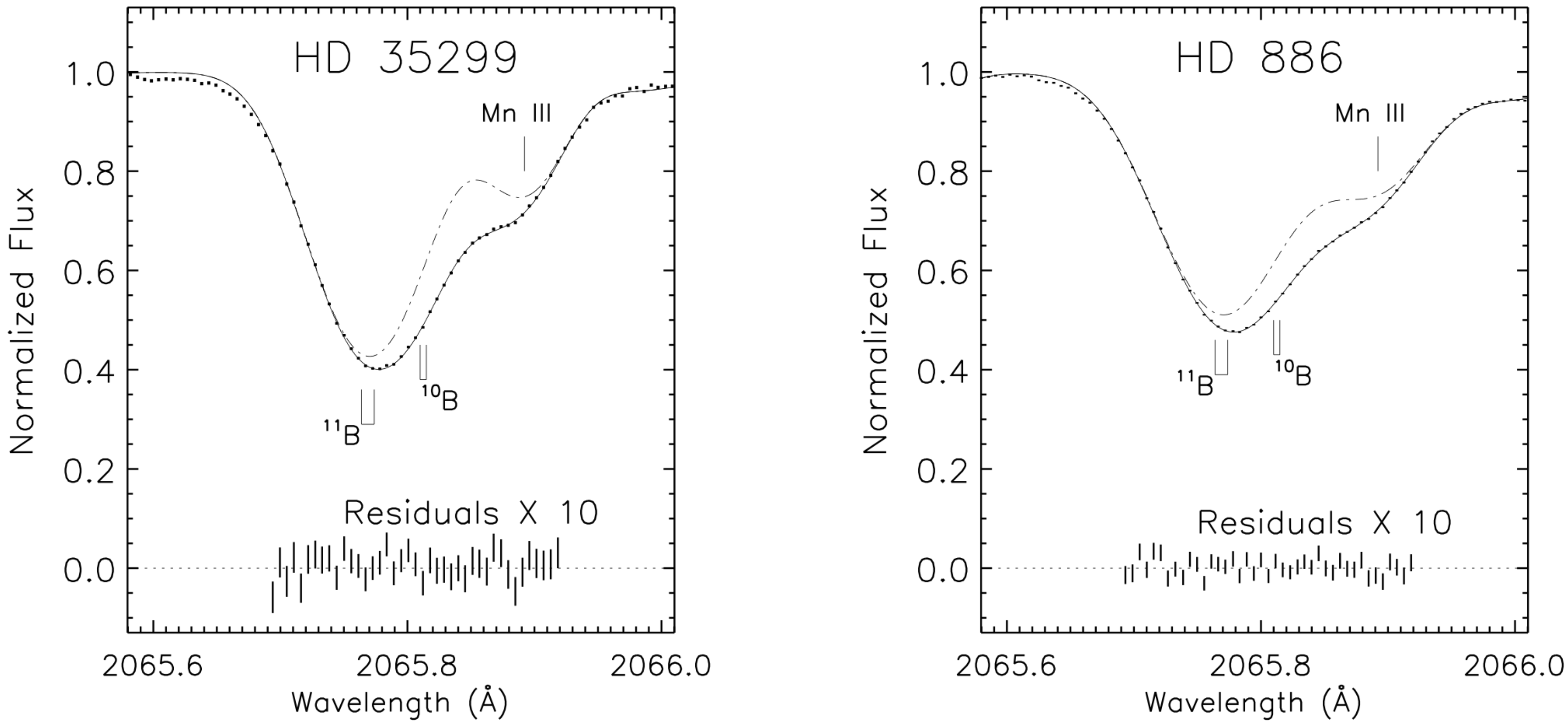

Venn et al. (2002)

# Observation




Venn et al. (2002), Cunha et al. (1997)

# Observation




$^{11}B/^{10}B \sim 4$
Consistent with meteoric value (Shima 1963)

Proffitt et al. (1999)

# From observations to abundances

- Detailed abundance analysis using:
  - 1D – line-blanketed LTE atmospheres.

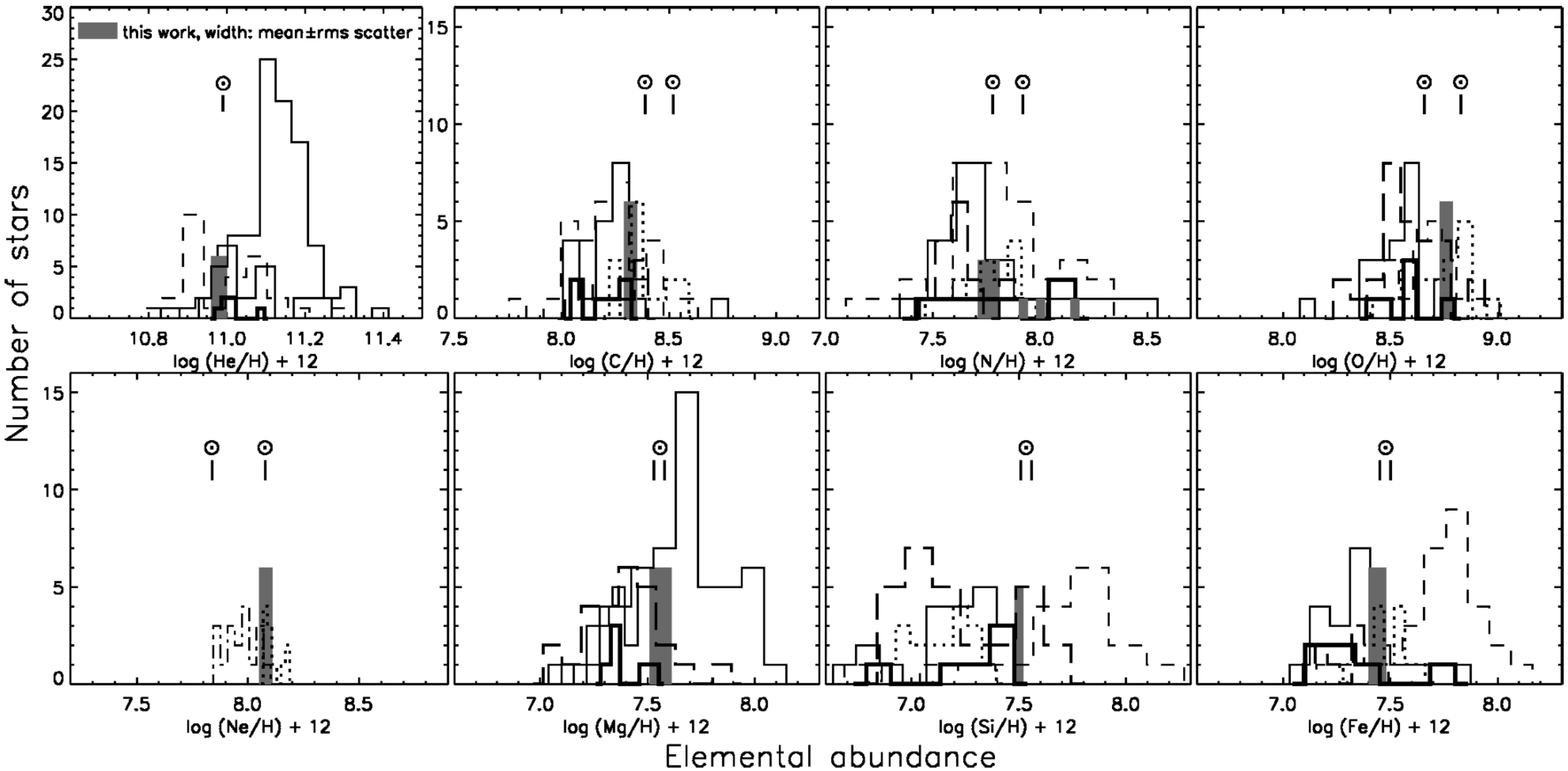
    Plane parallel, no expansion, no winds, …
  - 1D – (N)LTE Balmer line formation
    - Gravity from Balmer line wings through Stark broadening
  - 1D – LTE line formation + NLTE corrections

    or 1D – NLTE line formation
    - Temperature from "ionisation equilibrium" (SiII/III/IV or CII/III/IV or … all)
    - Microturbulence from sensitive lines (e.g. O or Fe)

    -> Line-by-line element abundances

# From observations to abundances

Sample of 6 MS and near MS early B-type stars within 500pc




Przybilla et al. (2008)
Nieva et al. (2007,2008)

# From observations to abundances

Sample of 6 MS and near MS early B-type stars within 500pc

TABLE 2

CHEMICAL COMPOSITION OF DIFFERENT OBJECT CLASSES IN THE SOLAR NEIGHBORHOOD AND OF THE SUN

| Elem. | Cosmic Standard B Stars–This Work[a] | | Orion Gas+Dust[b] | B Stars[c] | Young F&G Stars[c] | ISM Gas | ISM Dust[d] | Sun GS98[e] | Sun AGS05[e] |
|---|---|---|---|---|---|---|---|---|---|
| He | 10.98 ± 0.02 | … | 10.988 ± 0.003 | … | … | … | … | 10.99 ± 0.02 | |
| C | 8.32 ± 0.03 | 209 ± 15 | 8.52 ± 0.02 | 8.28 ± 0.17 | 8.55 ± 0.10 | 8.15 ± 0.06[f] | 68 ± 26 | 8.52 ± 0.06 | 8.39 ± 0.05 |
| N | 7.76 ± 0.05 | 58 ± 7 | 7.73 ± 0.09 | 7.81 ± 0.21 | … | 7.79 ± 0.03[g] | … | 7.92 ± 0.06 | 7.78 ± 0.06 |
| O | 8.76 ± 0.03 | 575 ± 41 | 8.73 ± 0.03 | 8.54 ± 0.16 | 8.65 ± 0.15 | 8.59 ± 0.01[h] | 186 ± 42 | 8.83 ± 0.06 | 8.66 ± 0.05 |
| Ne | 8.08 ± 0.03 | 120 ± 9 | 8.05 ± 0.07 | … | … | … | … | 8.08 ± 0.06 | 7.84 ± 0.06 |
| Mg | 7.56 ± 0.05 | 36 ± 4 | … | 7.36 ± 0.13 | 7.63 ± 0.17 | 6.17 ± 0.02[i] | 34.8 ± 4.4 | 7.58 ± 0.05 | 7.53 ± 0.09 |
| Si | 7.50 ± 0.02 | 32 ± 1 | … | 7.27 ± 0.20 | 7.60 ± 0.14 | 6.35 ± 0.05[i] | 29.6 ± 2.2 | 7.55 ± 0.05 | 7.51 ± 0.04 |
| Fe | 7.44 ± 0.04 | 28 ± 3 | … | 7.45 ± 0.26 | 7.45 ± 0.12 | 5.41 ± 0.04[i] | 27.3 ± 2.7 | 7.50 ± 0.05 | 7.45 ± 0.05 |

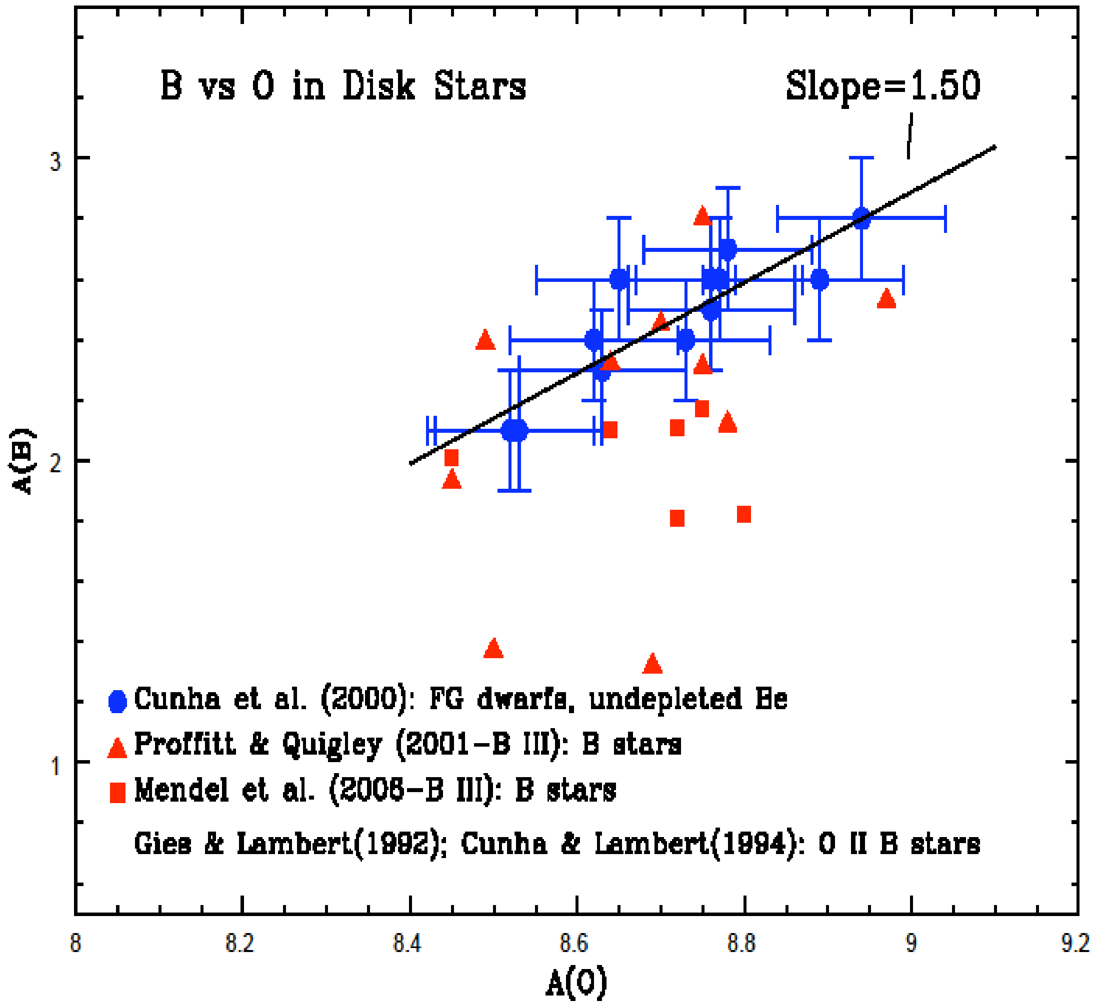
NOTES.—(a) In units of log(El/H) + 12 / atoms per $10^6$ nuclei, computed from average star abundances (mean values over all individual lines *per element*, equal weights per line); (b) Esteban et al. (2004); (c) Sofia & Meyer (2001); (d) difference between the cosmic standard and ISM gas-phase abundances, in units of atoms per $10^6$ H nuclei; (e) photospheric values; (f) Sofia (2004); (g) Meyer et al. (1997), corrected accordingly to Jensen et al. (2007); (h) Cartledge et al. (2004); (i) Cartledge et al. (2006).

Przybilla et al. (2008)
Asplund (2009)

*X=0.715 Y=0.271 Z=0.014 Z/X = 0.020 B stars*
*X=0.7154 Y=0.2703 Z=0.0142 Z/X = 0.0198 protosolar*

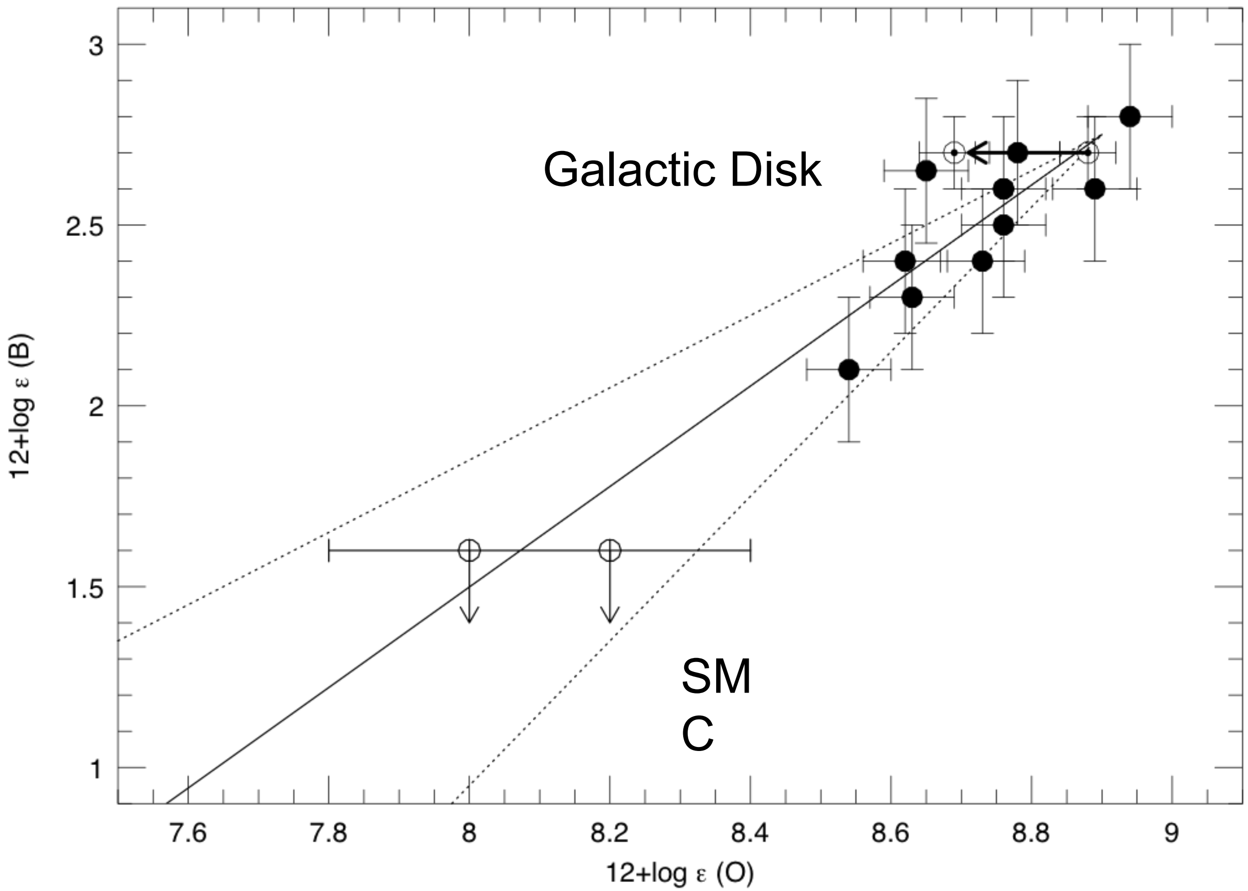
# Boron abundances

- State of affairs as of today (plot from Cunha's talk yesterday summarizing almost all available measurements).
- Considering the advances in B star abundance analysis it is probably worth to *revisit* this data.



# Boron abundances

- Two B stars in the SMC (V=15mag) with STIS@HST.
- Consistent with galactic slope of 1.5
- Constraints on Boron production via CR spallation.




Brooks, Venn et al. (2002)

# “Dubious” Boron vs Nitrogen

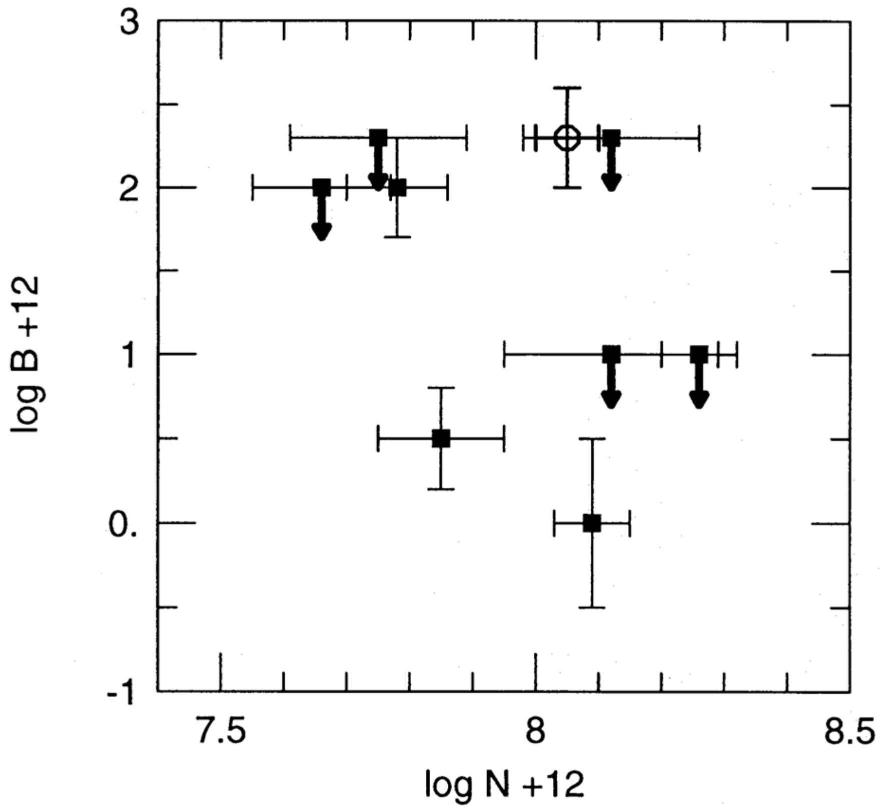
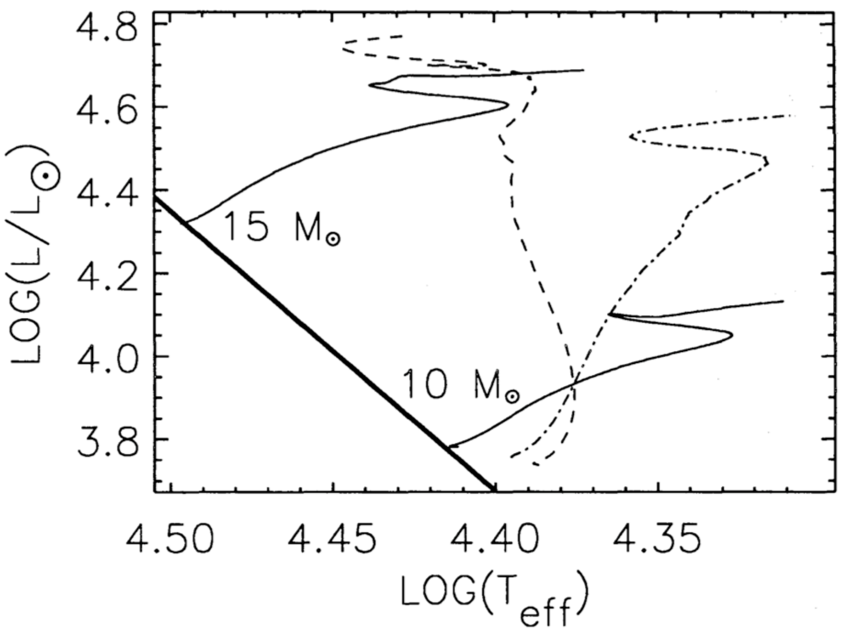
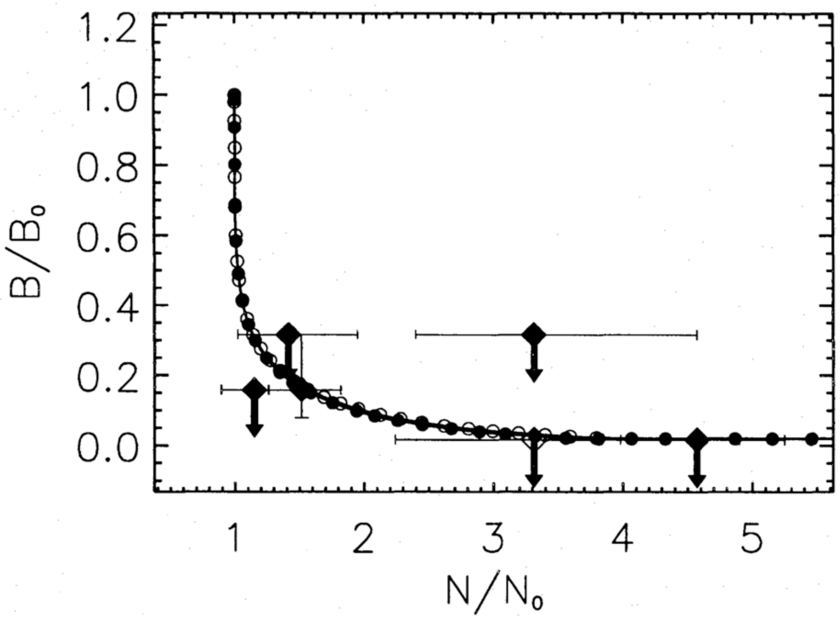



**Fig. 11.** Dubious relationship of boron with non-LTE nitrogen abundances.

Venn, Lembke & Lambert (1996)

# Explained by rotational mixing



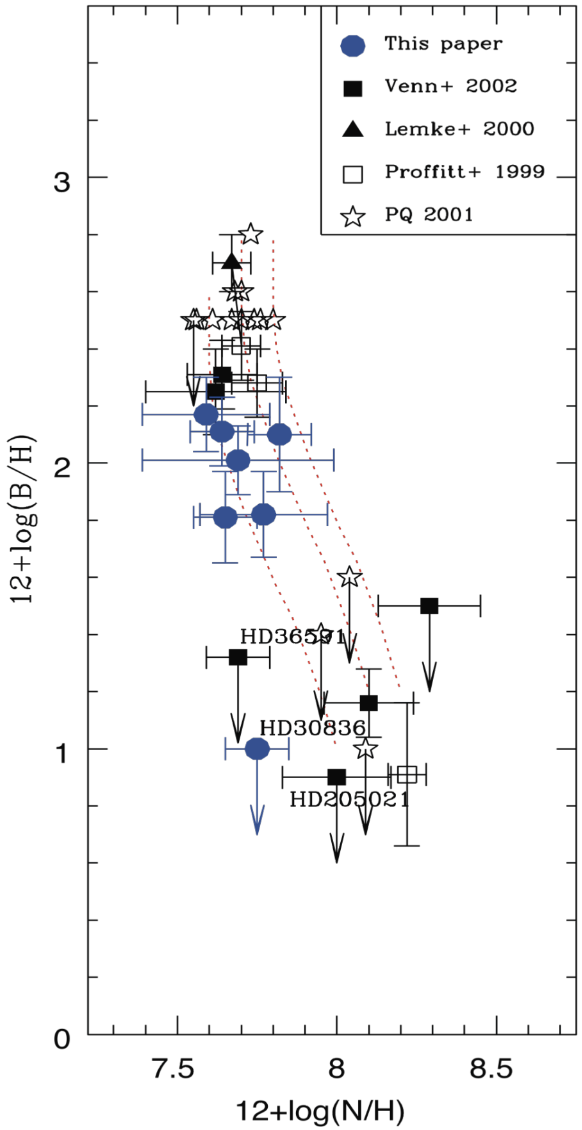




Fliegner, Langer & Venn (1996)

# Rotationally induced mixing

- Numerous observations indicating mixing in the radiative zones of massive stars
- Mass loss and mass transfer in binaries could also alter surface composition
- However, Boron depletion w/o simultaneous Nitrogen enrichment can only be explained by:
  - Boron is destroyed by proton capture at <6 x $10^6$ K (1 $M_{sun}$ below the surface of a B-type MS star)
  - Any mixing would deplete B while keeping less fragile elements like Nitrogen unchanged
  - In more evolved stages the same mixing process can enhance other elements like Nitrogen *(progressive mixing)*
- Mass transfer in a close binary would *simultaneously* deplete B and enhance N
- Mass loss does not play a strong role for B-type MS stars

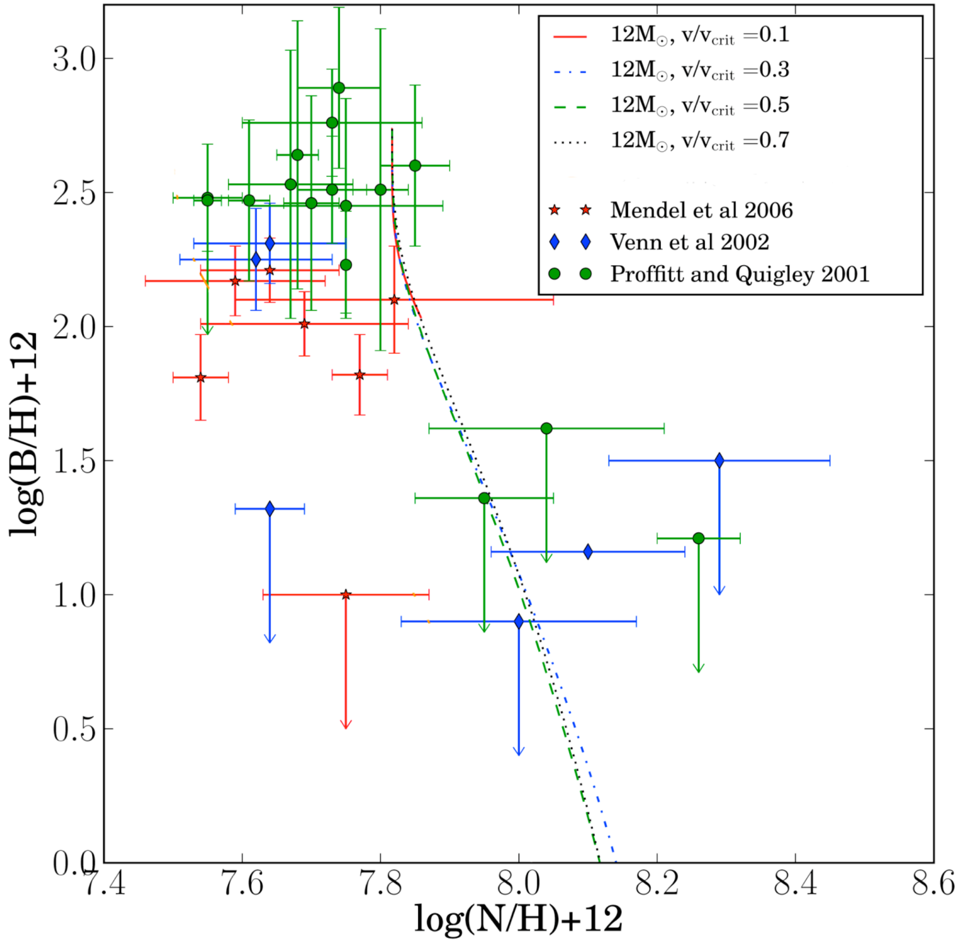
# Rotationally induced mixing




--- evolutionary tracks with 12 $M_{sun}$ $v_{rot}$=200km/s (Heger & Langer 2000) shifted to 3 different initial B – N abundances

Mendel et al. (2006)

# Rotationally induced mixing




- Geneva Stellar Evolution Code with rotational mixing
- Frischknecht et al. (2010 in prep, cf. poster) implemented extended reaction network including Li, Be, B
- Allows to better model the observed faster B depletion.

# Rotationally induced mixing

- Currently two objects (HD36591, HD30836) show B depletion w/o N enhancement.
- Further observations and analyses are needed to verify that mixing increases with
  - Age
  - Rotation rates
  - Mass
- Further high SNR observations could test prediction of $^{11}B/^{10}B$ as function of B depletion (NACRE vs REACLIB95 rates)

# Abundances & Stellar rotation rates

- Median equatorial rotational velocity of B-type MS stars is ~200 km/s (Howarth 2003)
- Abundance analyses are biased towards sharp-line stars ($v \sin i$ < 20 km/s), i.e., stars seen pole-on or they are really slow rotators
- We are trying to probe effects of high stellar rotation rates $v / v_{crit} > 0.2$
- Therefore, it is important to
  - include fast rotators in the abundance studies (Proffitt C17)
  - determine true stellar rotation rates
    - Rotation of surface patterns
      - Stellar spots
      - NRP patterns
    - Rotation of wind pattern locked to photosphere

# True stellar rotation rates from NRP and wind patterns

330 A. Kaufer et al.: Multi-periodic photospheric pulsations and connected wind structures in HD 64760

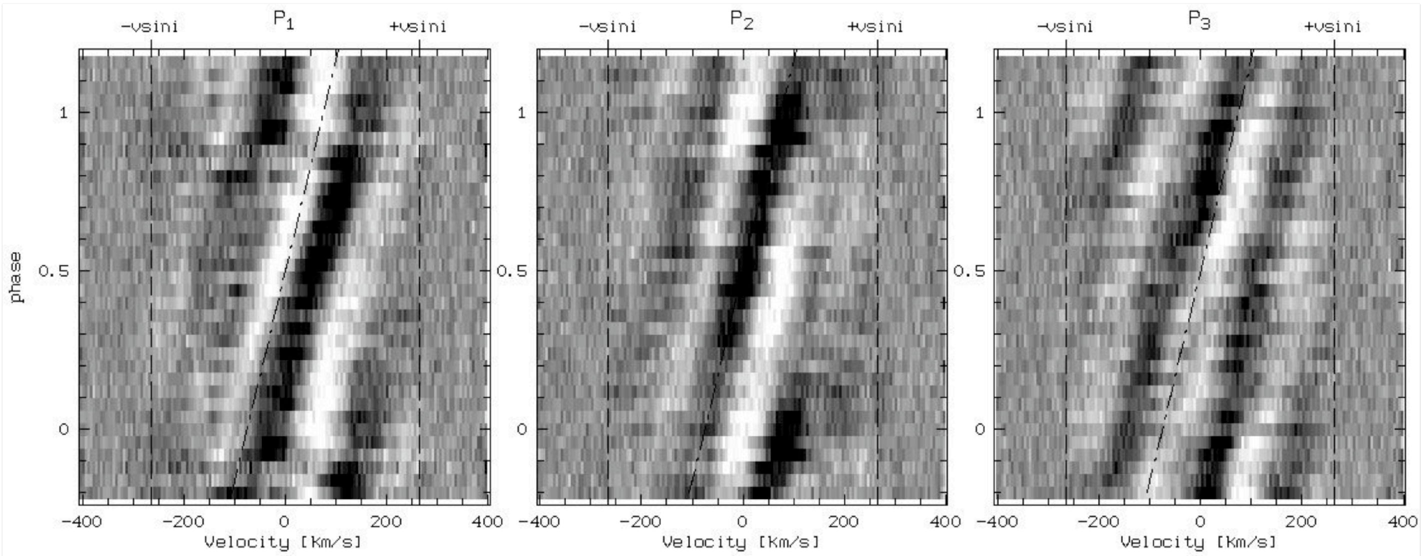



**Fig. 6.** Dynamical phase spectra of the Si III λ4553 line. The observed spectra are phased with $P_1 = 4.810$ h (*left*), $P_2 = 4.672$ h (*center*), $P_3 = 4.967$ h (*right*). 25 phase bins were used for the phase interval 0.0−1.0. All spectra are displayed with ±0.3% cut levels. The measured typical acceleration of the features over the line center of $(\mathrm{d}v/\mathrm{d}\phi) = -175\ \mathrm{km\,s^{-1}}$/cycle is indicated by a dot-dashed lines.

HD64760 (B0.5Ib)

Kaufer et al. (2006)

# True stellar rotation rates from NRP and wind patterns

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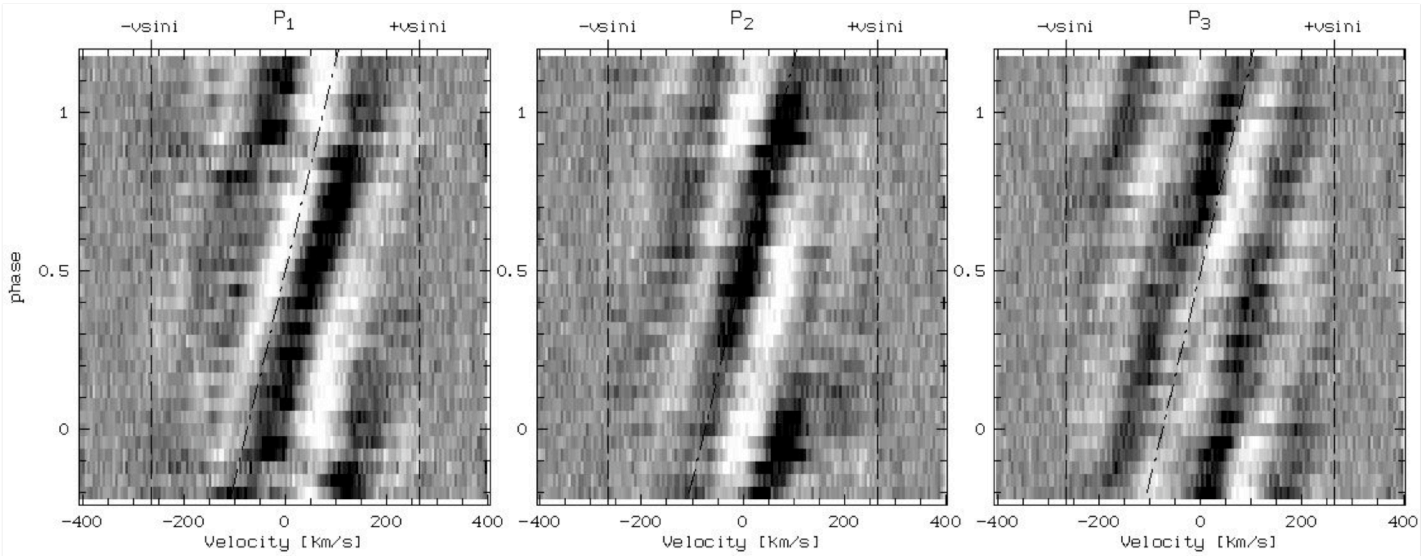


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Fullerton et al. (1997)

# True stellar rotation rates from NRP and wind patterns

330 A. Kaufe

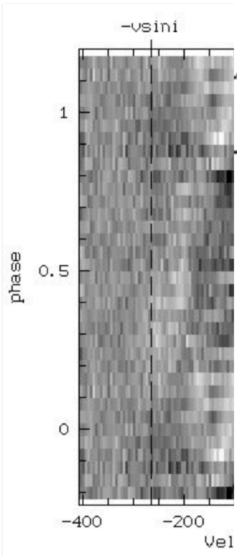
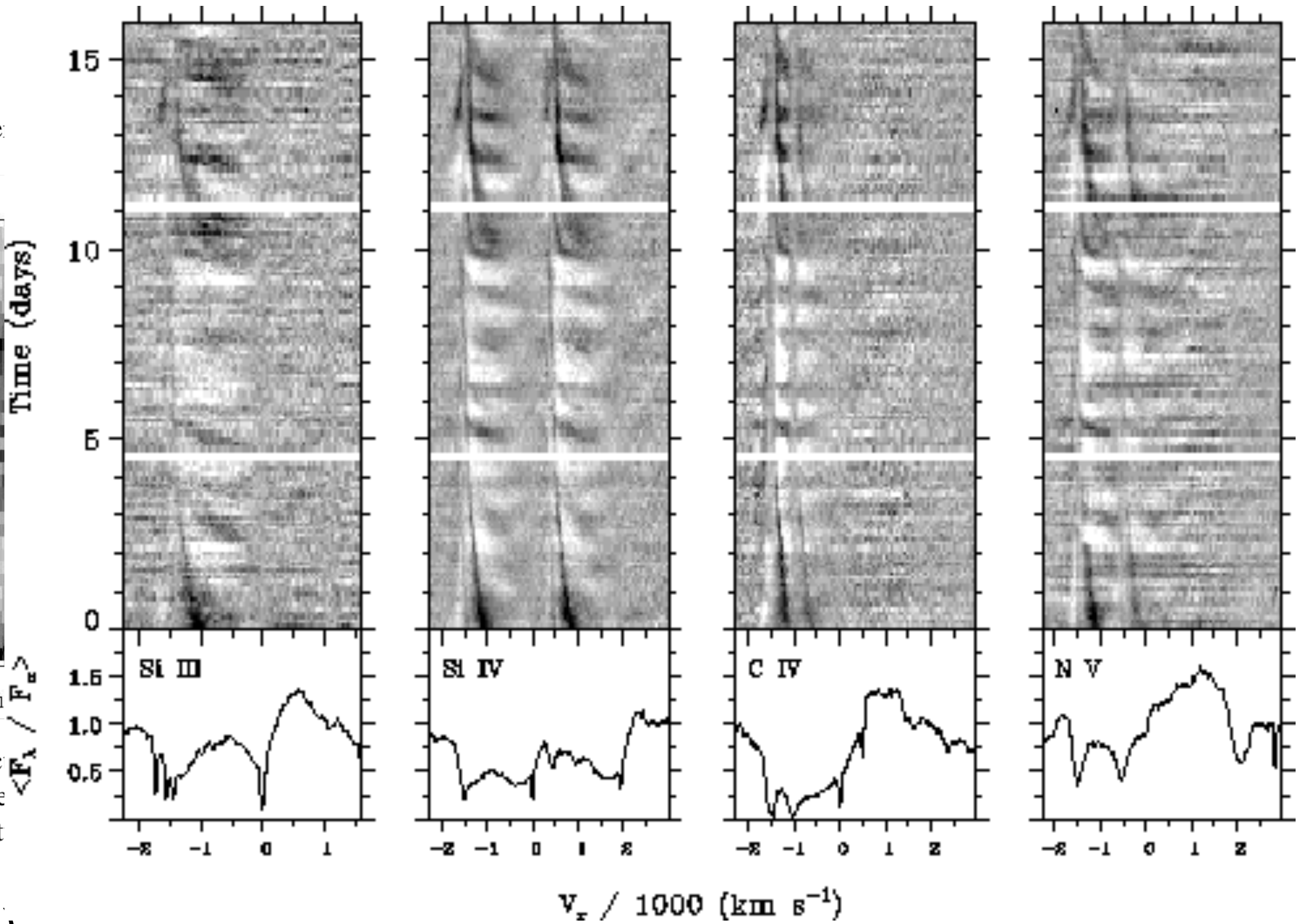


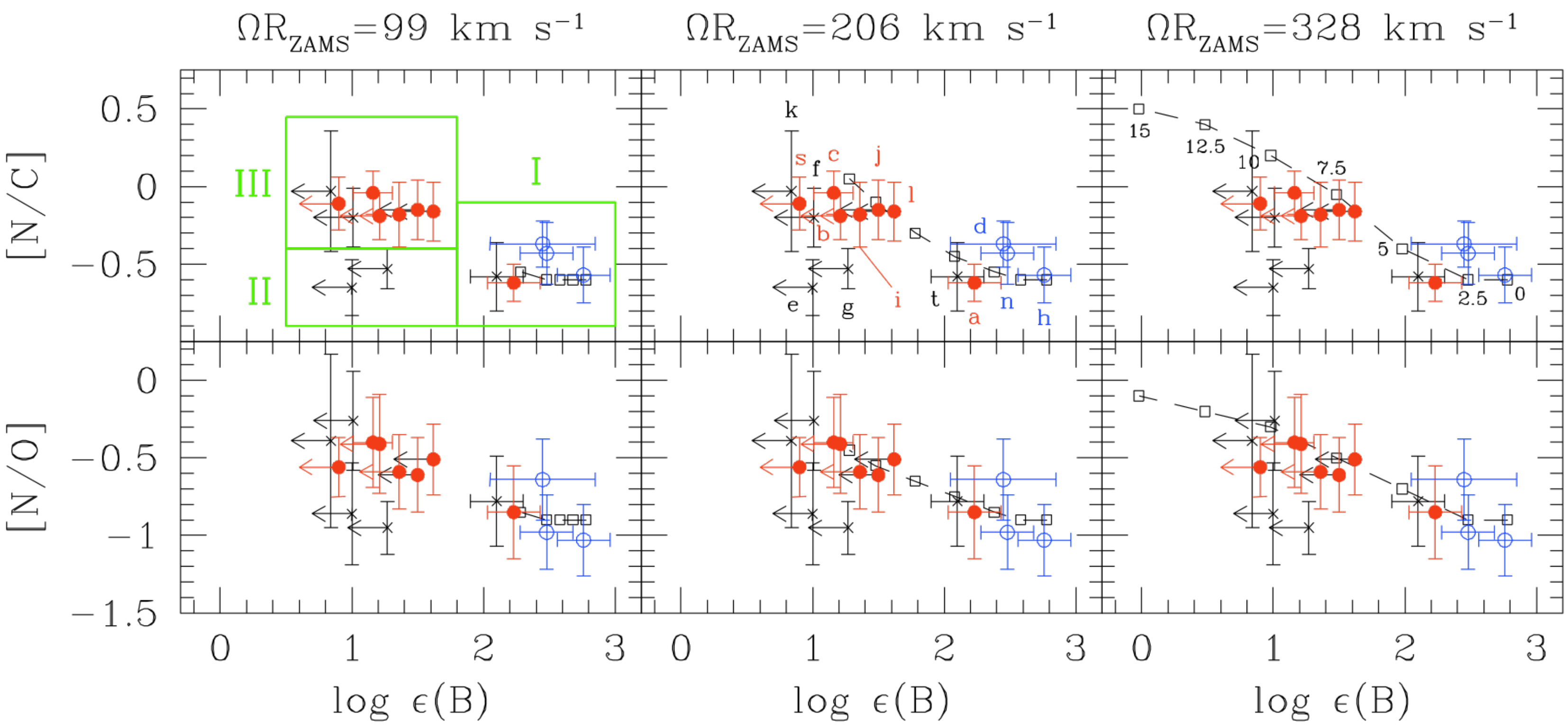

**Fig. 6.** Dynamical phase spec
$P_3$ = 4.967 h (*right*). 25 phase
typical acceleration of the feat




HD64760 (B0.5Ib)

Fullerton et al. (1997)

# B-N pattern & stellar rotation rates




Morel et al. (2008)

# B-N pattern & stellar rotation rates

- Morel et al. (2008) find 3 stars in Group III (B depleted, N enriched) which are *slow* rotators:
  - ζ Cas $v_{eq}$ = 55 km/s UV SPB + magn.field
  - δ Cet $v_{eq}$ = 14 or 28 km/s AS β Cep + magn.field
  - β Cep $v_{eq}$ = 26 km/s UV β Cep + magn.field
- Morel et al. propose that magnetic phenomena are important in altering the photospheric abundances of early B dwarfs, even for surface field strengths at the one hundred Gauss level.