A Brief Overview on Boron Abundances In Disk Stars

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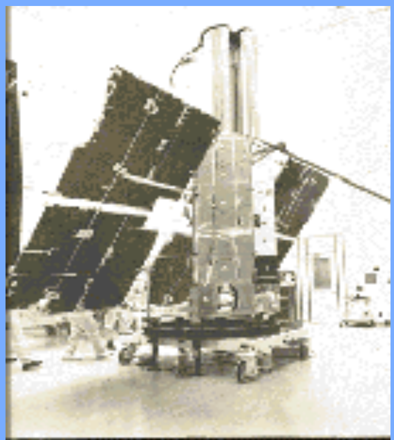
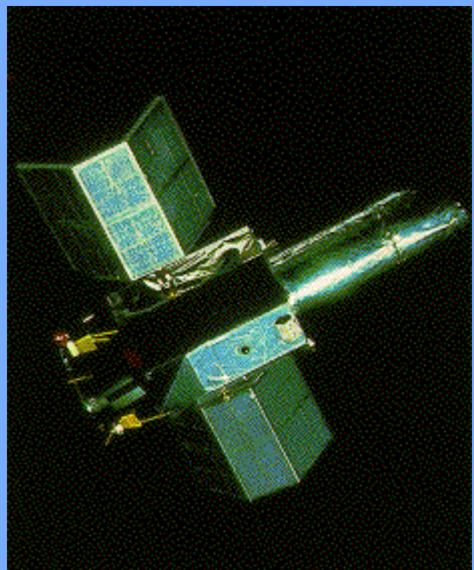
NOAO



Coppernicus Satellite



IUE Satellite

Huble Space Telescope

[.... No new data in the last few years ...]

Talk Outline

- Brief overview on boron production
- Observable B abundance indicators in different temperature regimes
- Abundance results for boron in Cool (FG dwarfs) and Hot stars (B stars)
- Behavior of boron with metallicity found for the Galactic disk in comparison with the trends obtained for the more metal poor stars in the halo.

Overview on Boron

• Synthesis of boron

It is one of the few elements whose formation is not dominated by nucleosynthesis in stellar interiors nor in BBN

• It has been known for almost 4 decades that Galactic Cosmic Rays are involved in the formation of LiBeB (Reeves, Fowler & Hoyle 1971)

• The B (and Be) – O Fe abundance trends encode the history of spallation in the Galaxy >> Our ability to infer this history >>> determined by accurate abundances

BUT

• Boron observations are still sparse: B measured in Galactic stars + ISM + SMC + $^{11}B/^{10}B$ isotopic ratios in a few stars and the ISM

Boron Production

Principal Source: Cosmic Ray Spallation Reactions in IS gas

- **STANDARD** (Secondary behavior; B proportional O^2):

Acceleration Mechanism — **CR** (p, α) → C, N, O → **Li (^{6}Li, ^{7}Li)**, **Be (^{9}Be)**, **B (^{10}B, ^{11}B)**

Prediction: ^{11}B / ^{10}B ~ 2.5 (if observed HECR energy spectrum of GCR)

Problem: underproduction of ^{11}B

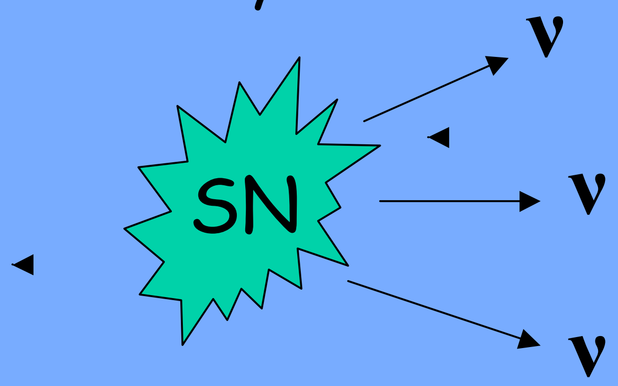
^{11}B / ^{10}B (meteorites) > 3.84 – 4.25 (Chaudisson & Robert 1995)

- **REVERSE** (Primary behavior; B proportional to O)

Acceleration Mechanism — **CR** (C N O) → H, He → **Li (^{6}Li, ^{7}Li)**, **Be (^{9}Be)**, **B (^{10}B10, ^{11}B)**

Boron Production ctd

Other possible Source: Synthesis in SN II via neutrino-induced nucleosynthesis



$$^{12}C + \nu \Rightarrow {}^{11}B + p + \nu'$$

Boron Destruction

- Easily destroyed in stellar interiors
- Sturdiest of the trio Li Be B; as boron is destroyed at higher temperatures than Li and Be

Boron Observations ... Difficult element to measure

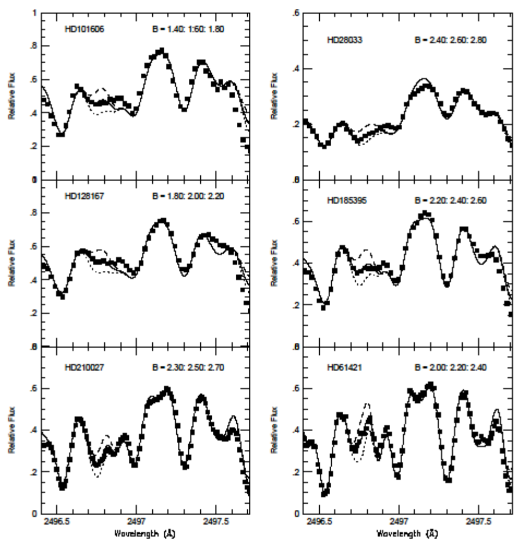
Fewer observations than Be and *far fewer* than Li

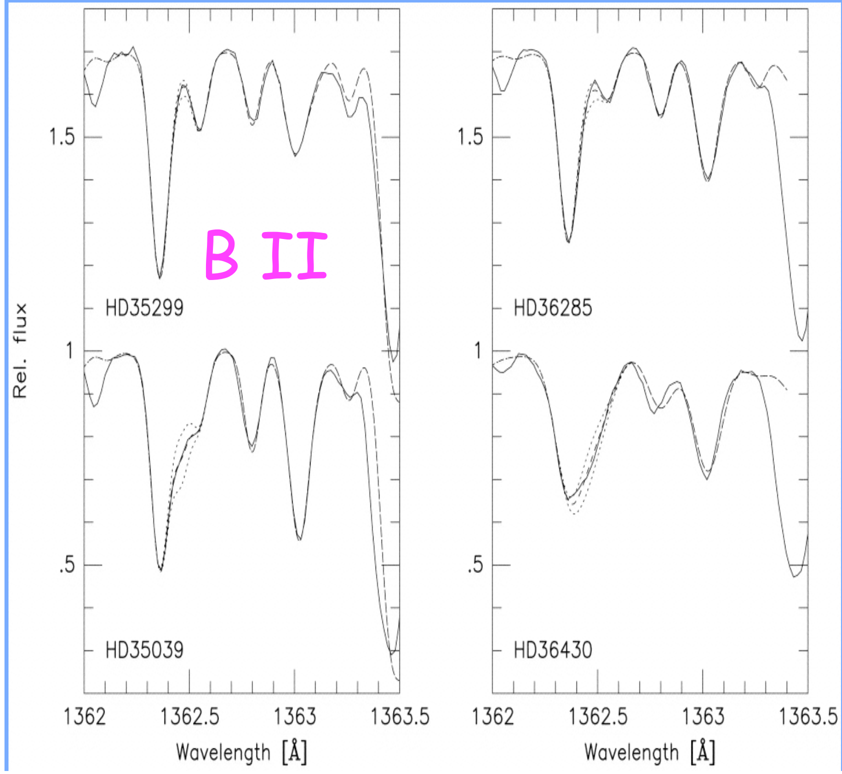
Boron has strong transitions in the uv; Not accessible from the ground

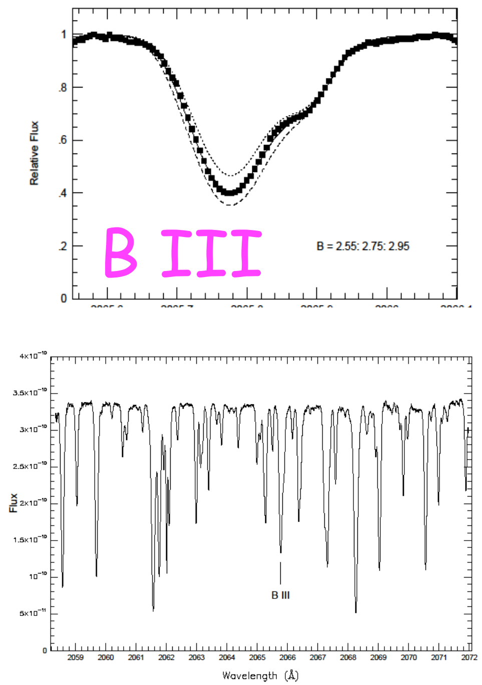
TRANSITIONS

- B I >> 2497A; F and G stars
- B II >> 1362A ; A and B stars + ISM
- B III >> 2066A ; Early B and O stars

B I







Pioneering Works

First Boron Studies in Stars:

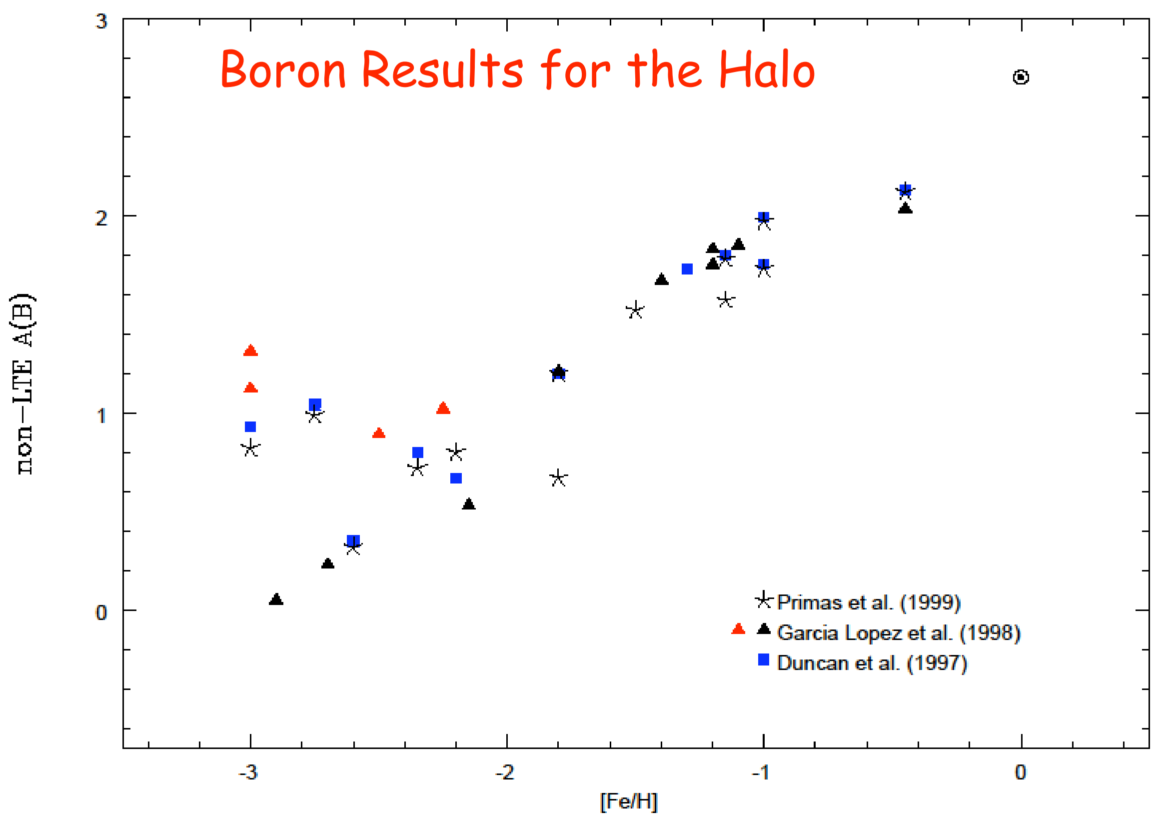
• **Sun** > Kohl et al. (1977) First positive detection of B I in cool stars (disk center and solar limb spectra; Aerobee rocket flight)
• ***A stars*** > Praderie et al. (1977) Copernicus observations (BII); one detection
• ***A-B stars*** > Boesgaard & Heacox (1978) Coppernicus Observations (BII)

• In the 90's new boron observations started to become available with HST spectrograph: GHRS

>> Surprising behavior of boron with metallicity

Metal Poor Stars:
slope ~1 fits most of the halo data (F. Primas talk)

•nonLTE corrections are large



Evolution of Boron in Disk Stars

- Analysis of the uv region in metal rich stars is more complex; large number of overlapping spectral lines

1) B I in FG stars with Solar metallicity

Boron Abundance Studies in Disk F-G stars to date:

Boesgaard et al. (1998) > 9 dwarfs; [Fe/H] from -0.75 to +0.15

Cunha & Smith (1999) : Re-Analysis of the Sun : an effort to place solar type near-metallicity stars on one consistent scale

Cunha et al. (2000) > 14 FG-dwarfs from HST archival data > most of them beryllium undepleted

Boesgaard et al. (2004) > 16 dwarfs with undepleted beryllium

Boesgaard et al. (2005) > 13 beryllium depleted stars; study mixing

Boron Abundance in the Sun (as a benchmark)

Has there been boron destruction in the Sun? Is the photospheric abundance meteoritic?

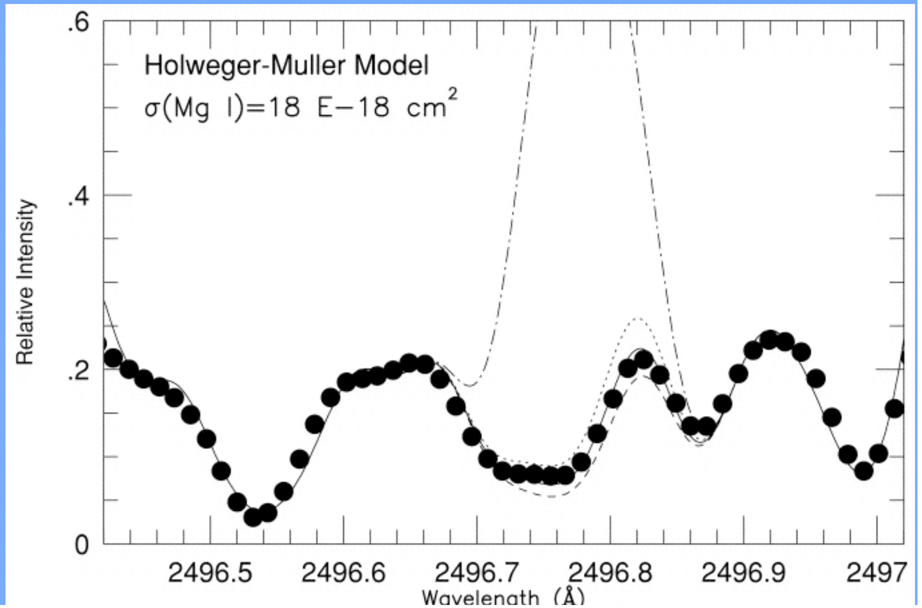
Previous results for the Sun:

- Kohl et al. (1977) derived A(B)= 2.6 +- 0.3 dex
- Hall & Engevold (1975; ir lines) > Upper limit A(B) < 2.1

Our analysis of B I at 2497A

- 1-D LTE; NLTE correction ~0.05dex
(Kiselman & Carlsson 1996)

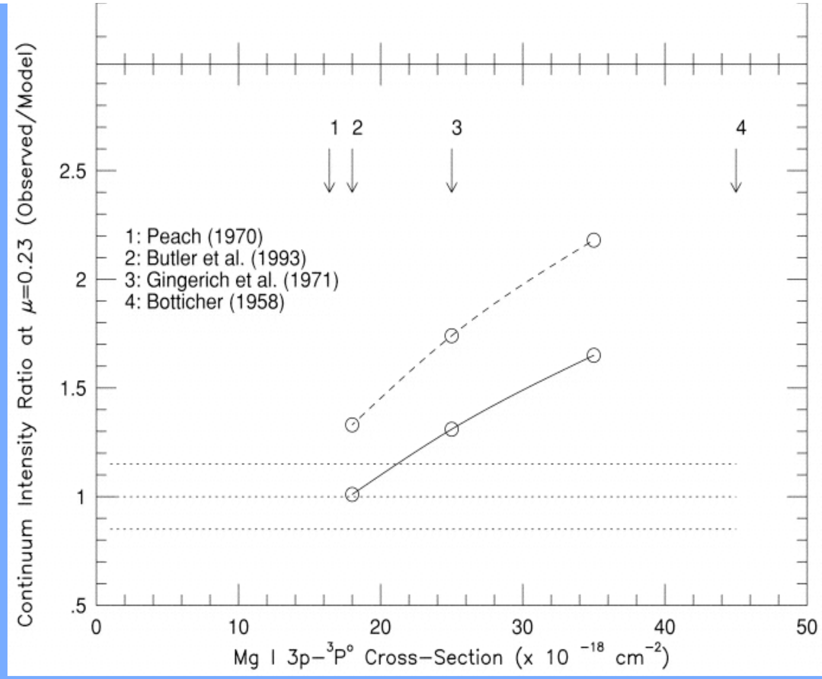
(Cunha & Smith 1999)



Linelist: originally from Duncan et al. (1998); including unclassified FeI lines ; adjusted to fit the Sun; A challenge; Biggest uncertainty

- [Also analyzed the weak B I @16,244A +-check agreement w/ uv]

- At solar metallicity the MgI bf opacity dominates the continuum opacity at 2500A
- Evaluate the sensitivity of continuum intensity relative to line depths as a function of the adopted photoionization cross-section
- Adopting more recent values for the photoionization cross section for Mg I 3p $^3P^o$ along with 2 different 1-D models we find: A(B)= 2.70 +0.12 -0.21 dex



Basic Conclusion: Photospheric B abundance is in ~agreement with the meteoritic value, provided the Mg I 3p $^3P^o$ photoionization cross section is ~$18X10^{18}$ cm^2 (Butler et al. 1993).

Result for Meteorites :
A(B)= 2.79 +- 0.04 (Lodders et al.2009)

No measurable depletion at the level of the uncertainties in the analysis

B Result in line with the fact that Be appears to be not depleted in the Sun. (Asplund et al. 2009; A(Be) =1.38vs 1.30)

[If Be is undepleted B is necessarily undepleted;

If boron is undepleted >> can still accomodate small amounts of Be depletion]

Results for Disk

- Cunha et al. (2000) sample (filled circles)

- Stars with **undepleted beryllium** >> Define the upper envelope

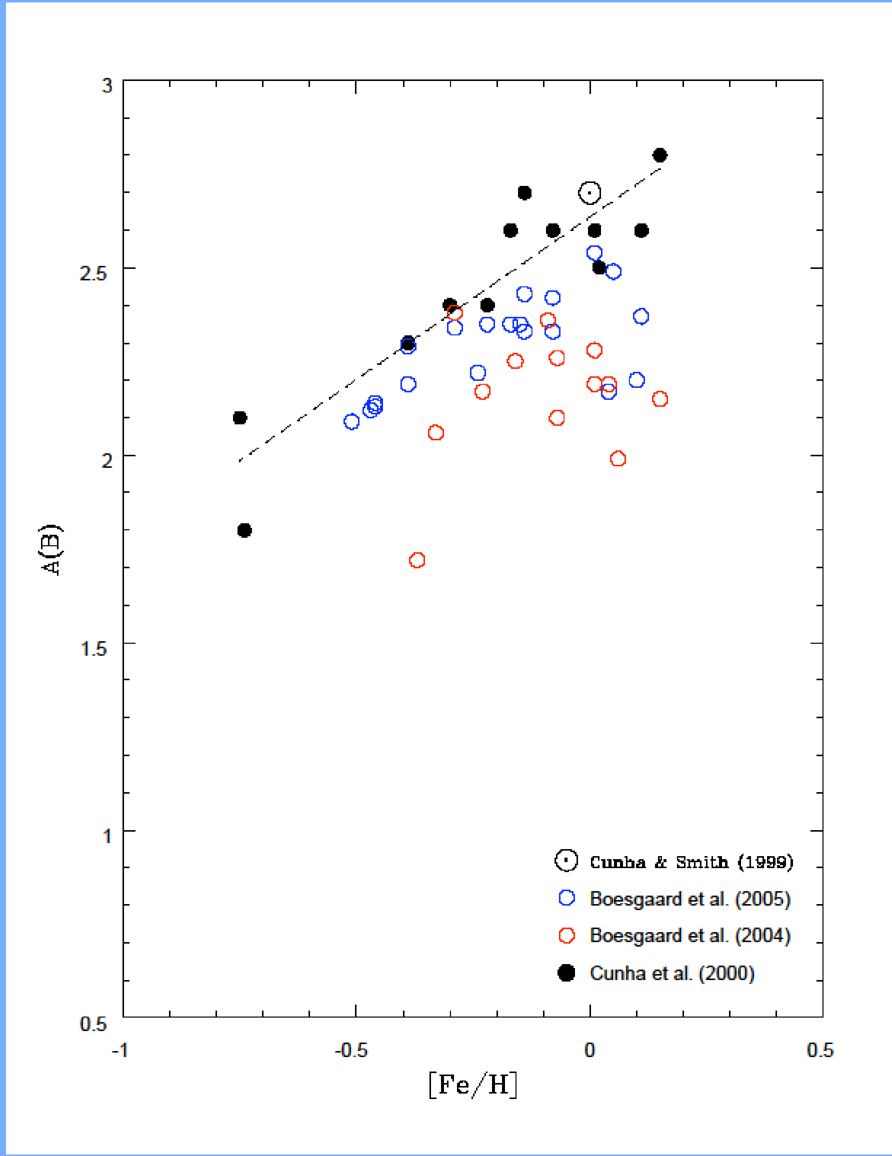
- Analysis: 'Differential' relative to the Sun; Same linelist from the Solar analysis

Boesgaard et al. (2004 & 2005): homogeneous analysis using the same linelist; results on the same scale

Systematic differences with Cunha et al. (2000) >> Partially due to depletion

- An overall increase of A(B) with [Fe/H]

B vs Fe trend for upper envelope: Slope = 0.87 +/- 0.08



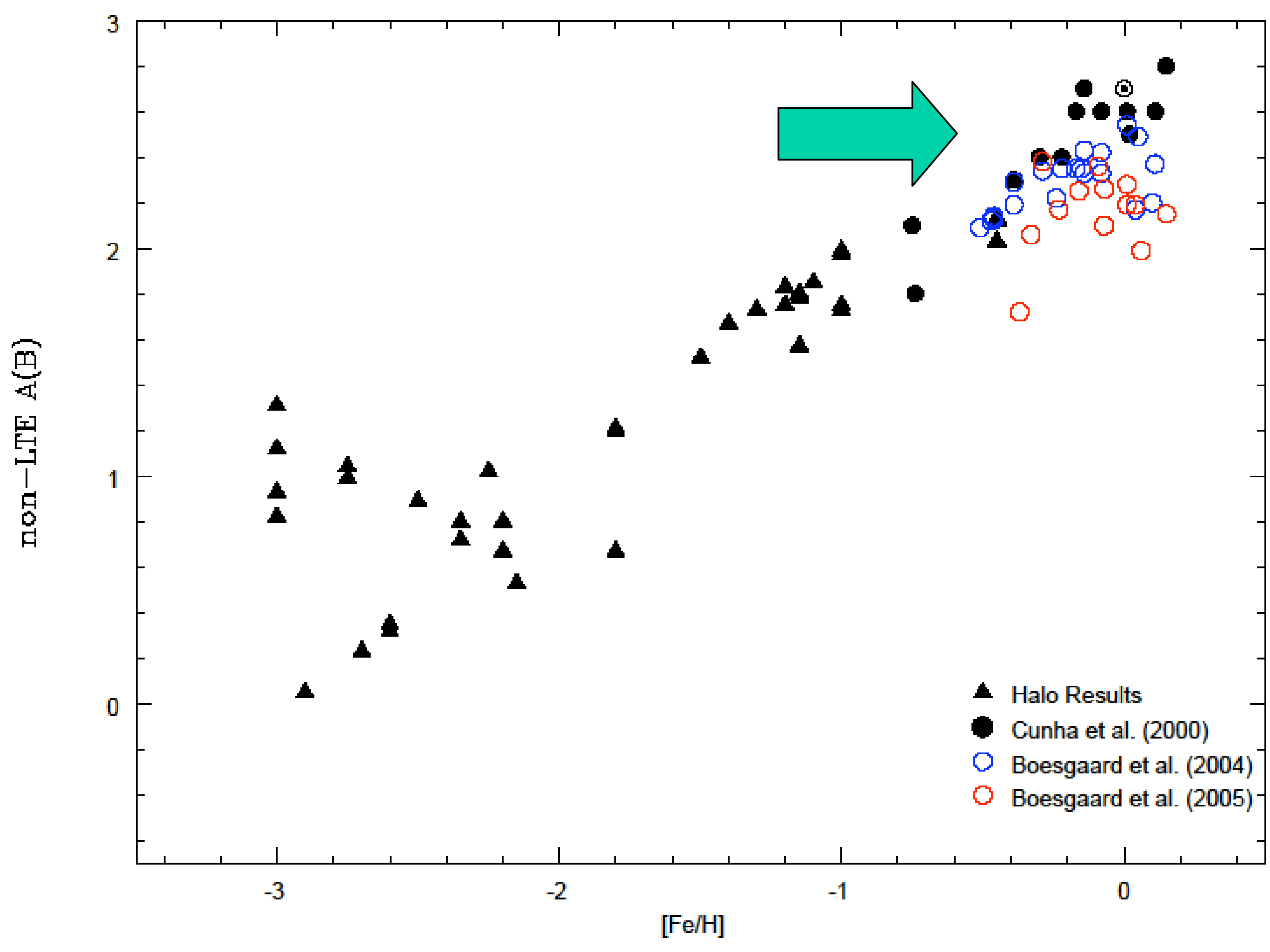
Delta A(B)=0.2 dex ; Delta A(Fe)=0.1 dex

Halo + Disk

- Overall the results for the Disk stars with <u>undepleted</u> Boron seem to connect smoothly with the results from the Halo

- One slope of ~0.9?

- Shallower slope at the disk?

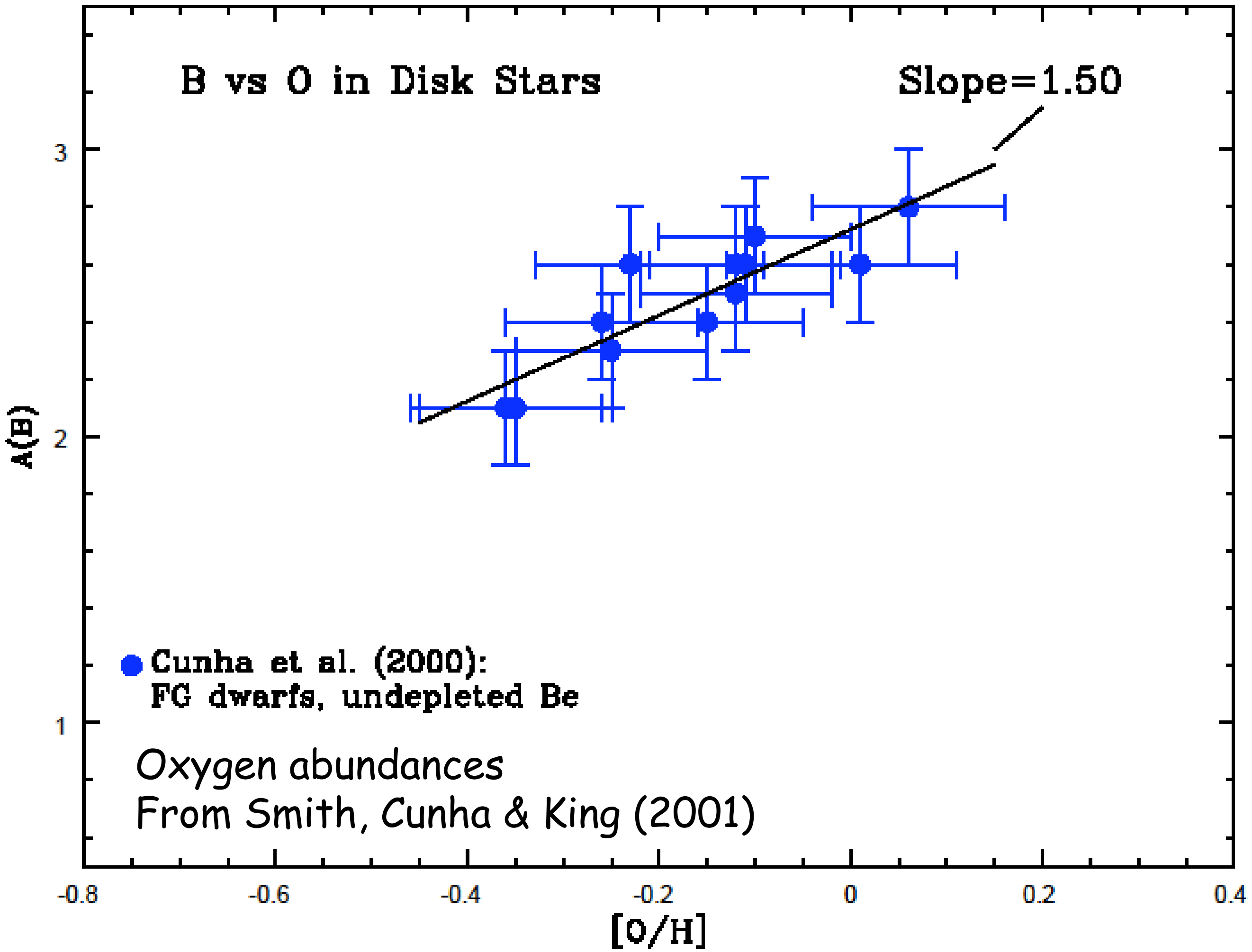


Trend with Oxygen for cool dwarfs

Oxygen:
investigate primary versus secondary behavior

• LTE 1-D analysis; based upon [OI] @6300A + OI @ 6158A

•Slope 1.5 +-0.08
• Could be some combination of primary and secondary source for boron production



Boron Abundances in OB STARS

- Provide an independent test on BI results for cool stars; different systematics
- Of the trio Li Be B, **only B** can be measured in early-type stars
- Problem in using OB stars to define the Galactic trend is the varying amounts of boron depletion
- Boron depletion proportional to mass, age and rotational velocity
- There is no monitor for depletion as in the case of observations of Be (and Li) in cool stars

Nitrogen and N/C abundances …

- The spread in B is at least 10x larger than in N … Thus, boron is far more sensitive to mixing and at earlier stages on the MS.

Prediction is that N ↑ *preceeded* by B ↓

B-type stars

Summary of Abundance Work to date:

1) **Venn, Lambert & Lemke (1996)** : Sample of 6 B-type stars (more evolved) ; 5 upper limits [B II from IUE SWP]

2) **Cunha et al. (1997):** Sample of 4 Orion B-stars [B II GHRS]

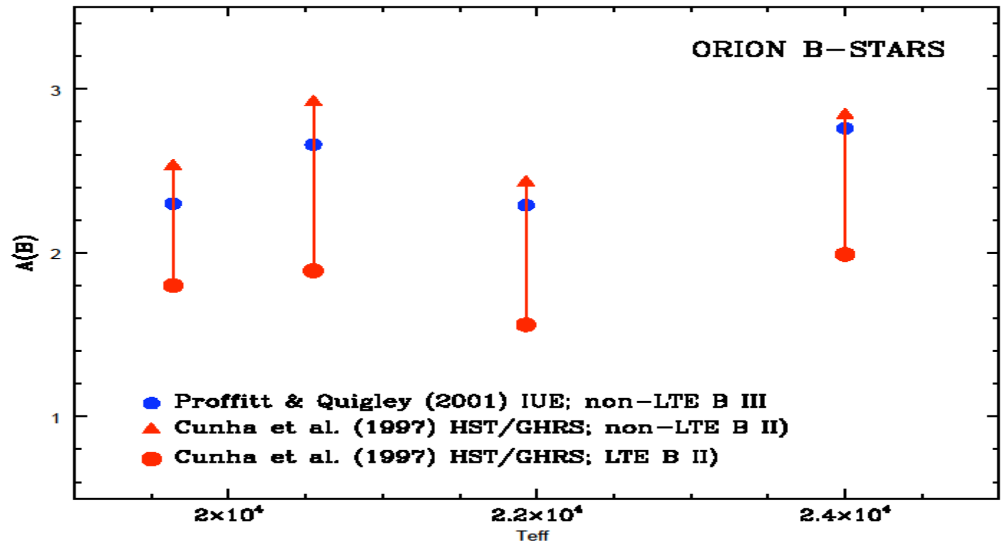
3) **Proffitt & Quigley (2001):** IUE archive observations of B III; large sample; more significant to look for trends

4) **Venn et al. (2002)** : B III [HST/STIS] in 7 MS stars; 4 boron upper limits

5) **Mendel et al. (2006):** B III [HST/STIS] in 7MS stars; most of them with depleted boron; 1 boron upper limit

Results for Orion: B II vs B III

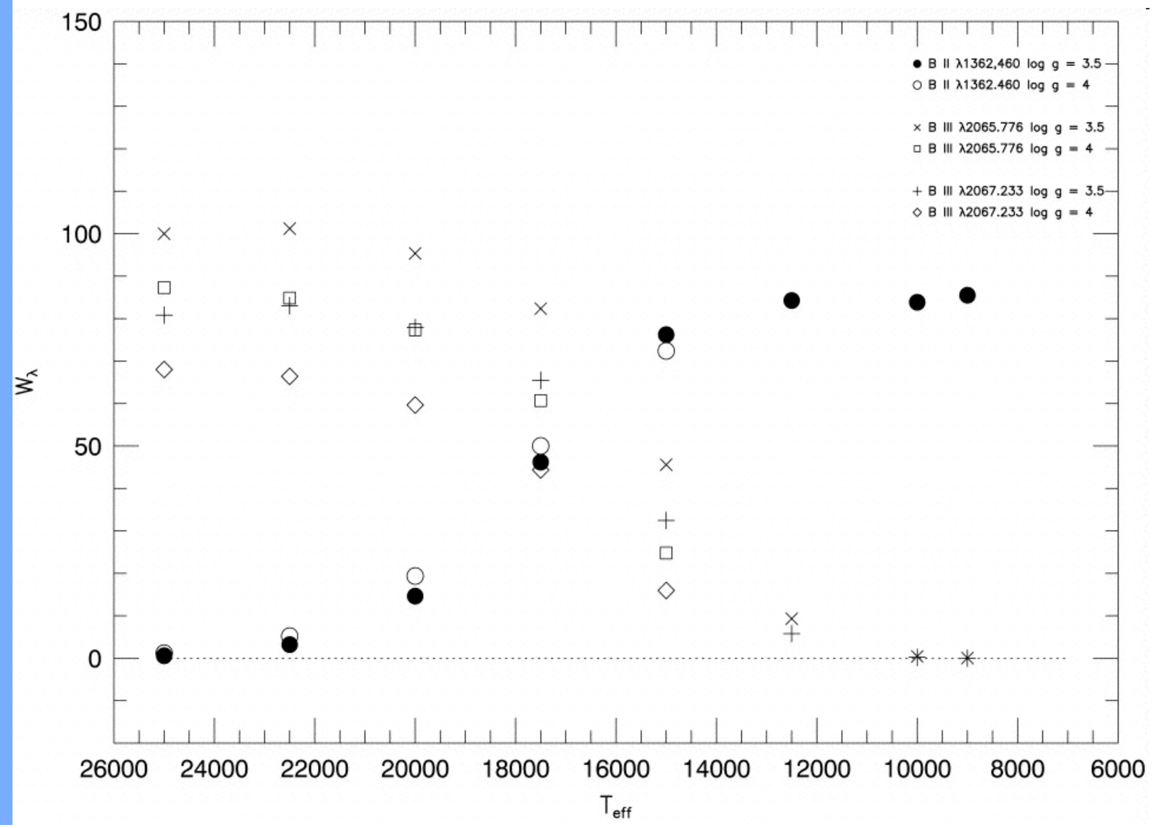
Cunha et al. (1997)
4 stars in Orion; used BII transition A(B) = 2.7 +- 0.2dex



- LTE BII results are much lower; [similar to results for ISM; boron depletion?]
- Non-LTE corrections are significant : ~ 1 dex! [M. Lemke (1997) calculations]

- **Large corrections**; The comparison of IUE BIII results suggest that the magnitude and sense of the non-LTE effects have been predicted correctly

- BIII results are preferred
- BII line is weaker & blended



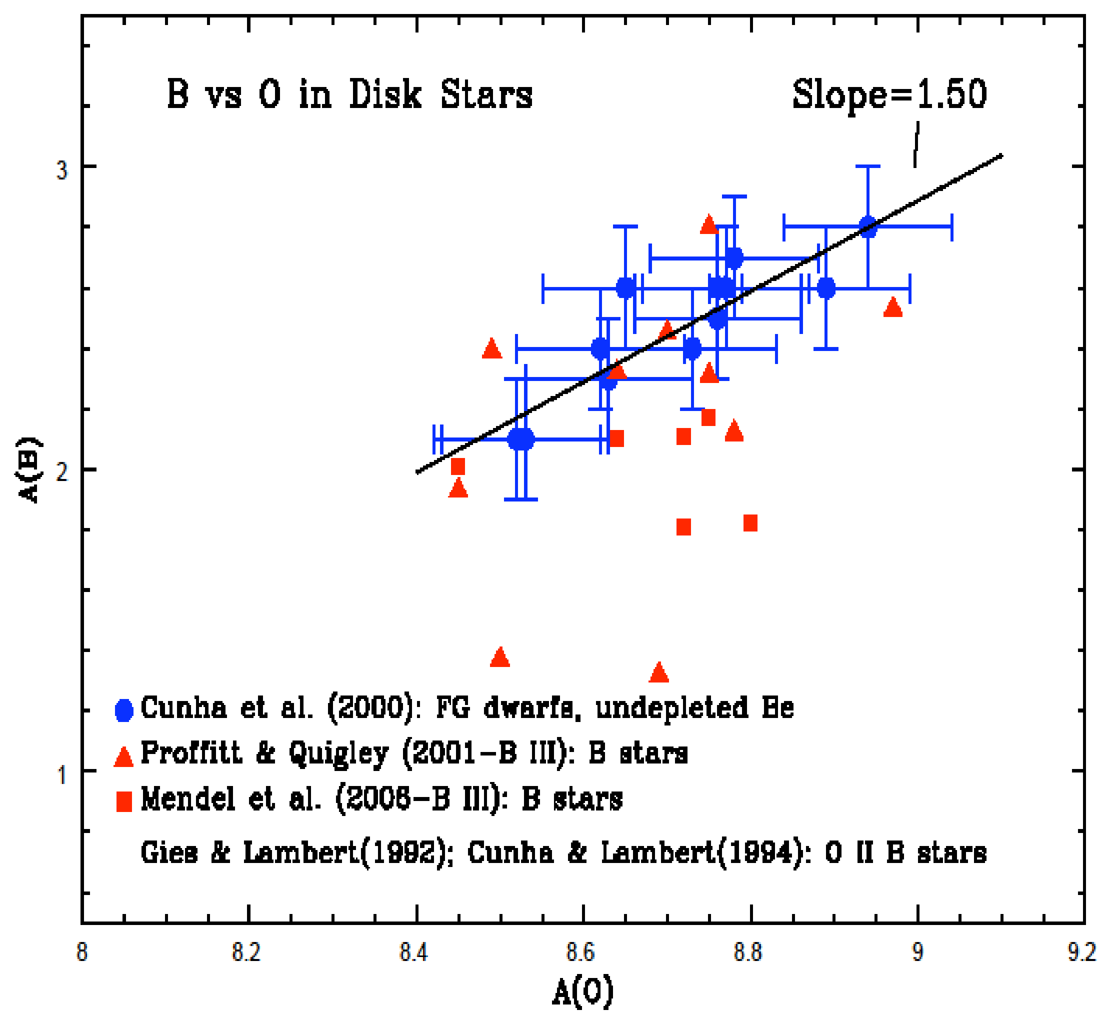
Adding the B-star Results to disk trend

- <u>Overlap is good</u>; especially given the very different temperatures and ionization stages (BI vs B III) in the analyses.

- Boron abs. only from the B III transition; Boron abs Upper limits not plotted

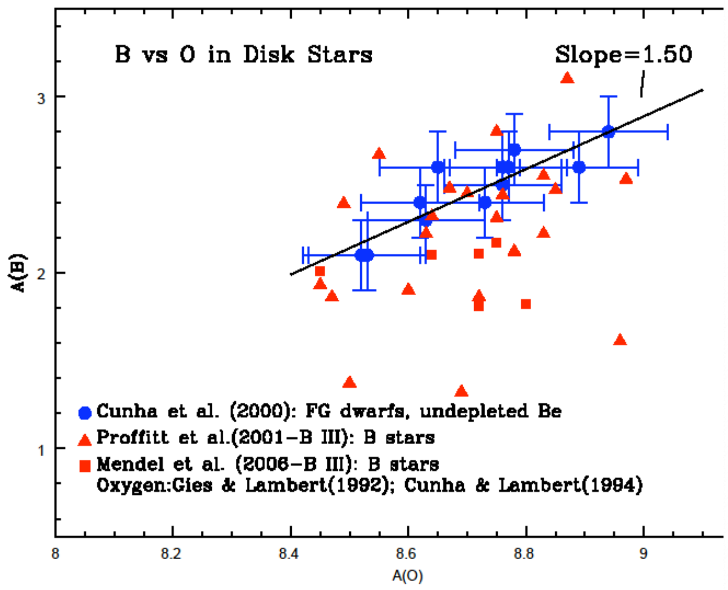
Large scatter; Evidence for depletion; B stars are a mixture of objects having differing amounts of boron depletion.

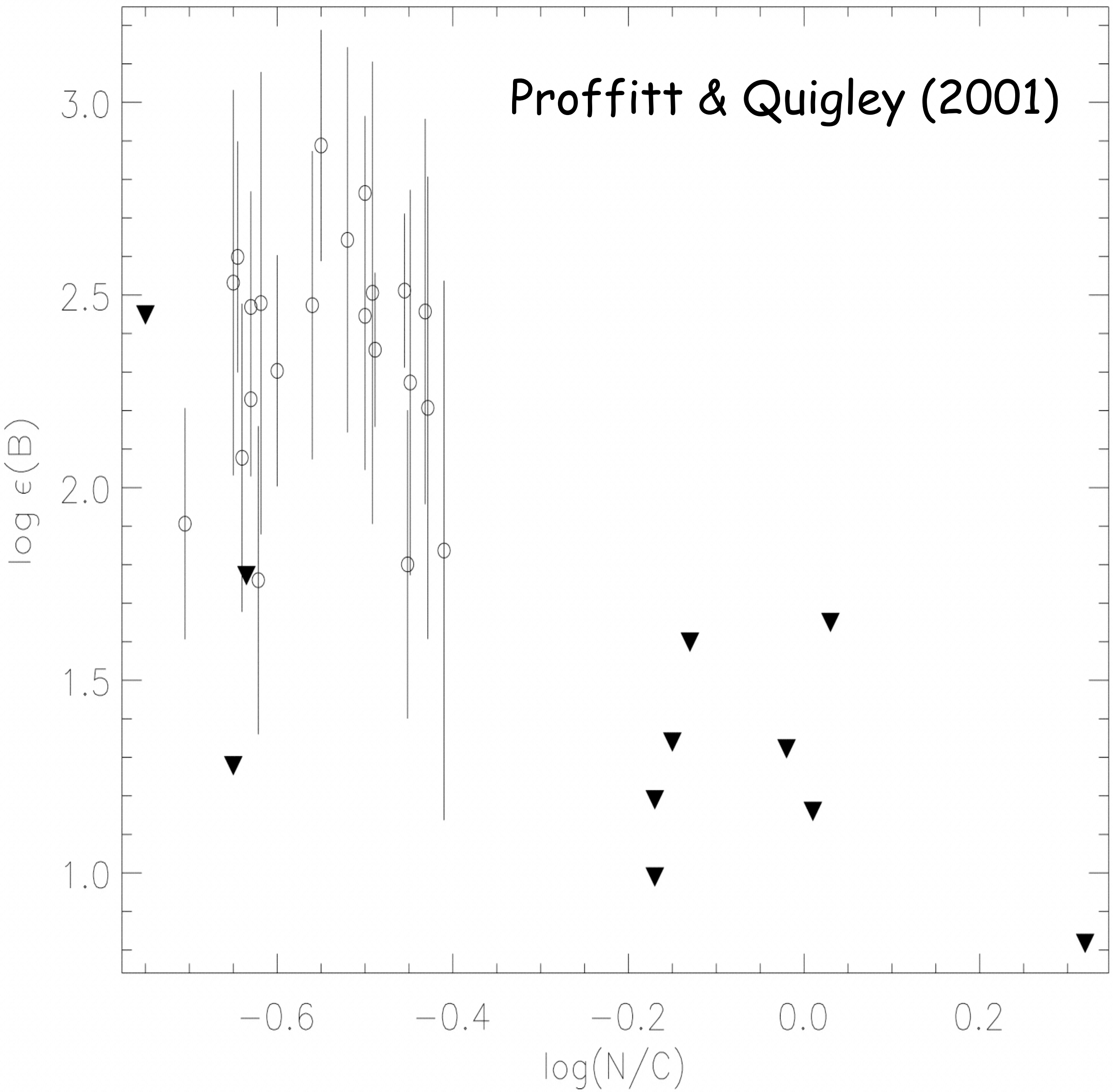
The agreement in the upper envelope is significant



•Stars with enhanced N/C ratios all show very low boron abundances

• Open circles correspond to red triangles





Some Conclusions & Perspectives

- Most the abundance work done for Boron in disk stars in the last ~10 years.
- Boron observations are still sparse when compared with the other light elements Be and Li
- The trend of B with Fe obtained from the cool FG dwarfs in the Galactic disk has a slope of ~0.87+- 0.08;
- This slope is similar to the slope of B with Fe found for the metal poor halo stars; there is a smooth connection
- The Disk trend of B with oxygen has a slope of ~1.5; This slope suggests an intermediate behavior between primary and secondary production for boron with respect to oxygen
- The slope with oxygen is consistent with the slope derived for Fe provided that [O/Fe] increases as [Fe/H] decreases, as observed in the disk.

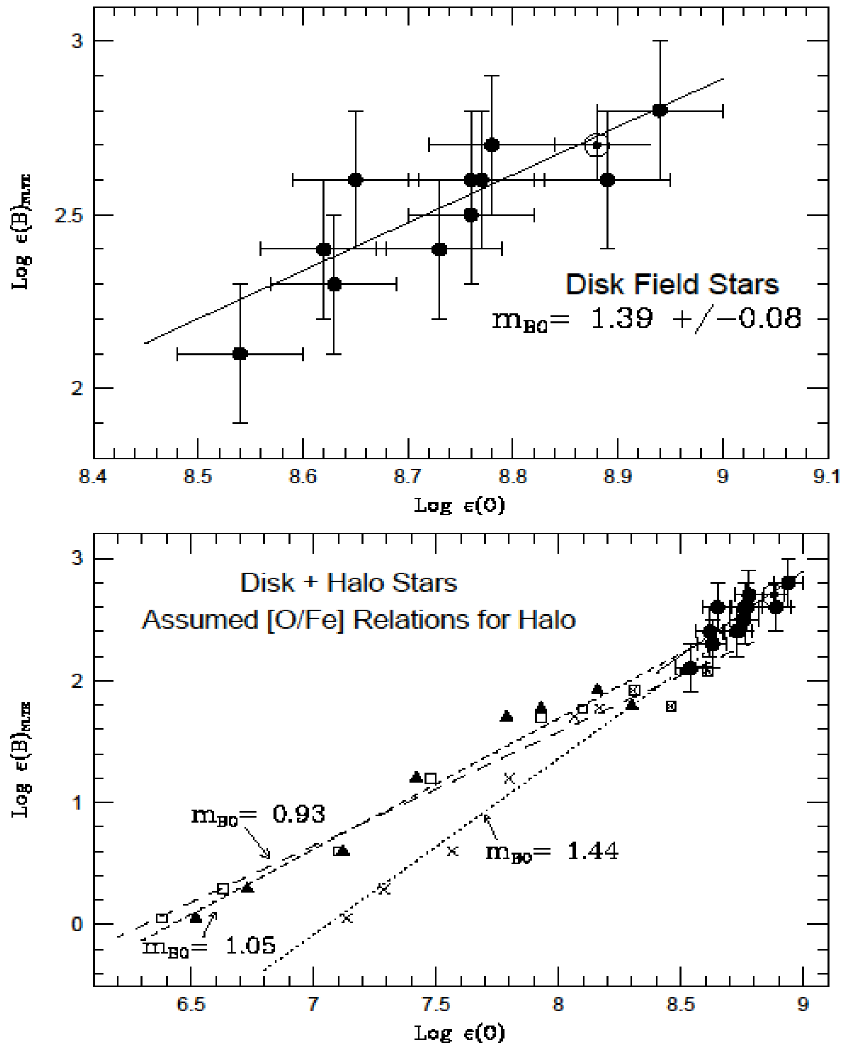
How do we move Forward?

- Improvements in the analysis
  Atomic Data: Better linelists in the uv
  full non-LTE treatment is needed
  Hydro- 3D modelling? …
  More observations needed

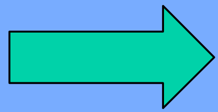
  Future Observations will come…

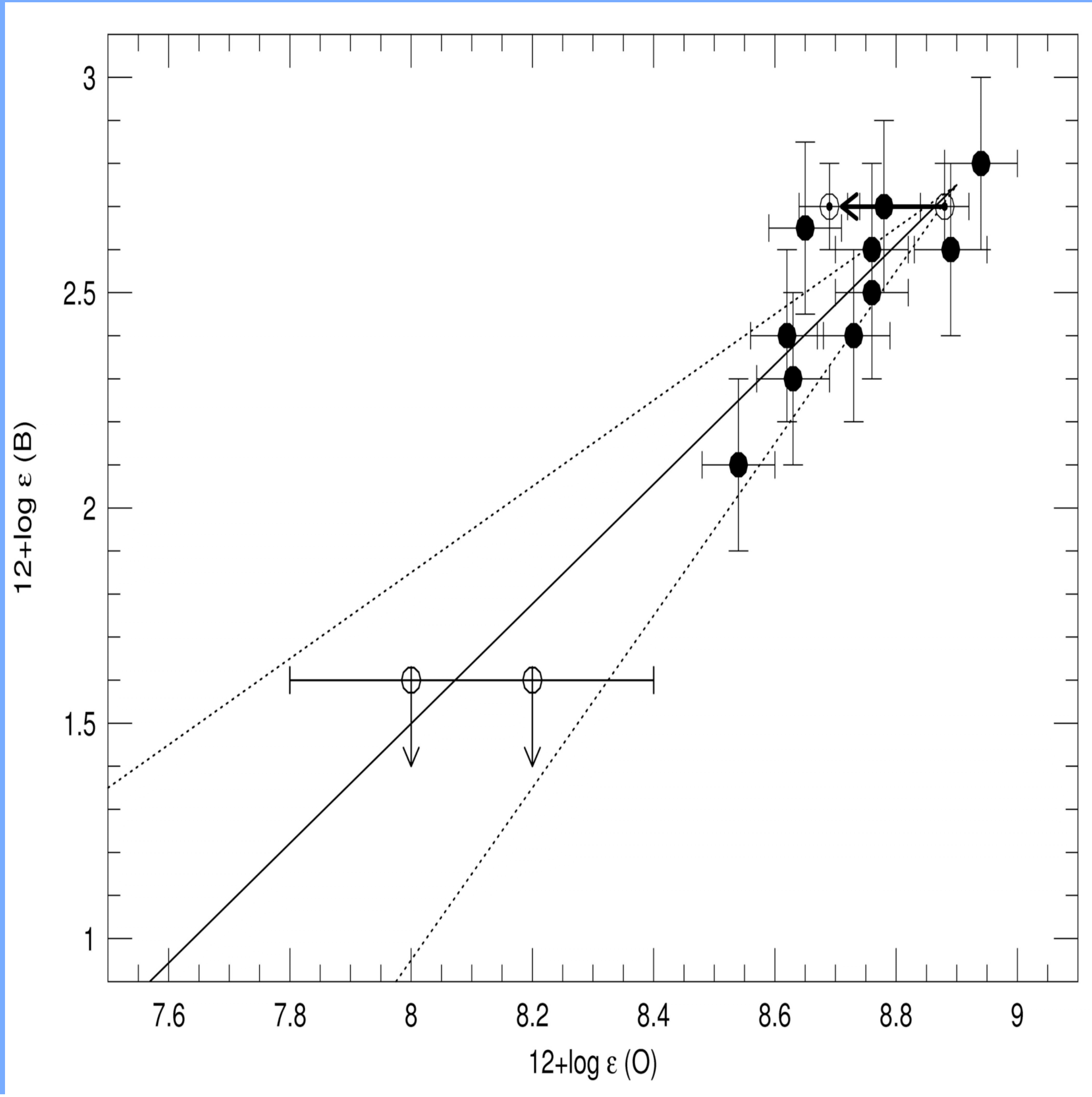
- The **Space Telescope Imaging Spectrograph** (STIS) was successfully repaired during SM4 and has resumed science operations with all channels. Most aspects of instrument performance are similar to what had been anticipated …
- The **Cosmic Origins Spectrograph** (COS) was installed on the Hubble Space Telescope (HST) in May 2009. COS is designed to perform high-sensitivity, medium- and low-resolution spectroscopy in the 1150-3200Å wavelength range (more moderate resolution)

[!Deadline for HST proposals is next week!]



Disk Field Stars
m_{BO}= 1.39 +/−0.08
Log ε(B)
Log ε(O)
Disk + Halo Stars
Assumed [O/Fe] Relations for Halo
m_{BO}= 0.93
m_{BO}= 1.44
m_{BO}= 1.05





3
2.5
2
1.5
1
12+log ε (B)
7.6
7.8
8
8.2
8.4
8.6
8.8
9
12+log ε (O)

What is expected for Boron versus Oxygen?

→ From neutrino-induced nucleosynthesis:

- B correlates with O

→ From Standard CR spallation in the ISM:

- Quadratic relation (secondary process) ← depends on the metallicity

$N_A(t)$ ← ab. of boron

$N_k(t)$ ← ab. of target species in the ISM

$\sigma_k(E)$ ← cross-section for spallation on species k at energy E

Φ ← cosmic ray flux

$$\frac{dN_A}{dt} = \sum N_k \int_E^{\infty} \sigma_k(E)\, \Phi\, dE$$

(Φ: $\propto \frac{dN(SN)}{dt}$)

$N_k = CNO$ (N_k: $\propto N(SN)$) → also seen the acceleration mechanism that produces CR's

$$\frac{dN_A}{dt} \propto N(SN) \frac{dN(SN)}{dt}$$

$$N_A \propto N(SN)^2 \propto N_k^2$$

→ FROM REVERSE PROCESS:

- LINEAR RELATION $N_k = p + \alpha$'s