Peculiar X-ray Emission Properties at Spectral Type B1 Indicate a Mass Loss Rate Discrepancy

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Abstract

We obtained XMM observations of several B supergiants, giants, and main sequence stars within the spectral region from B0.5 to B2. These observations confirm a substantial drop in the observed X-ray flux at spectral type B1 for all luminosity classes (marginally apparent in previous observations). Interestingly, the spectral location of this drop suggests that it may be related to another well-known phenomenon in this region, the bi-stability jump (***BSJ***). However, using a variety of stellar wind distributed X-ray source models, our analyses show that the observed X-ray spectra and derived wind properties are not consistent with the theoretical predictions of the ***BSJ***. This suggests a fundamental misunderstanding of the mass loss process within the vicinity of this B-star "X-ray dividing line".

Primary Goals of Our XMM Study

- Study the stellar X-ray properties along the entire B-star X-ray dividing using high S/N XMM EPIC observations

- Determine the compatibility of the predictions of the BSJ theory and "wind-momentum luminosity relations" (WLR) with the observed X-ray emission

- We find that X-rays are ***critical*** in constraining stellar wind structures, specifically, the fundamental wind parameter: the "wind efficiency" (η) or mass loss rate ($\dot{M}$)

- **Here we will focus only on the B supergiant results**

History of Drop in X-ray Flux at B1

- Einstein OB supergiant survey found no X-ray emission beyond B1 (Cassinelli et al. 1981)

- ROSAT observations of B main sequence stars found a well defined drop in X-rays at B1 (Cassinelli et al. 1994)

- ROSAT All-Sky Survey data confirmed this B1 drop is also present in B supergiants and giants – Evidence for a “B star dividing line” (Berghofer et al. 1997)

What is Source of X-ray Drop at B1?

- Since the BSJ also occurs at B1 it is the most likely candidate. The wind efficiency is defined as

$$\eta = \dot{M}V_\infty / (L_B / c)$$

- Observations show that V_∞ drops a factor of 2 at B1 and theory predicts η increases, thus an increase in $\dot{M}$ by a factor > 2 is expected

X-ray Flux Dependence on η and V_∞

- The characteristic scaling of the "*observed*" X-ray flux (F_X) produced by a wind distribution of X-ray sources is given by (Owocki & Cohen 1999)

$$F_X \sim (\dot{M} / V_\infty)^n \quad \text{- OR -} \quad F_X \sim (\eta / V_\infty^2)^n$$

where $n \sim 2$ (optically thin)

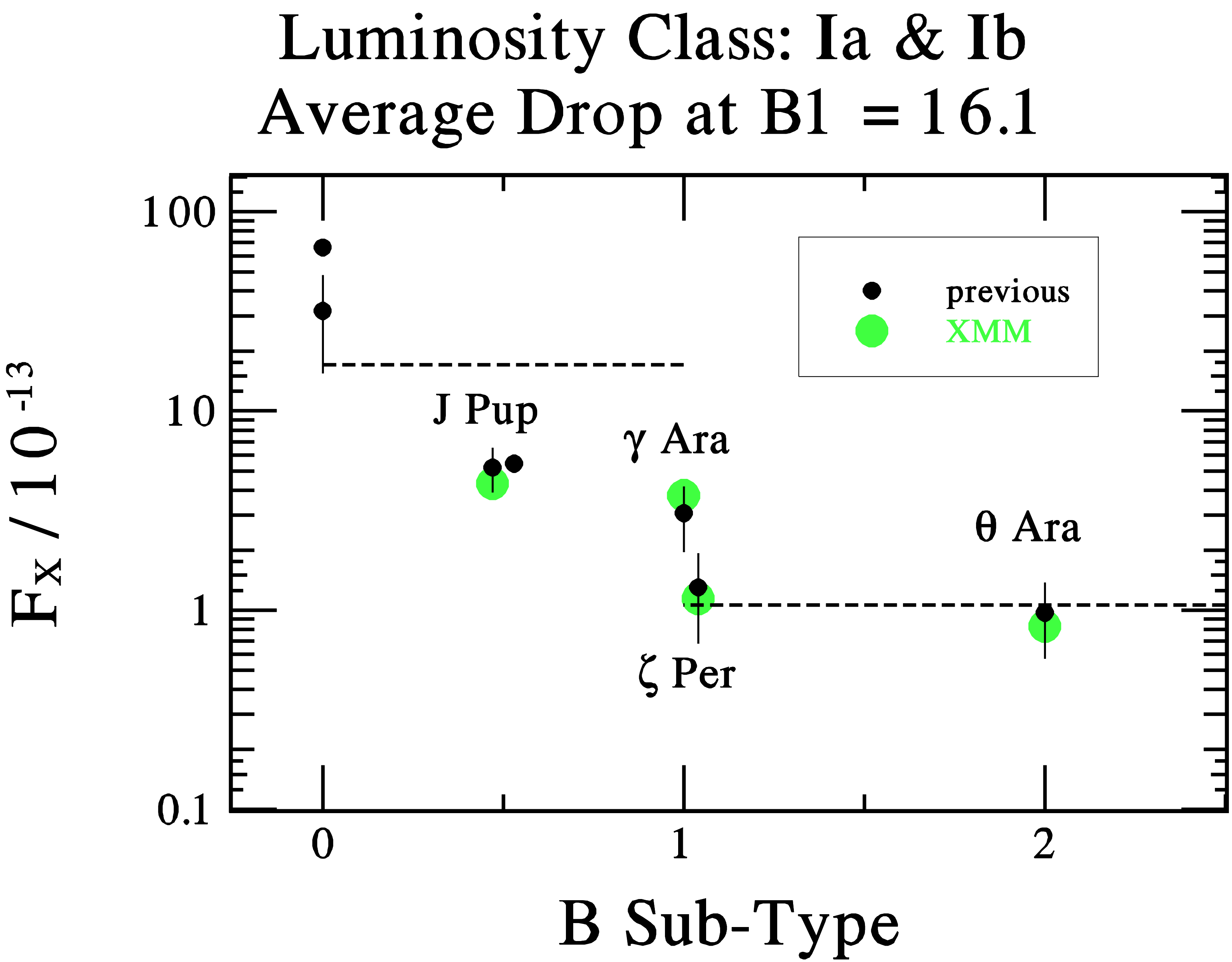
$n \sim 1$ (optically thick)

Thus any increase in η (or $\dot{M}$) and a decrease in V_∞ (as predicted at the BSJ) implies an increase in F_X

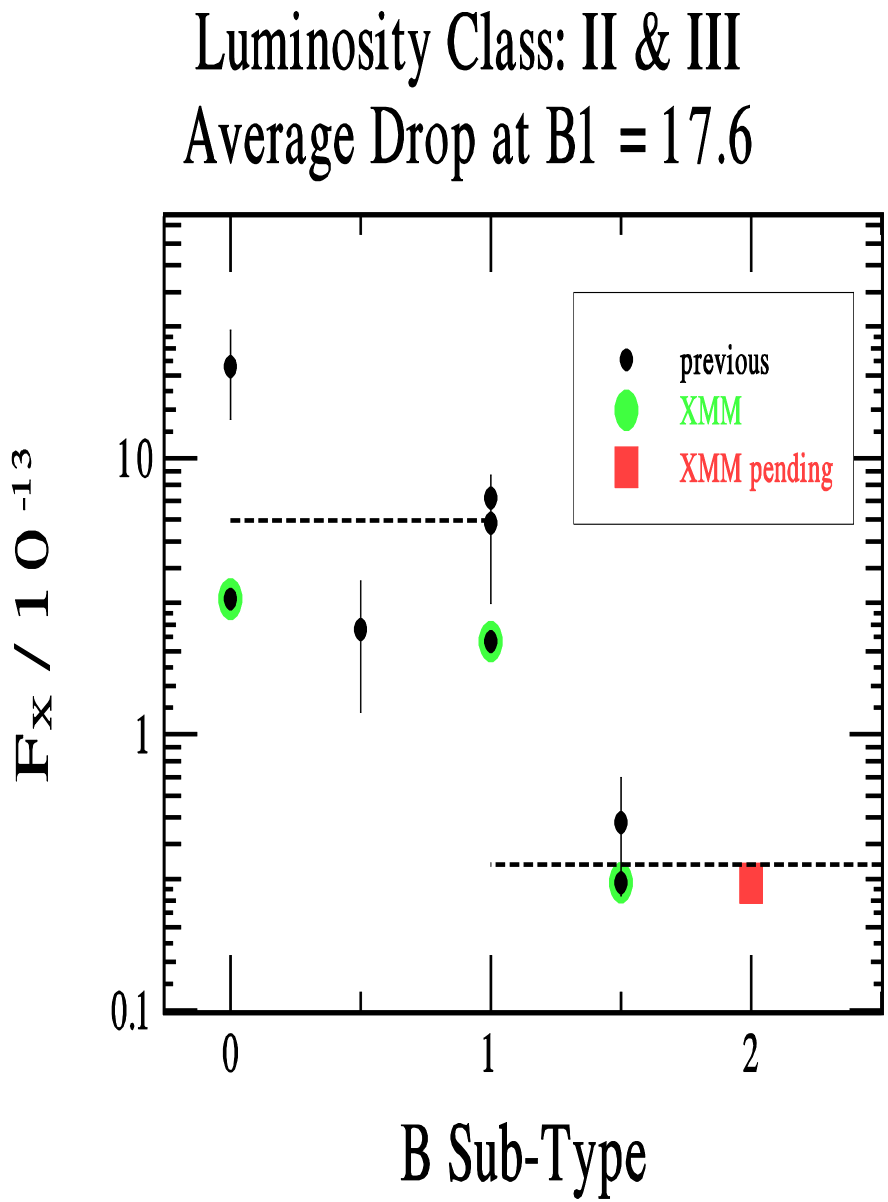
BUT THIS IS NOT OBSERVED

Observed F_X in Vicinity of the B Star X-ray Dividing Line

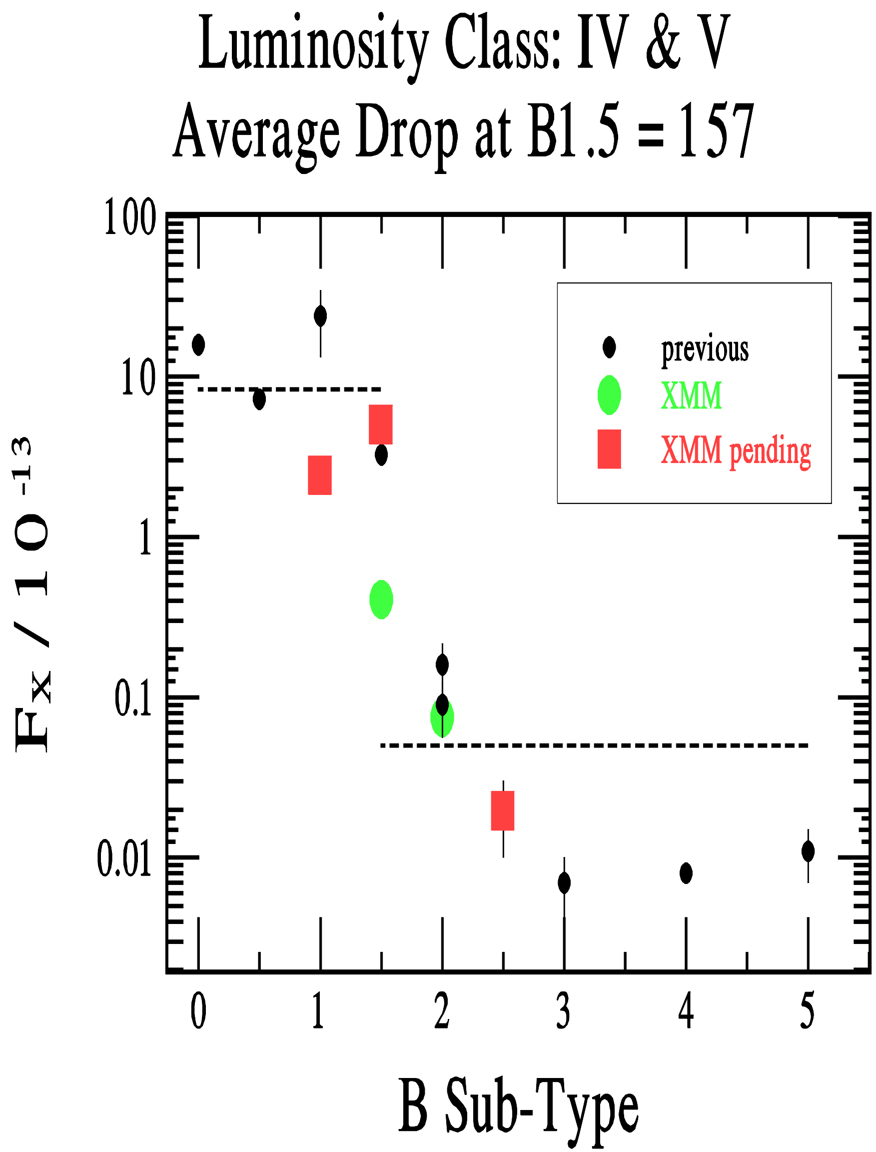
- All F_X are distance normalized to 500 pc
- Average Drop represents the ratio of average fluxes (hot-side average/cool-side average) – this drop is significantly larger in main sequence stars (actual BSJ drop is typically smaller)
- Plot legend – previous means either ROSAT and/or Einstein data – XMM means observed XMM targets – pending means unobserved accepted XMM targets



Luminosity Class: Ia & Ib
Average Drop at B1 = 16.1
100
10
1
0.1
F_X / 10^{-13}
0
1
2
B Sub-Type
previous
XMM
J Pup
γ Ara
ζ Per
θ Ara



Luminosity Class: II & III
Average Drop at B1 = 17.6
previous
XMM
XMM pending
Fx / 10 -13
10
1
0.1
0
1
2
B Sub-Type



Luminosity Class: IV & V
Average Drop at B1.5 = 157
previous
XMM
XMM pending
Fx / 10 -13
100
10
1
0.1
0.01
0
1
2
3
4
5
B Sub-Type

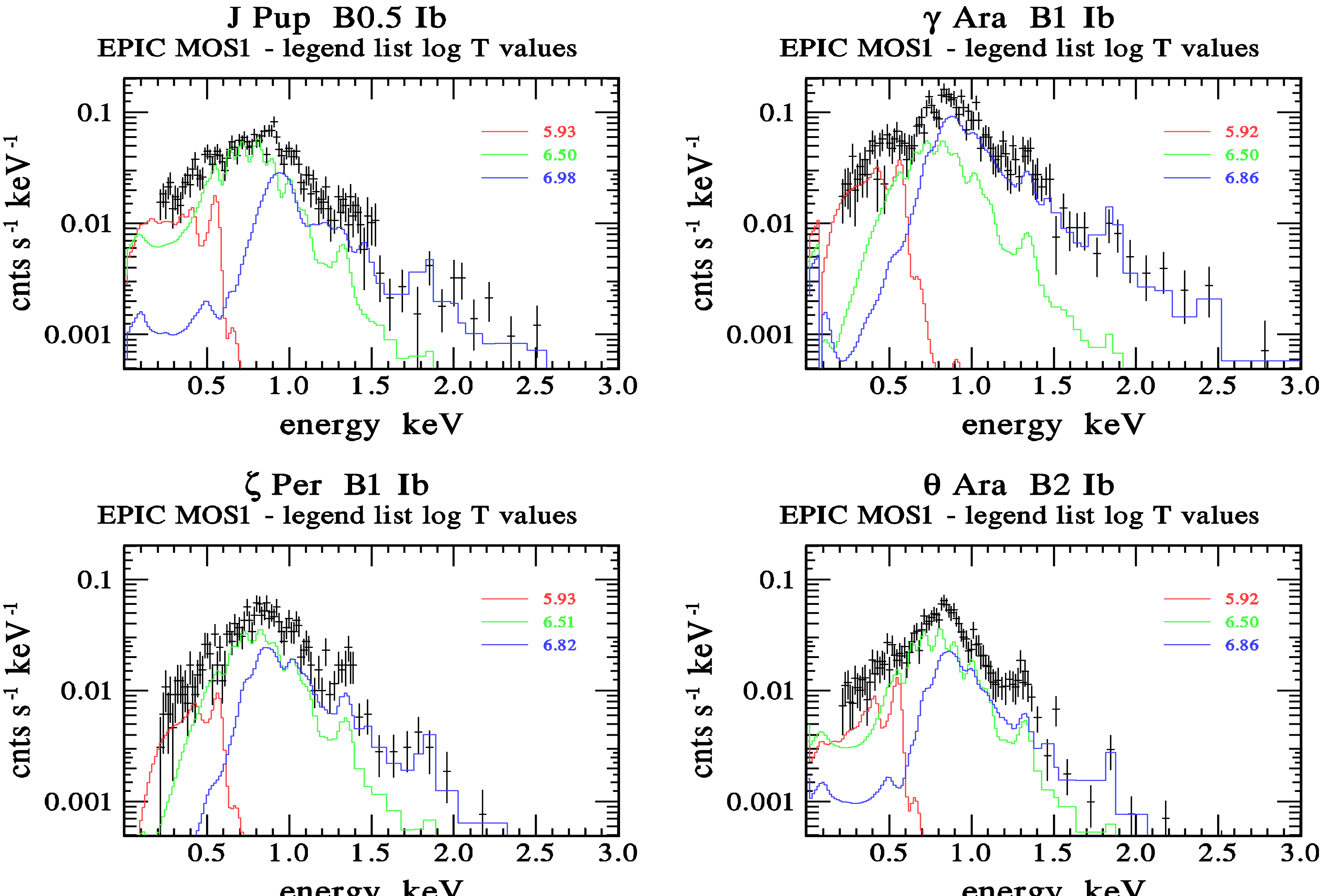
Spectral Fits

- All stars require 3 components and best fits are obtained by varying X-ray temperature (T_X), emission measure (EM), and wind column density (N_W) for each component (see Table)
- Except for EM, all T_X and N_W are essential identical for all stars
- The most surprising result is that all stars have very similar spectral shapes (see Figures) which explains why T_X and N_W are very similar (NOTE – the count rate spectra are **not** distance normalized)
- The primary parameter responsible for the BSJ drop in F_X is the decrease in the intrinsic emission measures (EM)

B Supergiant Best-Fit Parameters

(all F_X are normalized to a fixed distance = 500 pc)

Parameter	Source	J Pup	ϒ Ara	ς Per	ϑ Ara
		B0.5 Ib	B1 Ib	B1 Ib	B2 Ib
d (pc)		506	340	269	249
Log T_X	1	5.93	5.92	5.93	5.92
	2	6.50	6.50	6.51	6.50
	3	6.98	6.86	6.82	6.86
Log EM	1	55.15	55.31	54.69	54.77
	2	54.40	54.08	53.85	53.86
	3	53.99	54.10	53.64	53.34
Log N_W	1	21.24	21.20	21.20	21.20
	2	21.43	21.47	21.47	21.48
	3	21.68	21.66	21.72	21.55
F_X / 10^{-13}		4.31	3.76	1.14	0.83



J Pup B0.5 Ib
EPIC MOS1 - legend list log T values
5.93
6.50
6.98
γ Ara B1 Ib
EPIC MOS1 - legend list log T values
5.92
6.50
6.86
ζ Per B1 Ib
EPIC MOS1 - legend list log T values
5.93
6.51
6.82
θ Ara B2 Ib
EPIC MOS1 - legend list log T values
5.92
6.50
6.86
cnts s -1 keV -1
energy keV
0.1
0.01
0.001
0.5
1.0
1.5
2.0
2.5
3.0

X-ray Emission Model of BSJ Region

- Assumes a spherically symmetric wind with a $\beta = 1$ velocity law
- Wind density determined by η and V_∞
- X-rays distributed radially throughout wind at T_X (or multiple T_X)
- Wind absorption determined by LOS $\tau(r,\theta)$ – using wind opacity models and $N_W(r,\theta)$
- Total observed X-ray flux found by integration over entire wind volume (assuming a minimum X-ray cutoff radius)

Model X-ray Predictions

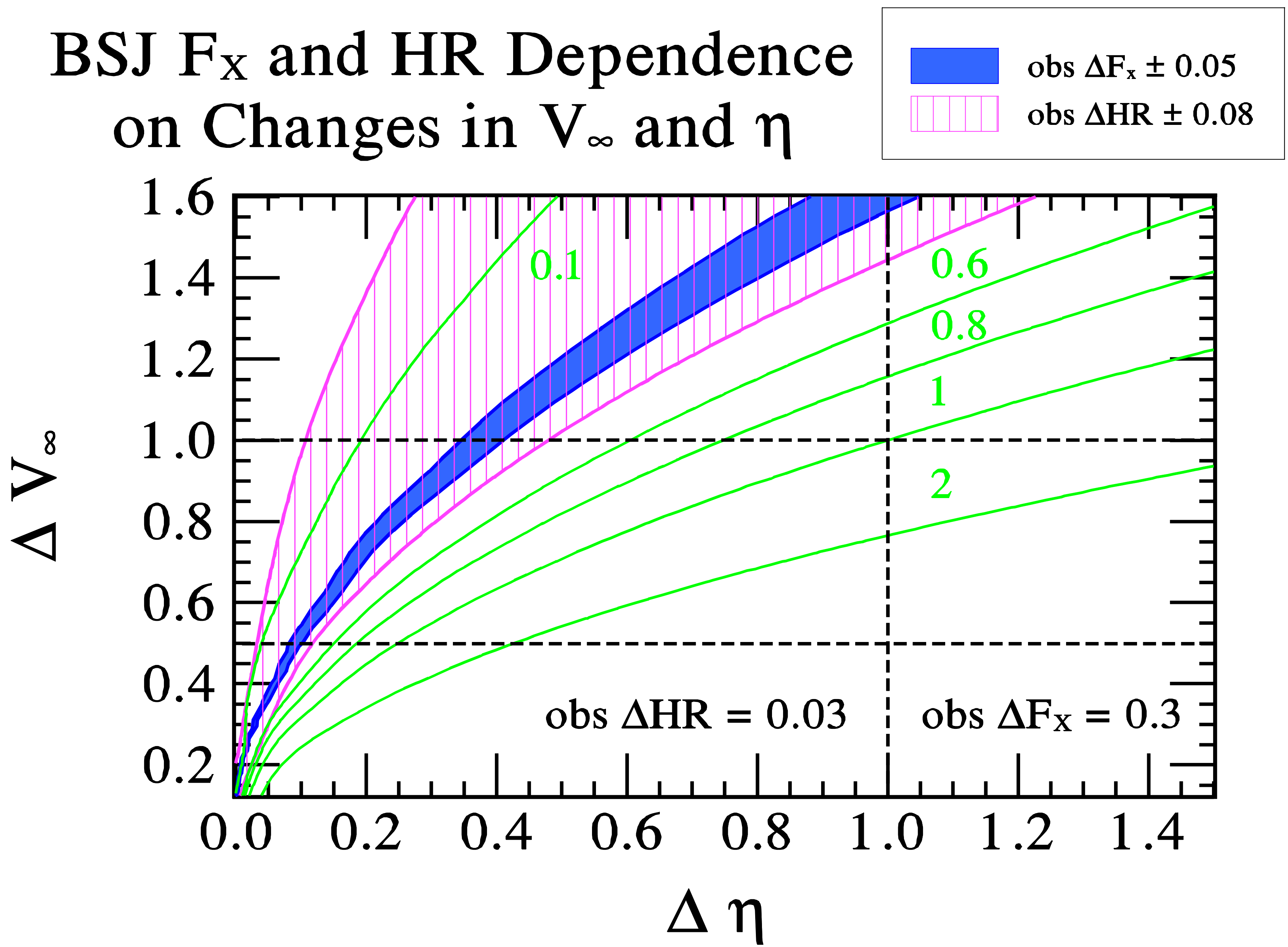
- First we examine the current theoretical η (Vink et al. 2000), and 3 WLR predicted η (Kudritzki et al. 1999; Mokiem et al. 2005; Searle et al. 2008)

- Then we determine the “best-fit” modified η that is required to explain the X-rays at the BSJ and on both sides of the BSJ

- ***NOTE, in addition to re-producing the observed F_X we must ALSO be able to re-produce the observed hardness ratio (HR)***

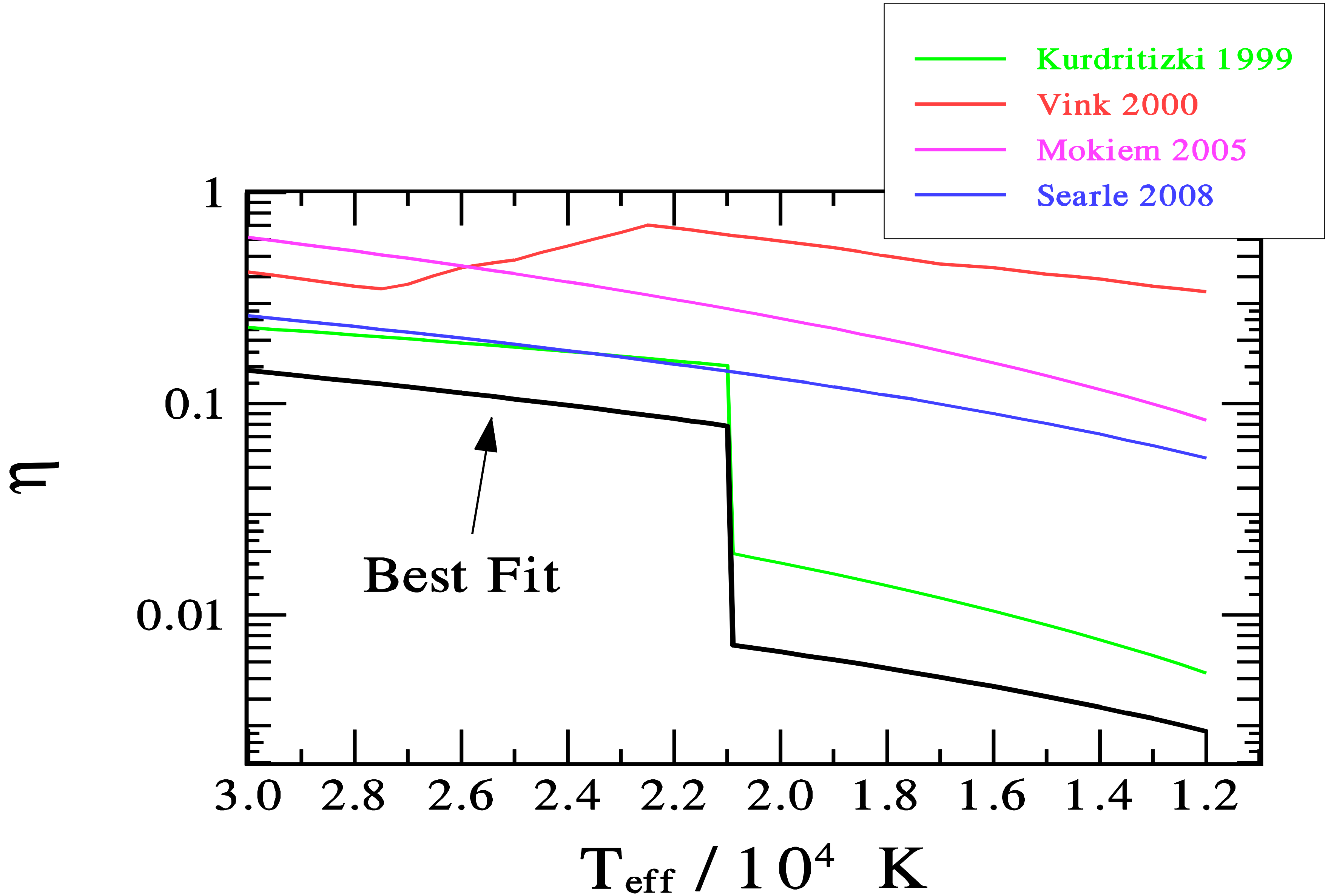
Conditions at the BSJ

- Generally all η models are capable of explaining the drop in X-rays at the BSJ, ***only if η is reduced***
- Contour map shows predicted X-ray change, ΔF_X, as a function of changes in η and V_∞ ($\Delta\eta$, ΔV_∞) at the BSJ [NOTATION: for a given parameter P, ΔP = fractional change in P at the BSJ (ratio of cool P to hot P)]
- Also shown are the *observed* range in ΔF_X and overlaid is the *observed* HR difference (ΔHR) that define the required changes in η and V_∞ to fit the observations [ΔHR = difference in HR at the BSJ (cool HR – hot HR)]

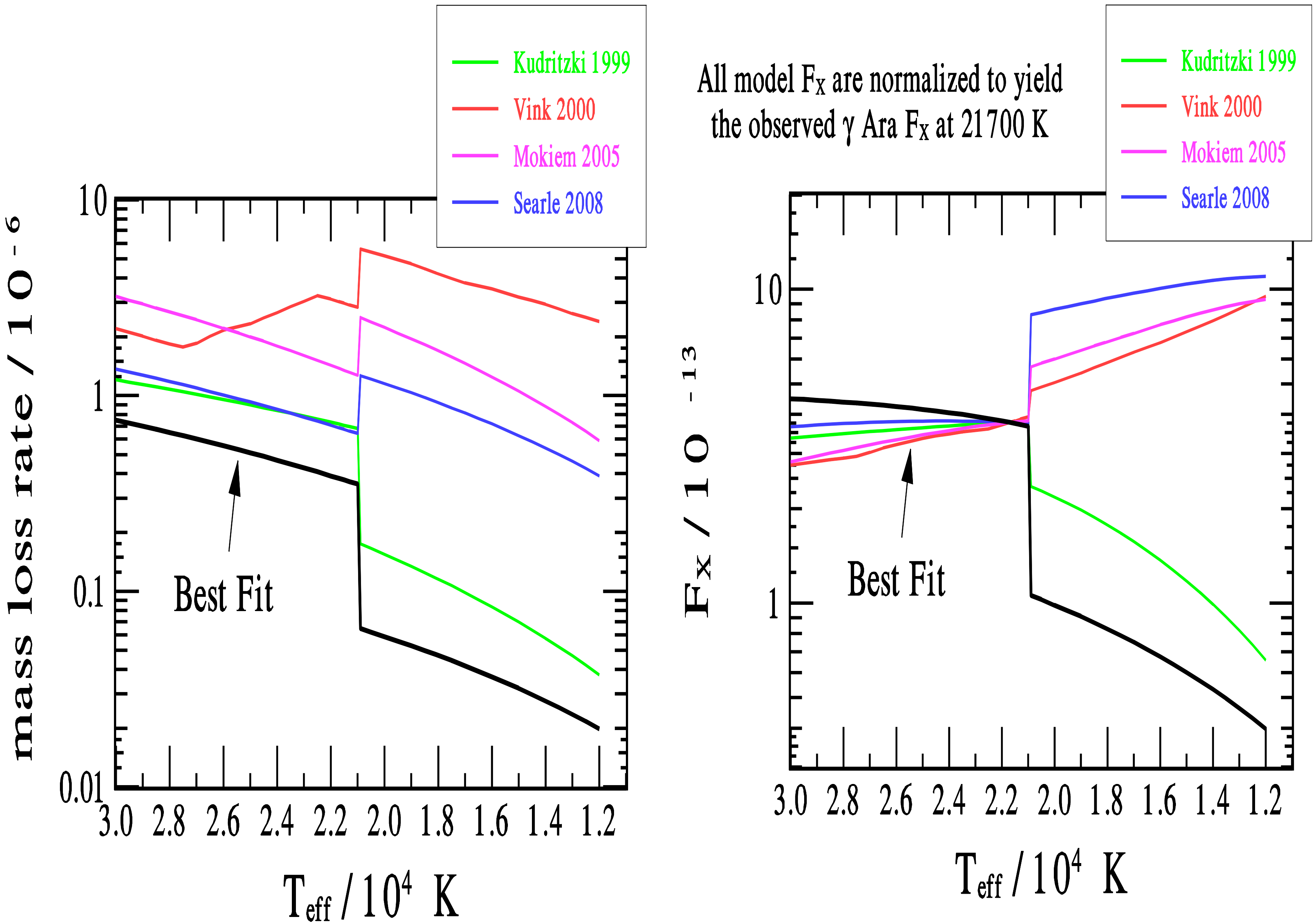

BSJ F_X and HR Dependence
on Changes in V_∞ and η
obs $\Delta F_x \pm 0.05$
obs $\Delta HR \pm 0.08$
0.1
0.6
0.8
1
2
obs $\Delta HR = 0.03$
obs $\Delta F_X = 0.3$
ΔV_∞
$\Delta \eta$
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4

Current Predictions of η, $\dot{M}$, and F_X and The Best-Fit Model

- All η have similar T_{eff} dependence but different scalings
- Except for the Kudritzki WLR model, all others predict an increase in $\dot{M}$ and F_X on the cool side of the BSJ
- The Kudritzki model is the only one comparable to the best-fit model
- The Best-Fit Model is basically a modified Kudritzki model using smaller scale factors on both sides of BSJ

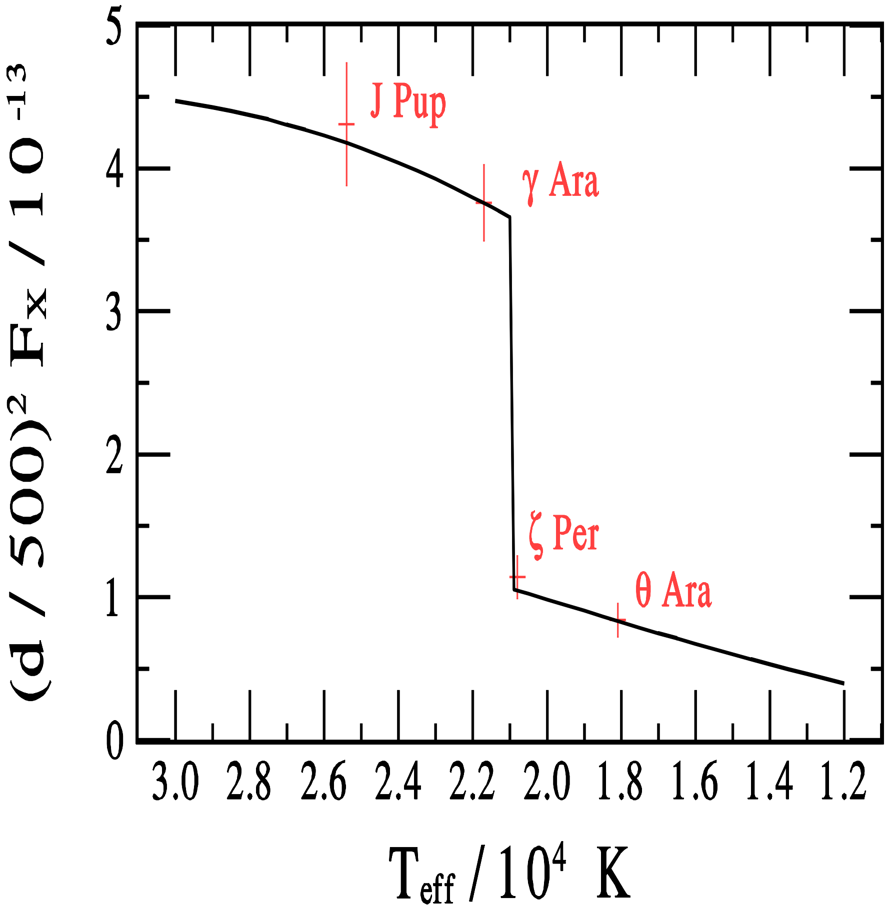


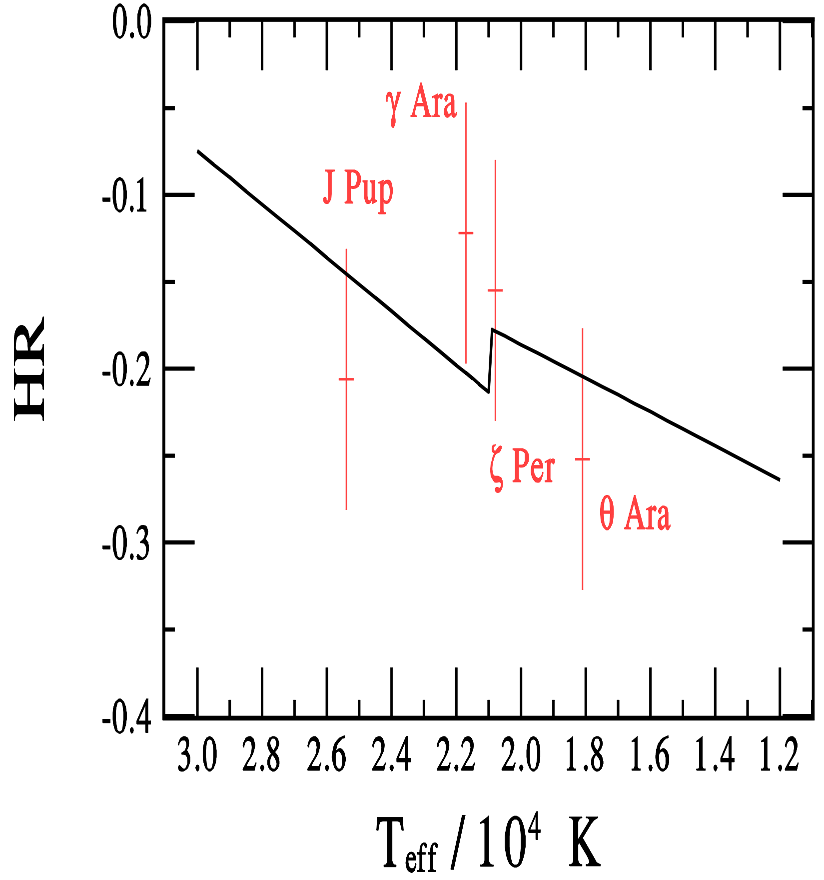
Kurdritizki 1999
Vink 2000
Mokiem 2005
Searle 2008
1
0.1
0.01
η
Best Fit
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
T_{eff} / 10^4 K



Kudritzki 1999
Vink 2000
Mokiem 2005
Searle 2008
mass loss rate / 10 -6
10
1
0.1
0.01
3.0 2.8 2.6 2.4 2.2 2.0 1.8 1.6 1.4 1.2
Best Fit
Teff / 10^4 K
All model Fx are normalized to yield
the observed γ Ara Fx at 21700 K
Fx / 10 -13
Best Fit

Best-Fit Model





SUMMARY OF OUR B SUPERGIANT ANALYSIS

- There ***cannot*** be ***large increases in η***, it must smoothly decrease towards later spectral types like the WLR models

- There must be a ***large drop in η*** at the BSJ

- The Kudritzki and Searle η appear to provide the best T_{eff} dependence, but both models require different reduced η scale factors on both sides of the BSJ

- The best-fit $\dot{M}$ are found to be much lower than previously thought on both sides of the BSJ, especially on the cool side

- This overall η and $\dot{M}$ reduction could be an artifact of wind clumping effects – we are currently investigating

- Our X-ray study of B giants and main sequence stars will provide additional clues on the physics of this ***B star X-ray Dividing Line***