# The Evolution of the Effective Temperature Scale of O-type Stars

Peter, Quantitative Spectroscopy, and Me

*Philip Massey, Lowell Observatory*
*Contifest, October 15, 2008*

# Good $T_{eff}$ scale is crucial!

- $T_{eff}$ is the key to all of the physical properties of a massive O-type star:
  - bolometric correction (luminosity)
    - ➡ mass, age
- Ionizing fluxes in HII regions, initial mass functions and SF history in clusters, etc.

# The evolution of $T_{eff}$

1. The introduction of NLTE
2. The introduction of mass-loss
3. Inclusion of hydrodynamics and metals
4. Full inclusion of line blanketing

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THE ASTROPHYSICAL JOURNAL, **179**:181–188, 1973 January 1


## SPECTROSCOPIC STUDIES OF O-TYPE STARS. III. THE EFFECTIVE-TEMPERATURE SCALE

PETER S. CONTI
Joint Institute for Laboratory Astrophysics, University of Colorado, Boulder
*Received 1972 June 23*

ABSTRACT

An effective-temperature scale for O-type stars is presented, based upon a comparison of measures of λ4471 He I/λ4541 He II and predictions from the non-LTE models of Auer and Mihalas. There is reasonably good agreement between this scale and the effective temperatures inferred from O stars in H II regions by the Zanstra method. The problems associated with the low effective temperature derived for ζ Pup by interferometric methods are also discussed.
*Subject headings:* atmospheres, stellar — early-type stars — emission-line stars — Of stars

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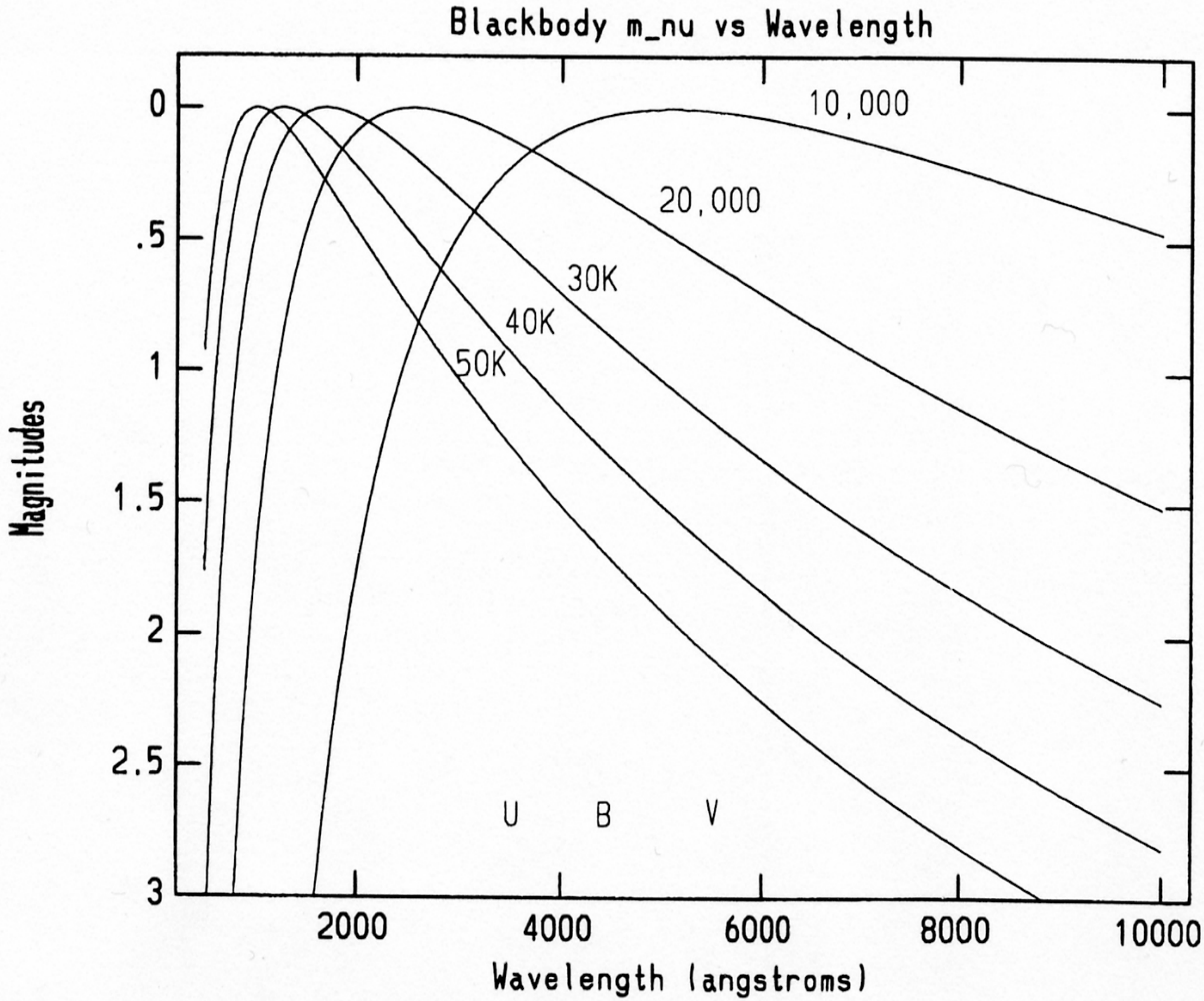
*Subject headings:* atmospheres, stellar — early-type stars — emission-line stars — Of stars

# How to Do It?

- The effective temperatures of O-type stars is hard go get right!
  - Optical photometry (good enough for A-K) is too insensitive to Teff for the hottest (and coolest) types.



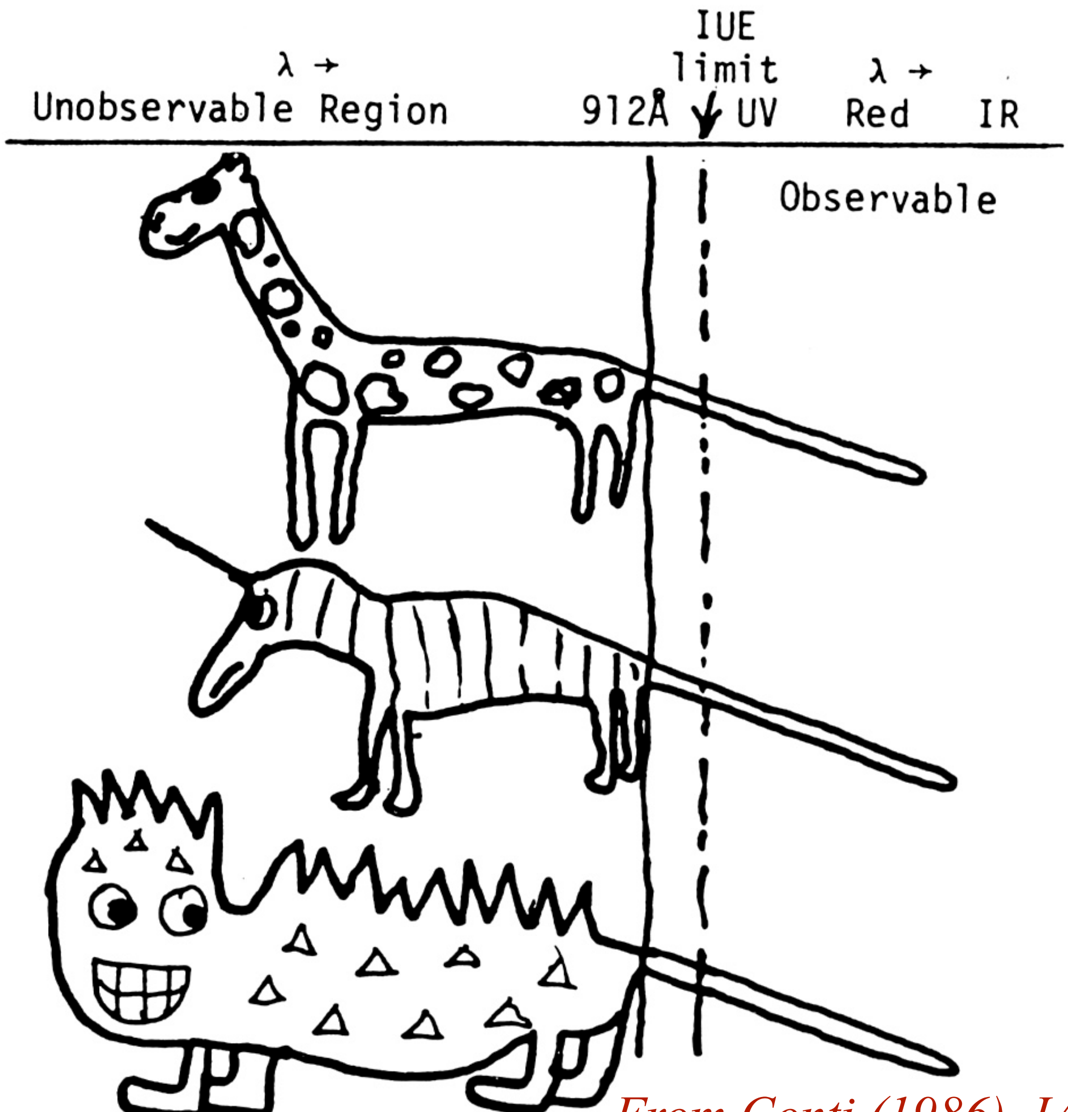
Blackbody m_nu vs Wavelength
Magnitudes
Wavelength (angstroms)
0
.5
1
1.5
2
2.5
3
2000
4000
6000
8000
10000
10,000
20,000
30K
40K
50K
U
B
V

# BC = f($T_{eff}$)

| Teff | B-V | BC |
|---|---|---|
| 50,000 K | -0.32 | -4.45 |
| 45,000 K | -0.32 | -4.12 |
| 40,000 K | -0.31 | -3.75 |
| 35,000 K | -0.29 | -3.35 |
| 30,000 K | -0.28 | -3.00 |

# PROBLEMS WITH CONTINUUM MEASURES OF HOT STARS ...

(with apologies to H.J.G.L.M.L.)




*From Conti (1986), IAU Symp. 116*

# How to Do It?

- Trying to do this with equivalent widths (EWs) and LTE models (Mihalas 1964) gave self-consistent, but obviously crazy, results:
  - log g=4.5 (much higher than mass-radius relation)
  - He abundances needed were too high (0.15-0.20, not 0.10 indicated by analysis of nebulae).
- Line profiles didn't match observations at all.

# How to Do It?

- Morton & Adams (1968) used the Balmer jump to determine a Teff scale
  - Only a few hundredths of a mag in O stars
  - Based on LTE atmospheres.

# How to Do It?

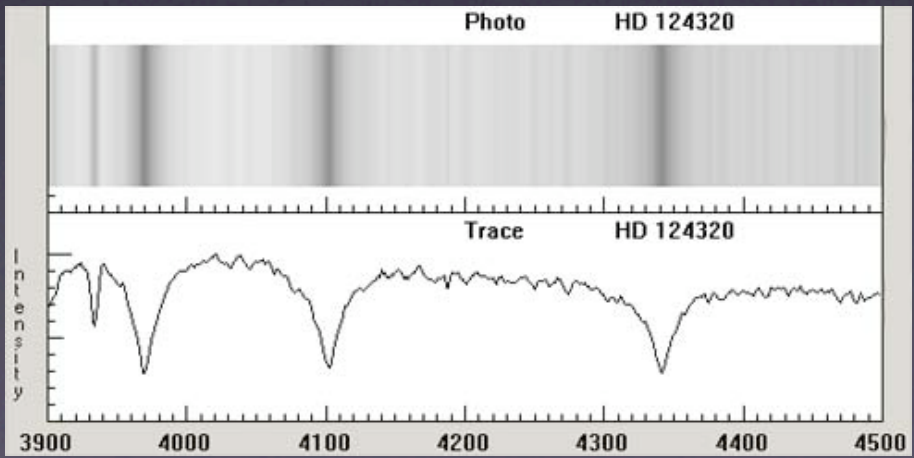
- Hjellming (1968) and Morton (1969) used Zanstra method in HII regions
  - Ionization vs density bounded?
  - Dust?
  - Unseen extra stars?
  - Still required model atmospheres for determining Lyman continua.

# How to Do It?

- Fit the spectral lines with a model atmosphere ("ionization equilibrium")
  - Need good models:
    - Atmospheres are complicated by NLTE, hydrodynamics of stellar wind, etc.
  - Also need good observations:
    - Accurate EWs ("*quantitative spectroscopy*")

# Measuring EWs from IIa-O coude spectrograms

•Photographic plates were non-linear detectors that had to be traced and then calibrated (density to intensity) as well as wavelength calibrated....



# Planimeter

From Wikipedia, the free encyclopedia

A **planimeter** is a measuring instrument used to measure the area of an arbitrary two-dimensional shape. The most common use is to measure the area of a plane shape.

There are many different kinds of planimeters but all operate in a similar way. A pointer on the planimeter is used to trace around the boundary of the shape. T

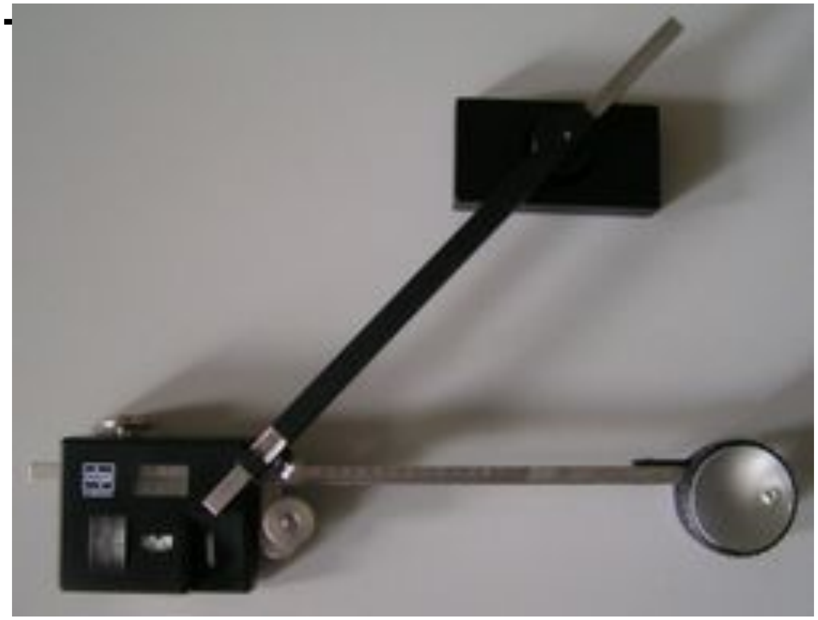


TABLE 2

EQUIVALENT WIDTHS LOG *W*

| NAME | He I | | | He II | | Si IV | |
|---|---|---|---|---|---|---|---|
| HD OR BD | 4120 | 4143 | 4471 | 4541 | 4686 | 4089 | 4116 |
| 108 | | P? | 2.72 | 2.95 | 2.20 | 2.39 | E |
| 1337 | 2.25 | 2.14 | 2.81 | 2.12 | 2.27 | 2.60 | P |
| 5005 | | | 2.44 | 2.91 | 2.87 | | |
| 5005C | 2.22 | 2.26 | 2.95 | 2.63 | 2.65 | 2.38 | 2.21 |
| 12323 | 2.42 | 2.74 | 3.04 | 2.60 | 2.99 | 2.60 | 2.38 |
| 12993 | 2.07 | 2.26 | 2.83 | 3.02 | 2.98 | 2.30 | 1.98 |
| 13268 | | | 2.66 | 2.70 | 2.59 | 2.15 | |
| 14434 | | | 2.70 | 2.87 | 2.56 | | |
| 14442 | | | 2.65 | 2.92 | 2.59E | | |
| 14633 | 2.29 | 2.51 | 2.94 | 2.65 | 2.78 | 2.60 | 2.30 |
| 14947 | | | 2.37 | 2.86 | 3.36E | 2.09E | 2.45E |
| 15137 | P | 2.54 | 3.02 | 2.50 | 2.73 | 2.73 | P |
| +60498 | 2.66 | 2.75 | 3.10 | 2.25 | 2.72 | 2.54 | P |
| +60501 | | P | 2.71 | 2.86 | 2.98 | 2.43 | |
| 15558 | | | 2.31 | 2.86 | E | | |
| 15570 | | | <1.68 | 2.88 | 3.45E | 2.39E | 2.29E |
| 15629 | | | 2.41 | 2.97 | 2.72 | | |
| +60512 | | | 2.90 | 2.90 | 3.04 | | |
| 16429 | 2.19 | 2.31 | 2.99 | 2.38 | 2.53 | 2.73 | 2.39 |
| 16691 | | | 2.43 | 2.94 | 3.78E | 2.63E | 2.53E |
| 17505 | | | 2.62 | 2.84 | 2.36 | | |
| 17520 | 2.11 | 2.53 | 3.00 | 2.67 | 2.94 | 2.53 | 2.20 |
| 17603 | | 1.85 | 2.88 | 2.68 | E? | 2.56 | 2.08 |
| +60586 | | 2.38 | 2.93 | 2.82 | 3.02 | 2.52 | 2.20 |
| +60594 | | | 3.02 | 2.72 | 2.95 | 2.64 | |
| 19820 | 2.23 | 2.36 | 2.92 | 2.51 | 2.43 | 2.53 | 2.23 |
| 24431 | 2.22 | 2.49 | 2.91 | 2.58 | 2.66 | 2.50 | 2.36 |
| ξ Per | | 2.12 | 2.87 | 2.82 | 2.79 | 2.48 | 1.95 |
| α Cam | 2.22 | 2.43 | 3.03 | 2.40 | 2.13E | 2.87 | 2.65 |
| AE Aur | 2.29 | 2.64 | 2.99 | 2.27 | 2.85 | 2.52 | 2.30 |
| 34656 | 2.00 | 2.05 | 2.89 | 2.90 | 2.58 | 2.42 | 2.25 |
| 35921 | | | 2.74 | 2.25 | 2.99 | P | |
| δ Ori | 2.23 | 2.31 | 2.91 | 2.33 | 2.47 | 2.69 | 2.59 |

From Conti & Alschuler (1971)

# How Well Do these Hold Up?

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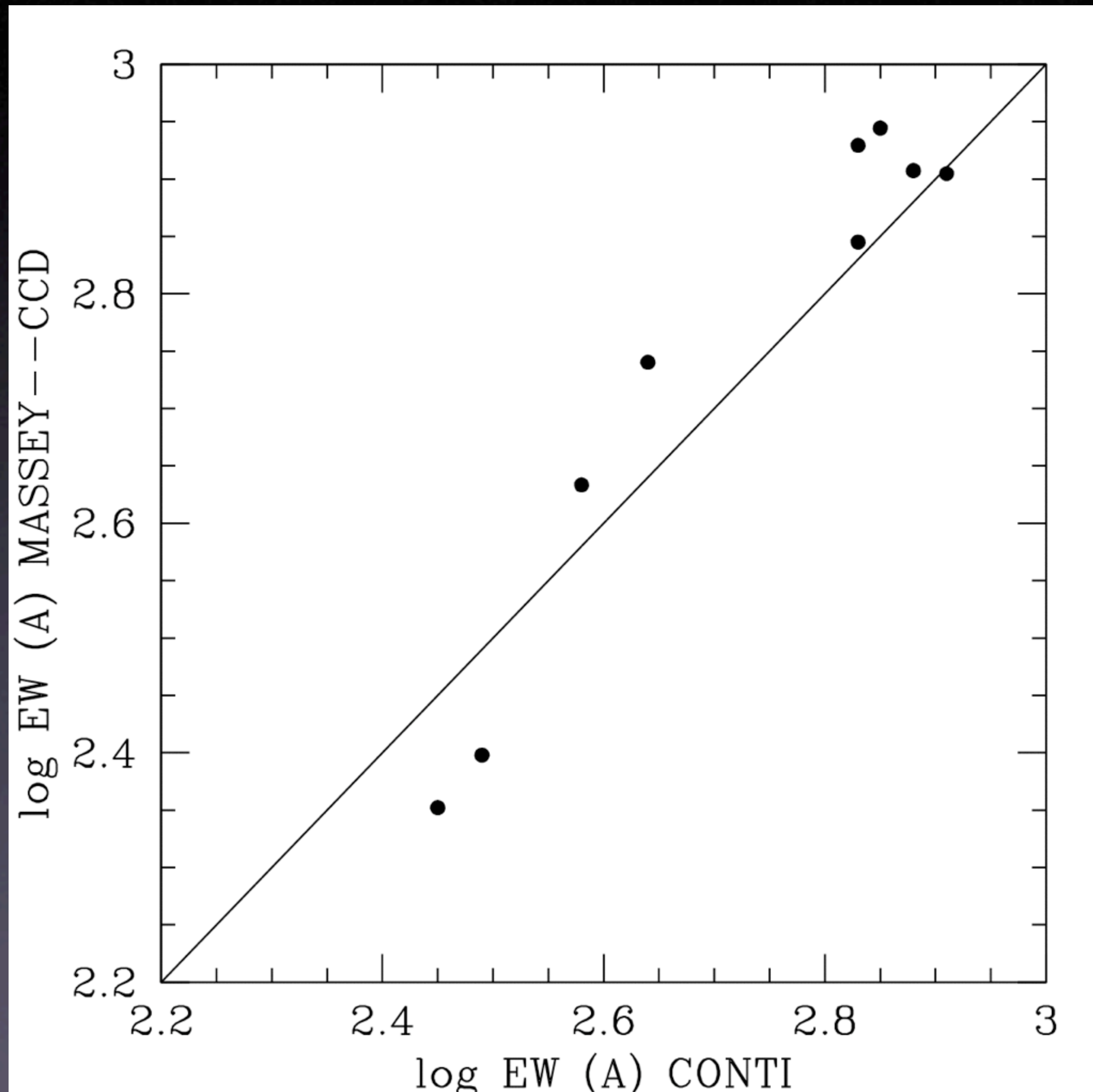
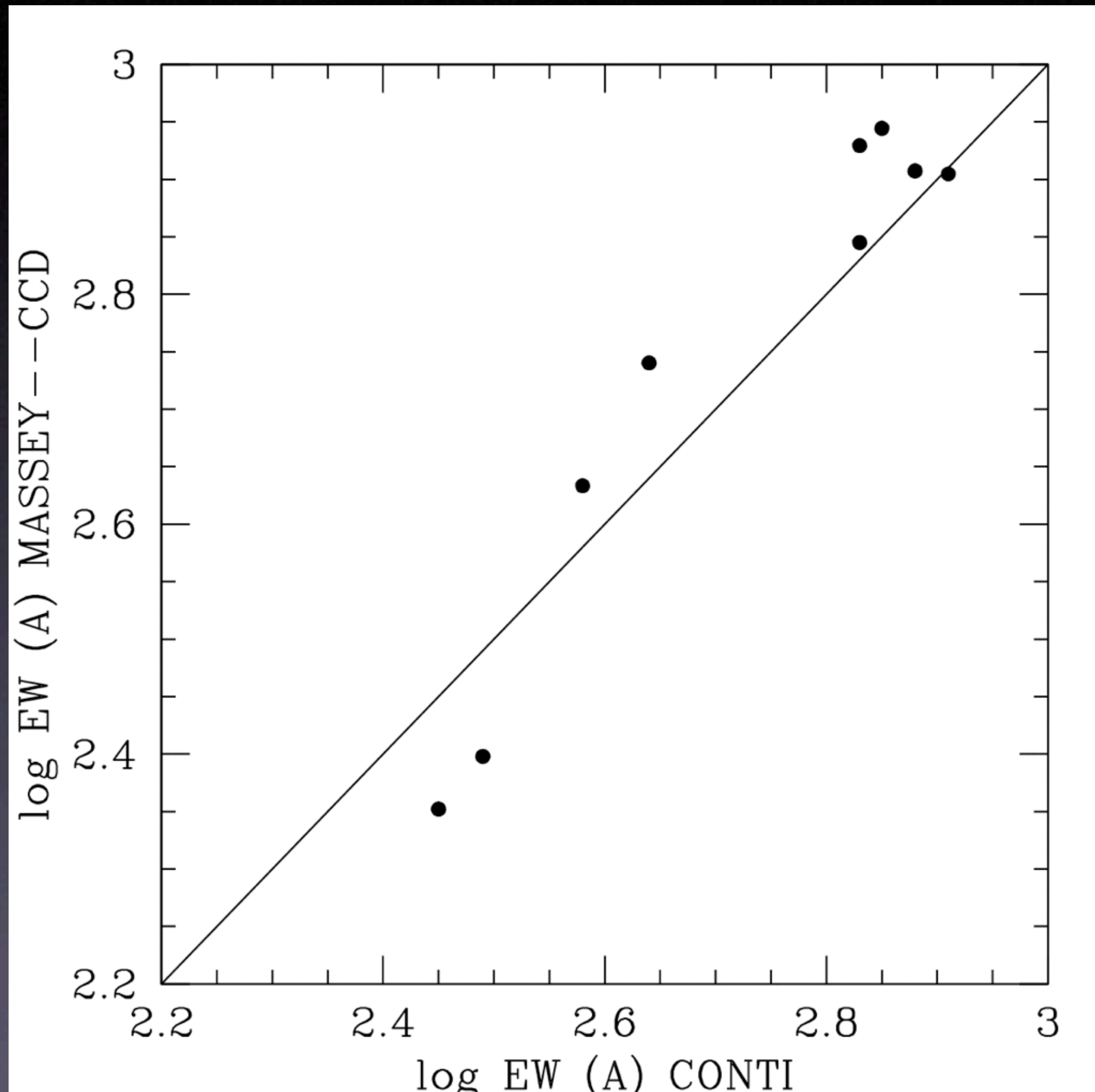


# How Well Do these Hold Up?

~0.05-0.1 dex,
or ~10-20%



# Non-LTE Model Atmosphere

THE ASTROPHYSICAL JOURNAL SUPPLEMENT SERIES No. 205, **24**:193–246


# NON-LTE MODEL ATMOSPHERES. VII. THE HYDROGEN AND HELIUM SPECTRA OF THE O STARS

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*Received 1971 May 10*

## ABSTRACT

An extensive series of non-LTE calculations of the H, He I, and He II spectra of O stars has been carried out by using relatively complete atomic models, allowing for several levels and lines simultaneously. Results are presented for continuum fluxes and for equivalent widths and profiles of the lines. Detailed comparisons are made with the spectra of eleven O and B0 stars. It is found that *major* departures from LTE play a *dominant* role in the formation of the H and He spectra of these stars. With the non-LTE models we are able to obtain for the first time a consistent explanation of the observations of both lines and continua. The present results show that an assumed helium/hydrogen ratio of 0.10 reproduces the observations; thus present estimates of abundances in O stars helium are consistent with those derived by other methods.

# Non-LTE Model Atmosphere

- Non-LTE but otherwise
  - static
  - plane-parallel
  - pure H and He
    - no line blanketing

But they worked!

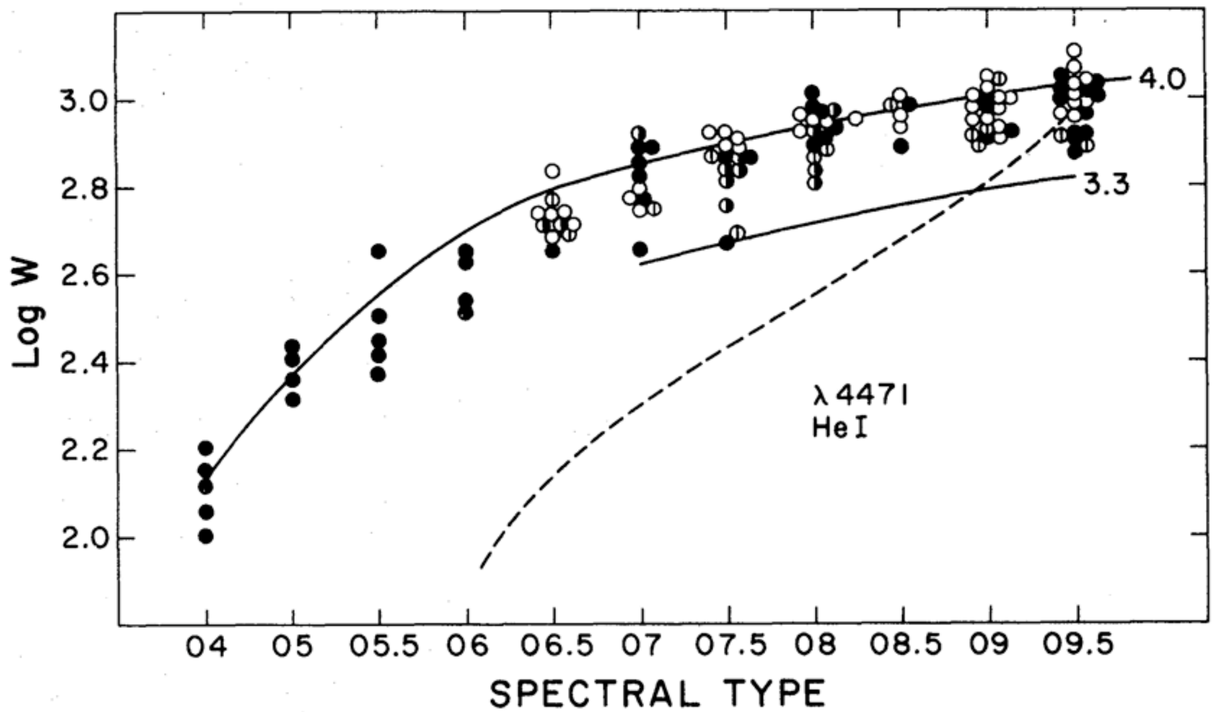



FIG. 1.—*Solid lines*, the non-LTE predictions for λ4471 He I, labeled with log gravity, from models of Auer and Mihalas (1972); *dashed line*, their LTE predictions (log $g = 4.0$). The circular symbols represent values from individual stars as follows: *open circles*, type V luminosity; *circle with vertical line*, type III luminosity; *half-filled circles*, type IIIf; *filled circles*, type I or If. (These symbols are the same on figs. 2–10, following.) There is very good agreement between the non-LTE models predictions and the strengths of this line.

*From Conti Paper II (1973, ApJ, 179, 161)*

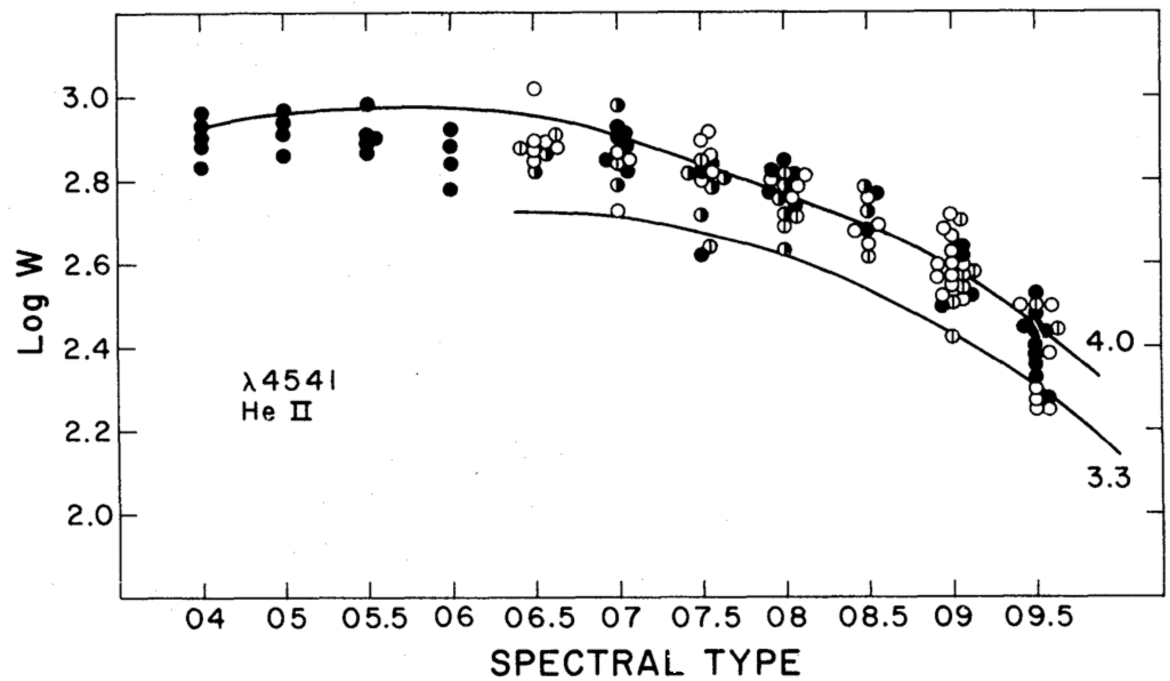



FIG. 2.—*Solid lines*, the non-LTE predictions for λ4541 He II, labeled with the log gravity, from models of Auer and Mihalas (1972). Symbols as in fig. 1. There is very good agreement between the predictions and the observed values.

*From Conti Paper II (1973, ApJ, 179, 161)*

- In addition, the spectral types were *defined* in terms of the relative strengths of He I 4471 and He II 4542

TABLE 3

SPECTRAL TYPES BASED ON 4471/4541 RATIO $W'$

| Log $W'$ Limit | Type | Limit | Log $W'$ Limit | Type | Limit |
|---|---|---|---|---|---|
| | O9.5 | $\geq +0.45$ | 0........ | >O7 | $\geq -0.10$ |
| +0.45..... | >O9 | $\geq +0.30$ | −0.10..... | >O6.5 | $\geq -0.20$ |
| +0.30..... | >O8.5 | $\geq +0.20$ | −0.20..... | >O6 | $\geq -0.30$ |
| +0.20..... | >O8 | $\geq +0.10$ | −0.30..... | >O5.5 | $\geq -0.50$ |
| +0.10..... | >O7.5 | $\geq 0$ | −0.50..... | >O5 | $\geq -0.70$ |
| | | | −0.70..... | >O4 | ... |

NOTE.—The log $W'$ limits for each type refer to the *difference* log $W(4471)$ − log $W(4541)$.

# New Effective Temperature Scale



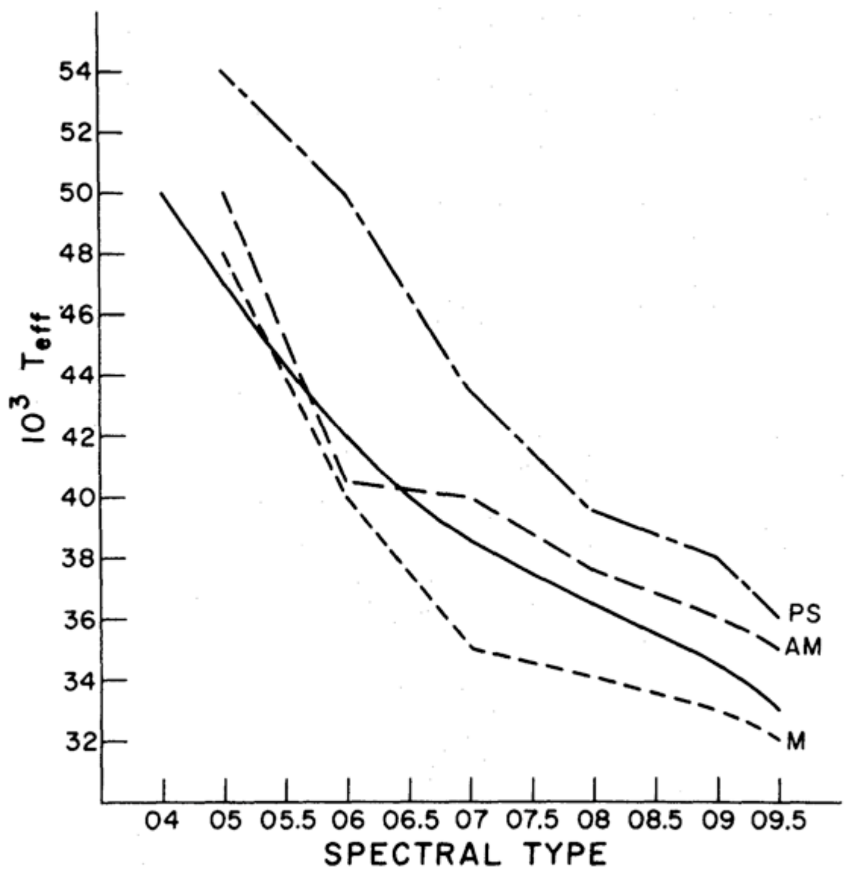
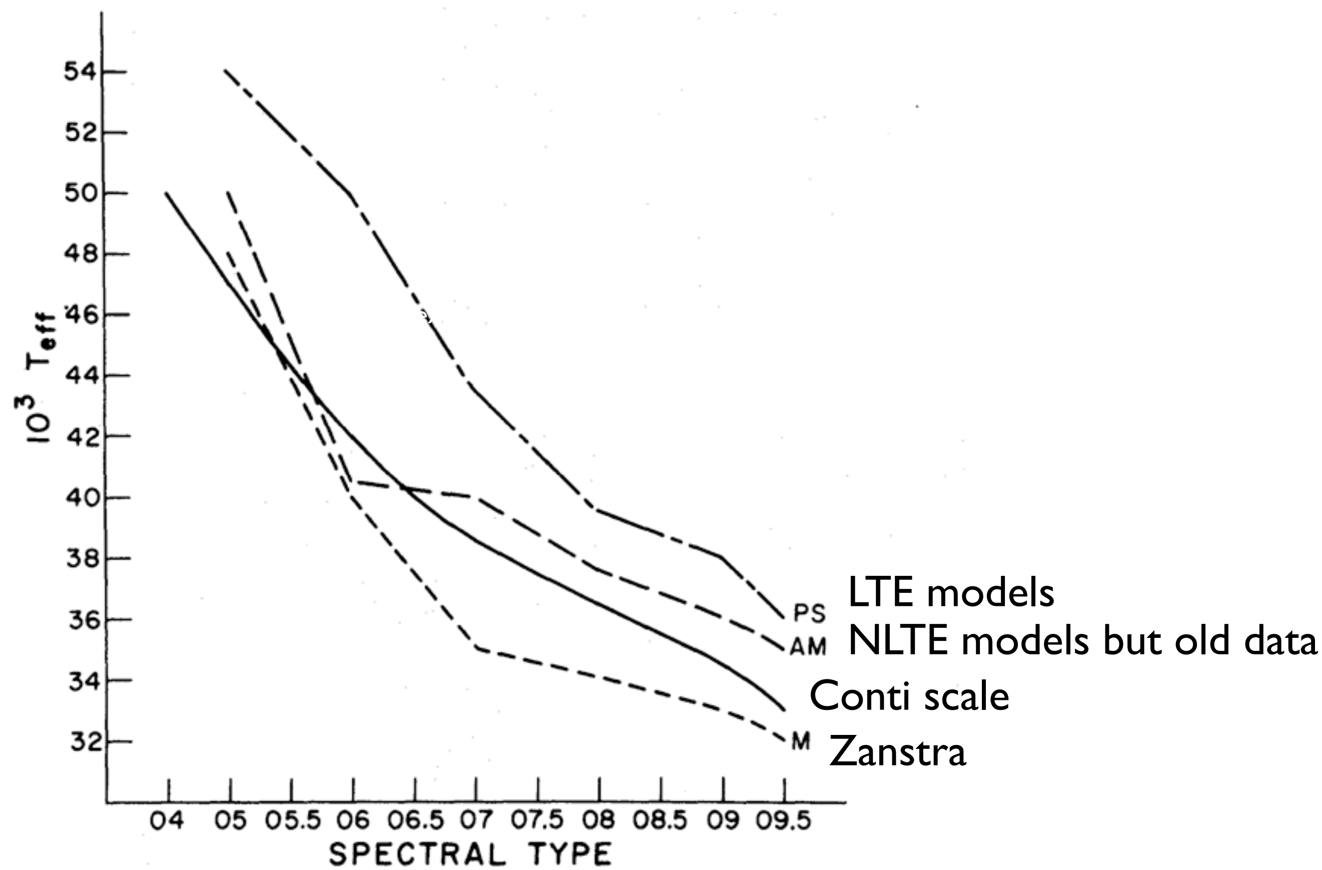



FIG. 2.—Comparison of several effective temperature scales for O stars. *Solid line*, the relation from this paper; *long dashed line*, from Auer and Mihalas (1972); *short dashed line*, from Morton (1969); *dashed dot line*, from Peterson and Scholz (1971).

# New Effective Temperature Scale



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# What We Learned

- The EWs of He I 4471 and He II 4542 from these simple NLTE models matched the new data very well!
- NLTE predictions of He II 4686 did *not* match the data---need "spherically extended"
- Also knew that the NIII 4640, 42 came into emission through a selective mechanism, not formed in the wind.

# But more, it set the philosophical stage

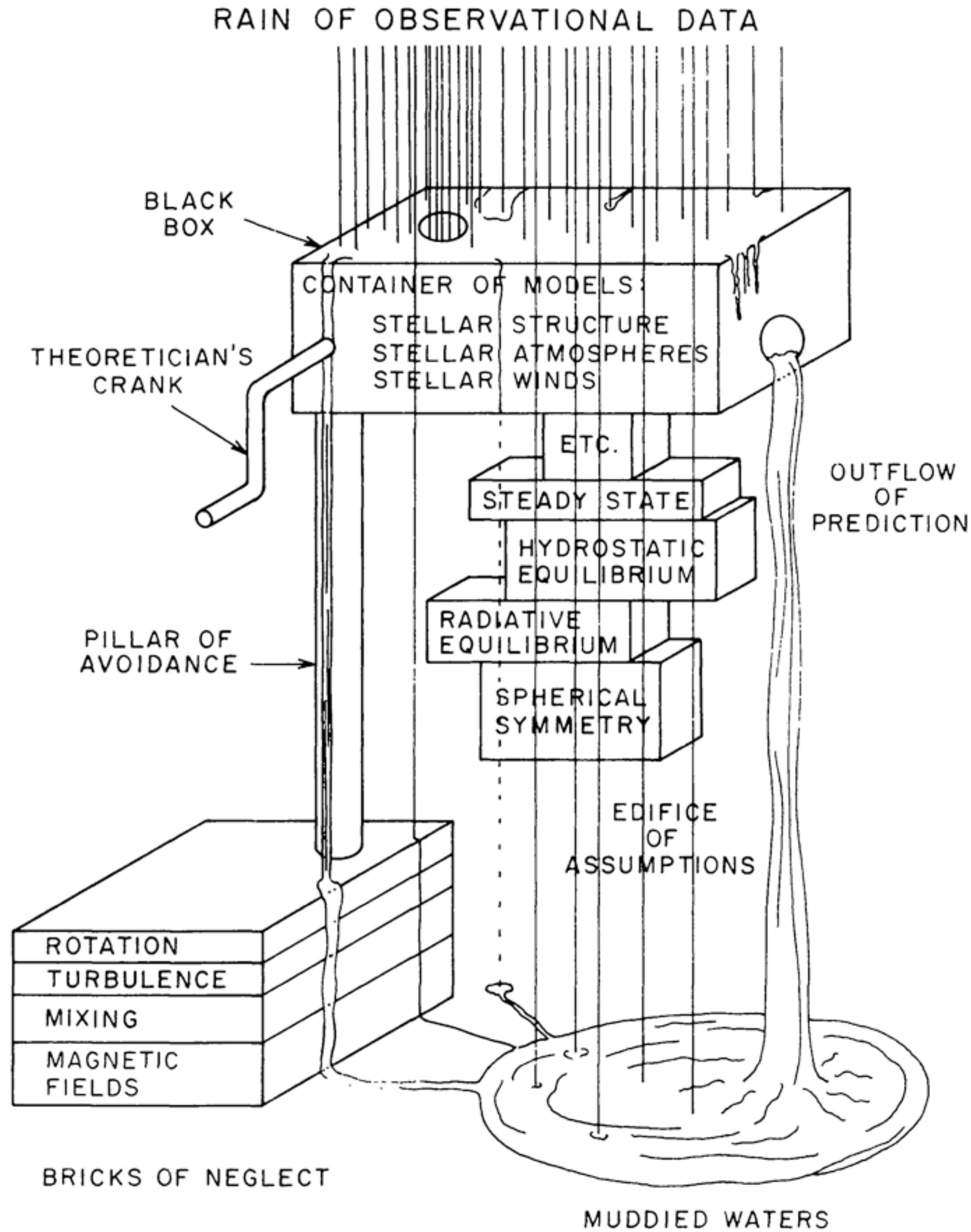
- Blurred the line between "observer" and "theoretician"
- A good observer makes use of the latest and greatest models to interpret their data and guide what questions to answer next.
- Really defined “quantitative spectroscopy”
  - Conclusions were based on measured EWs, not conjecture or touchy-feely criteria.

"If it can't be expressed in [numbers], it is not science; it's opinion."

*---Robert A. Heinlein*

# But, guided by intuition ==> physical insight

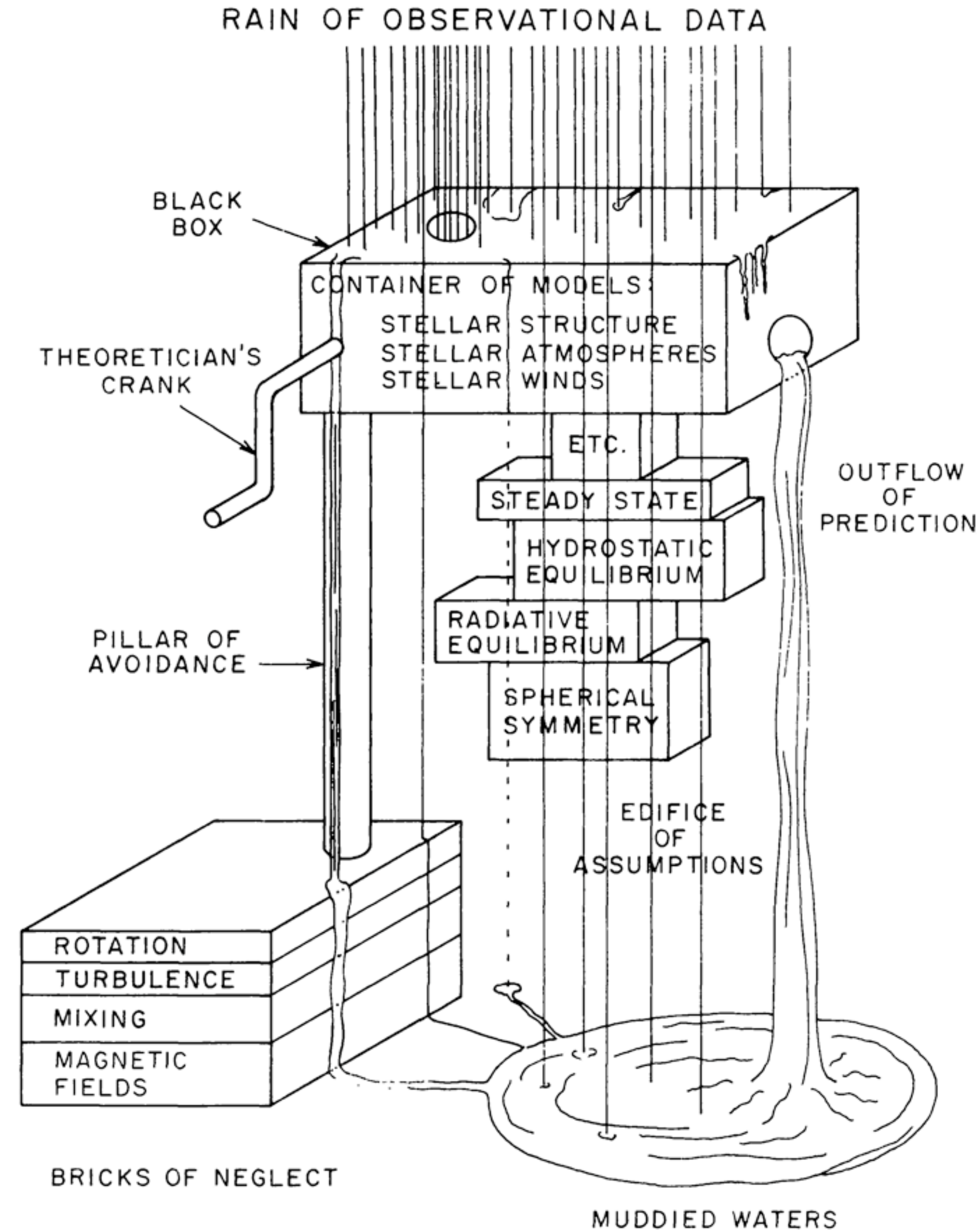
*"Are we having fun yet?"*




Conti (1982, IAU Symp 99)

Figure 5. An observer's view of stellar theory: the central feature is a black box in which the models are contained. This is driven by a theoretician's crank, which is turned rapidly or slowly, depending on the computer budget. The black box is held up by the edifice of assumptions of steady state, hydrostatic equilibrium, radiative equilibrium and spherical symmetry, among others, and by the pillar of avoidance of difficulties, such as the neglect of rotation, turbulence, mixing (until very recently) and magnetic fields. The input to the models in the black box is a rain of observational data, which falls onto the box. Notice that only a fraction of this rain of data ever enters the black box as its top is covered and only a small hole admits the information; most of the rain flows off the container to the ground where it mixes with the outflow of prediction from the end of the black box and muddies the waters.

Conti (1982, IAU Symp 99)



# The evolution of $T_{eff}$

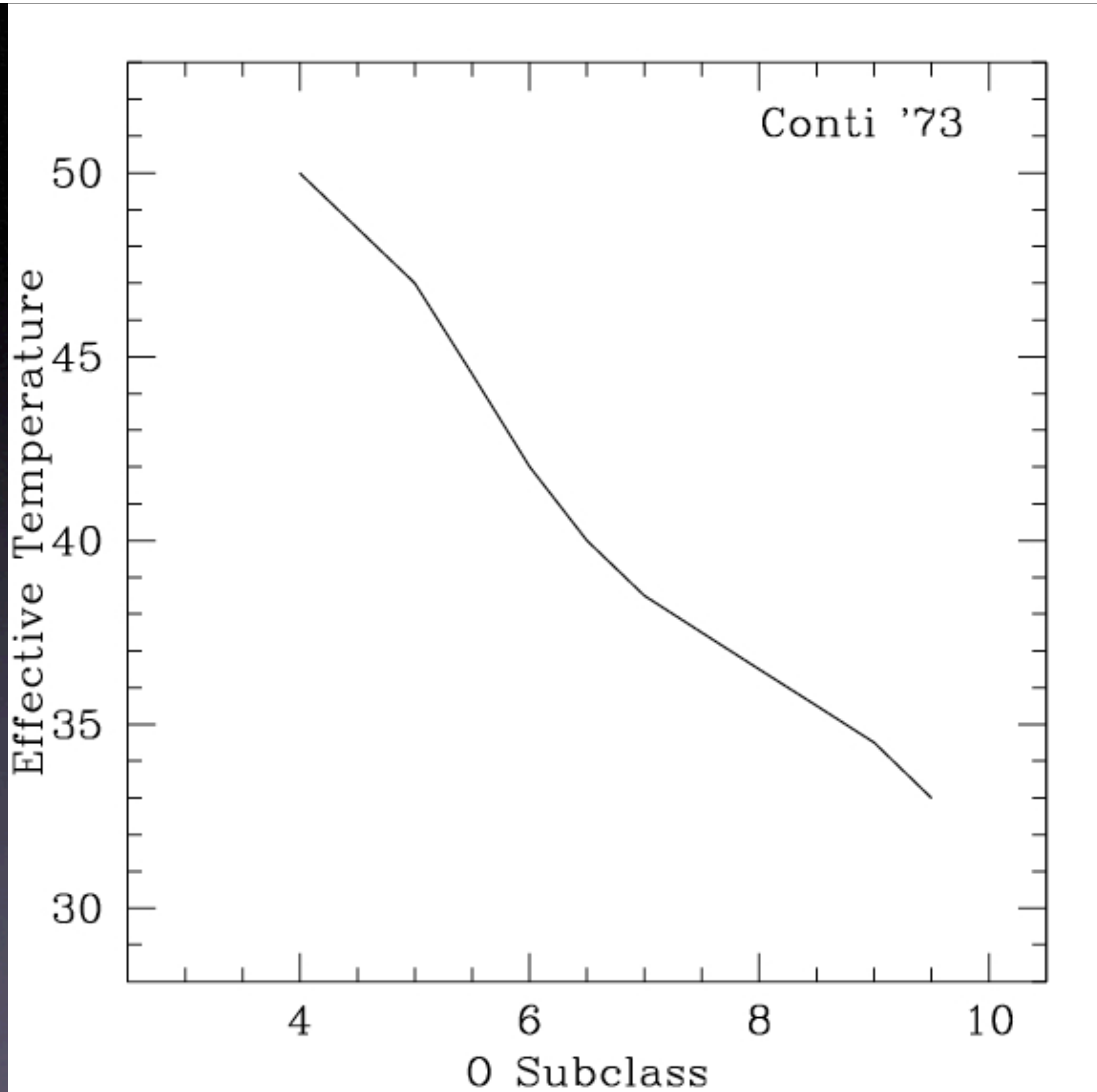
1. The introduction of NLTE
2. The introduction of mass-loss
3. Inclusions of hydrodynamics and metals
4. Full inclusion of line blanketing

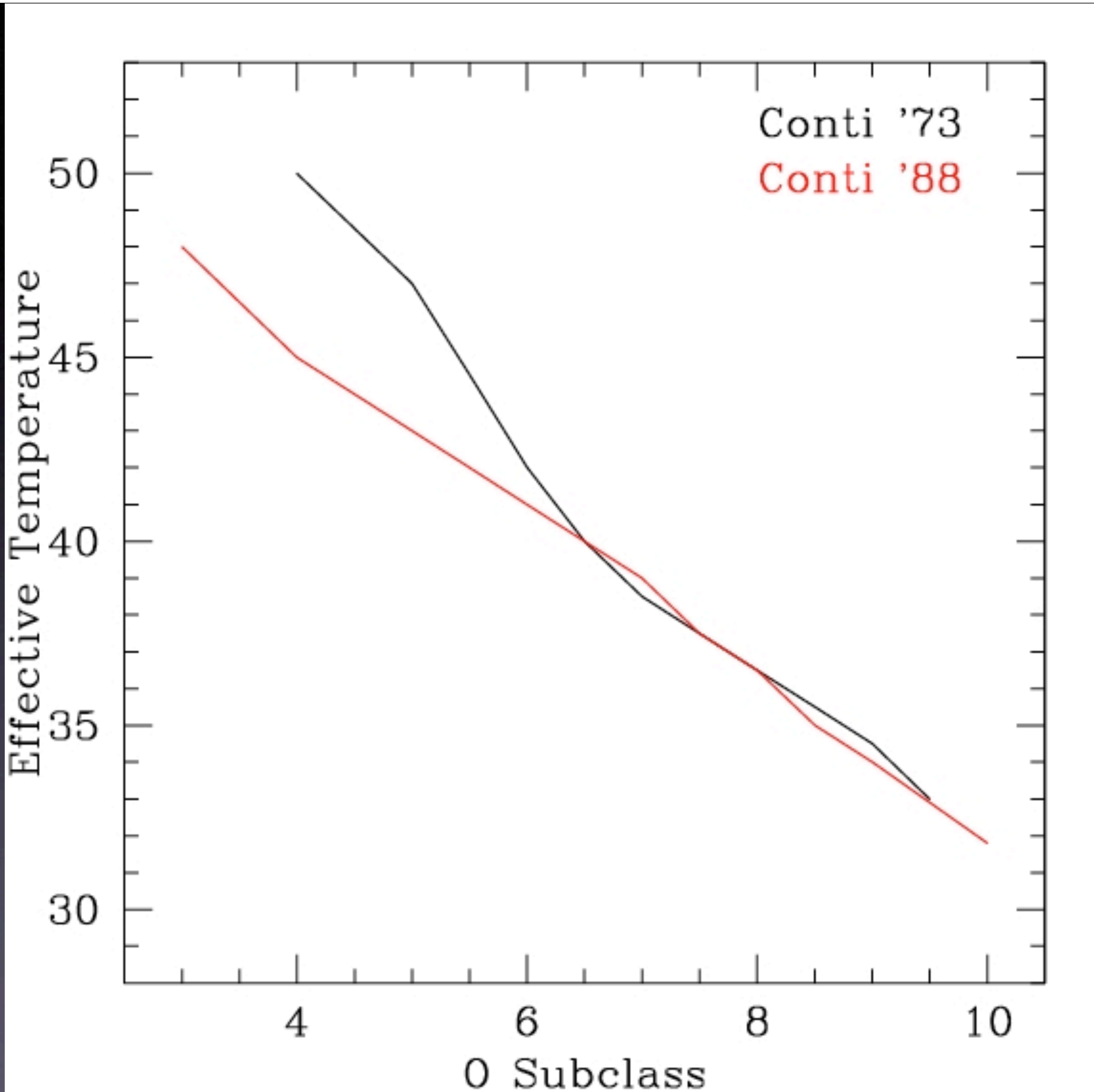
# Introduction of mass-loss

- Abbott & Hummer (1985) demonstrated that the presence of stellar winds had a significant effect on the HeI/HeII ratios. Although the lines are formed in a (nearly) static part of the atmosphere, scattering by the stellar winds back into the photosphere results in substantial heating of the surface: "wind blanketing".
- Substantial. Without it, 42K model matches O5.5V but with it, it matches an O3 V.

# Introduction of mass-loss

- Led to Conti (1988) revision of effective temperature scale downwards.
- Vacca, Garmany & Shull (1996) scale included *some* wind-blanketed results but mostly not (e.g., Herrero et al 1992), so their scale was higher.


Conti '73
Effective Temperature
50
45
40
35
30
4
6
8
10
O Subclass



Conti '73
Conti '88
50
45
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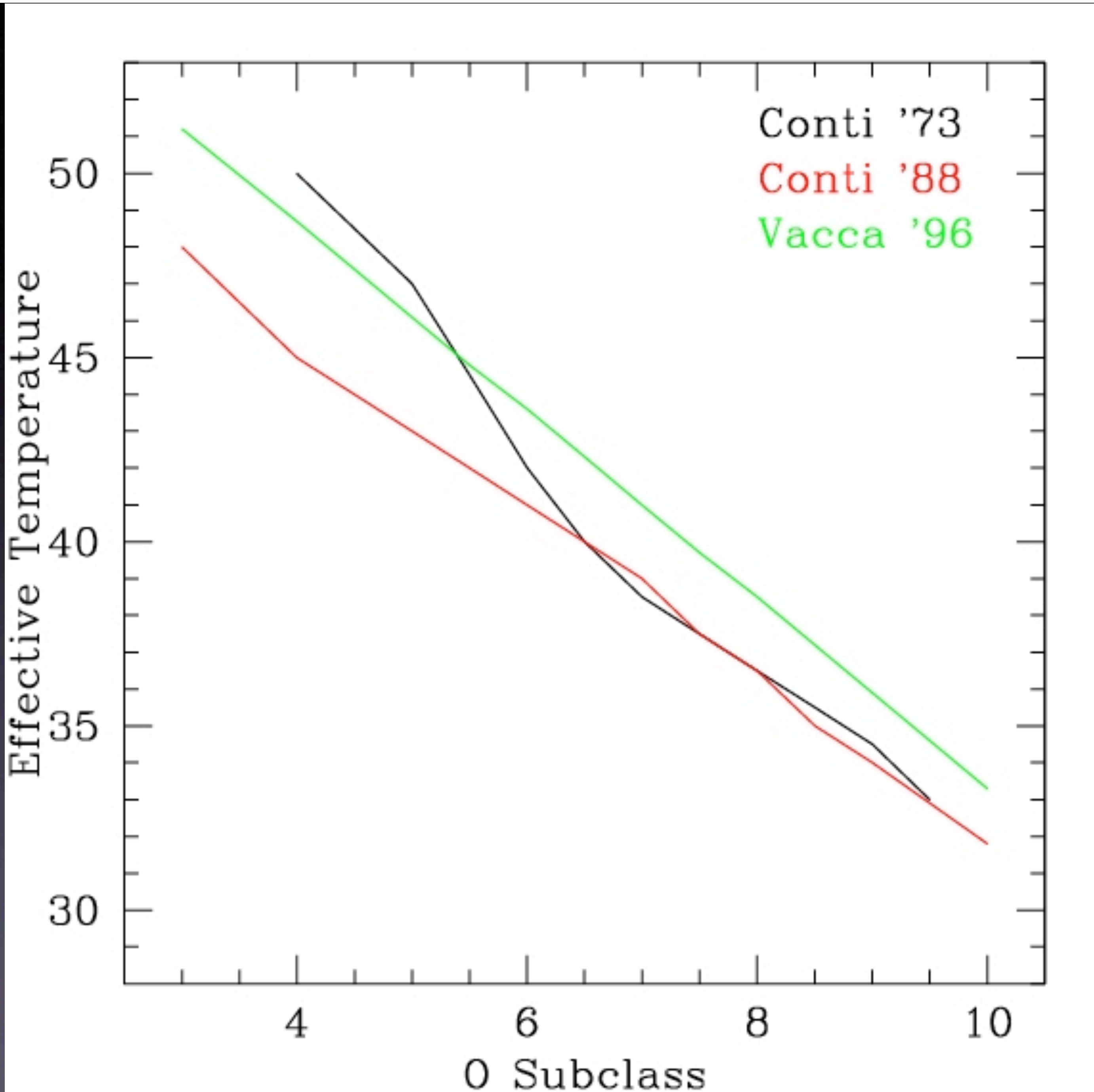
35
30
Effective Temperature
4
6
8
10
O Subclass


Conti '73
Conti '88
Vacca '96
Effective Temperature
50
45
40
35
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6
8
10
O Subclass

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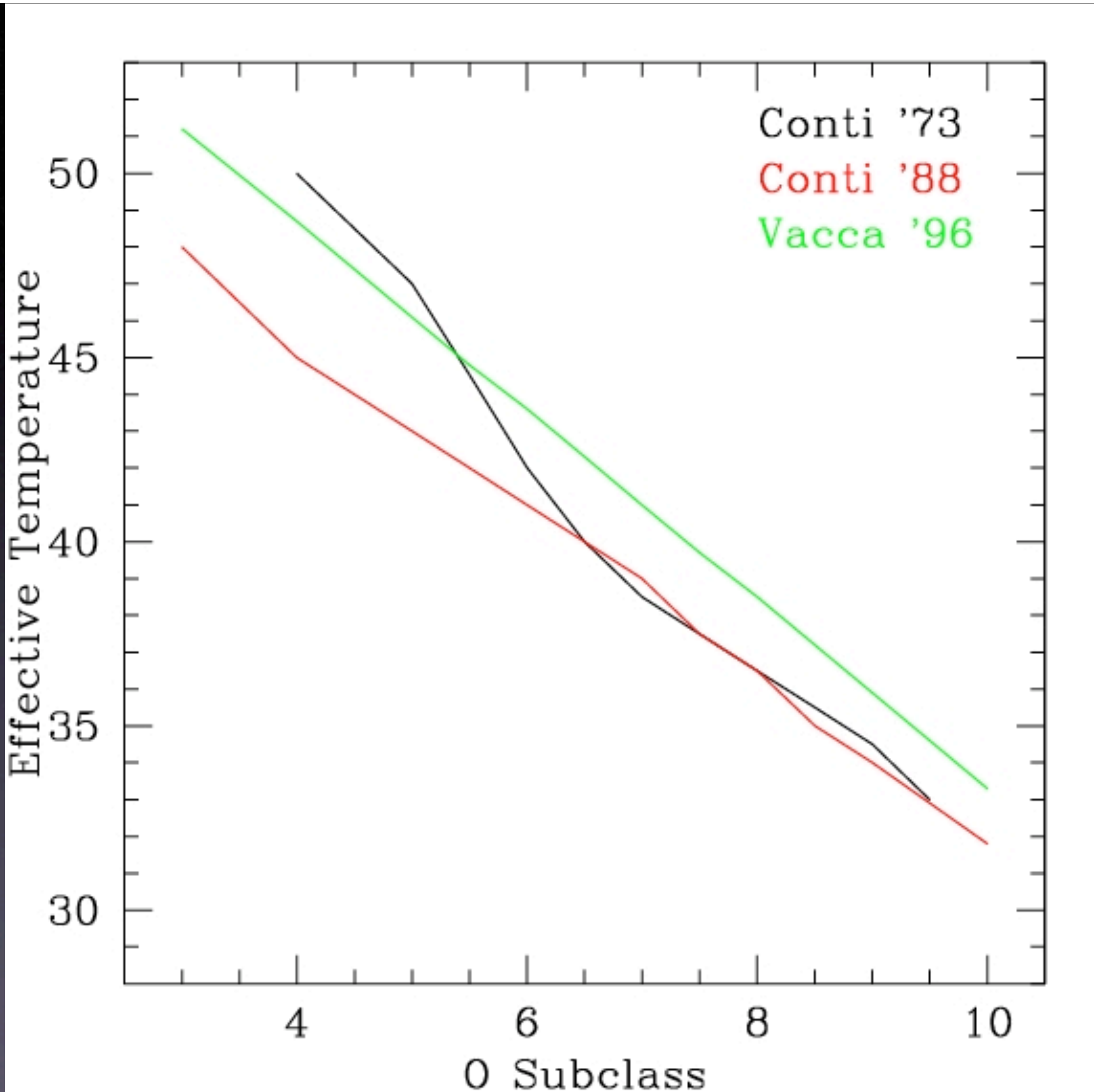
# hydrodynamics and metals (mid 1990's)

- spherical extension
- hydrodynamics of stellar winds, in sub- and supersonic regions (Kudritzki et al)
- Stellar winds produced emission, partially filling in He I lines (Sellmaler et al 1993)

➡Puls et al (1996) analysis of MW and MC stars



Conti '73
Conti '88
Vacca '96
Effective Temperature
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45
40
35
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4
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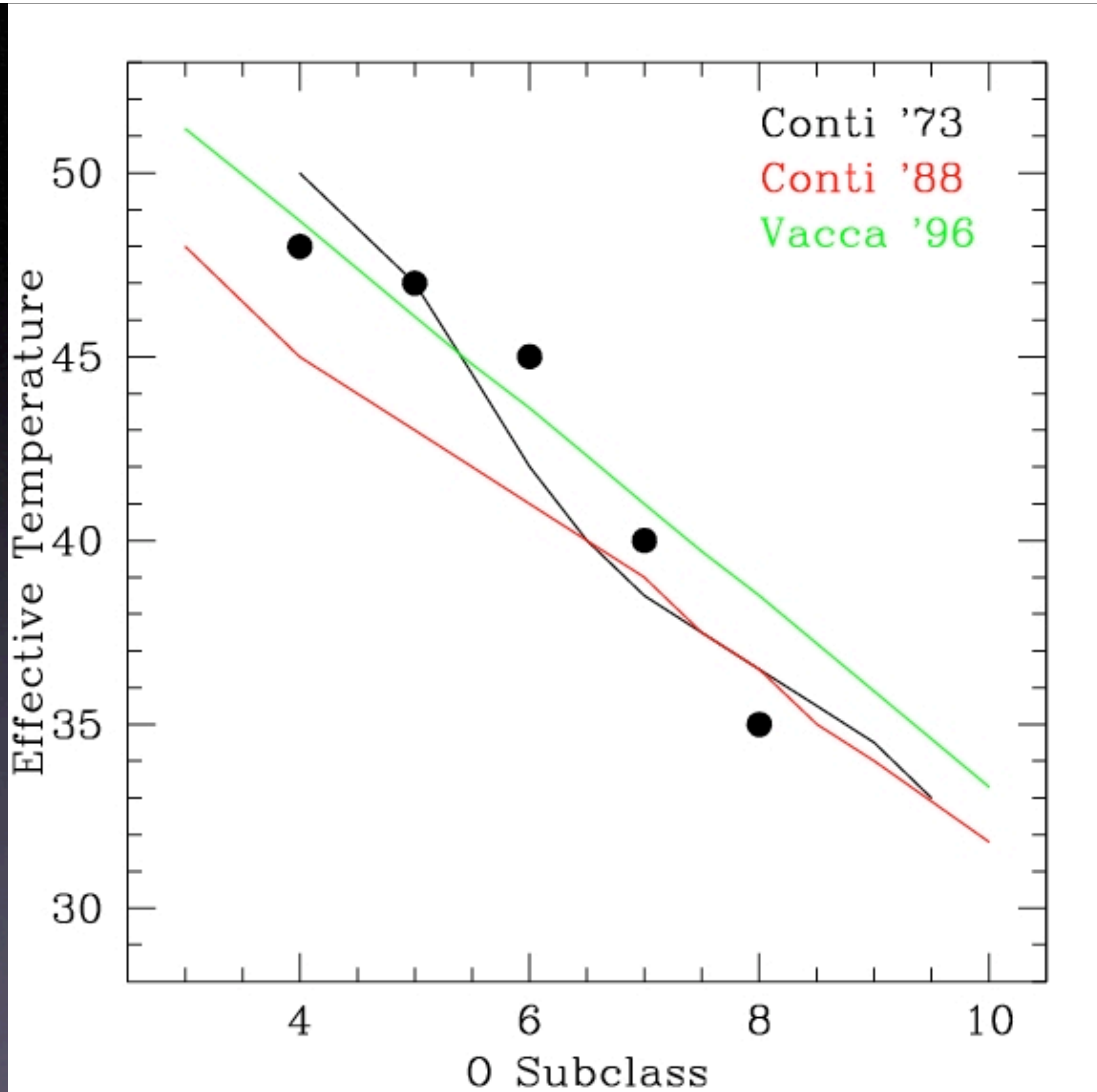
8
10
O Subclass



Conti '73
Conti '88
Vacca '96
Effective Temperature
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35
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8
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O Subclass

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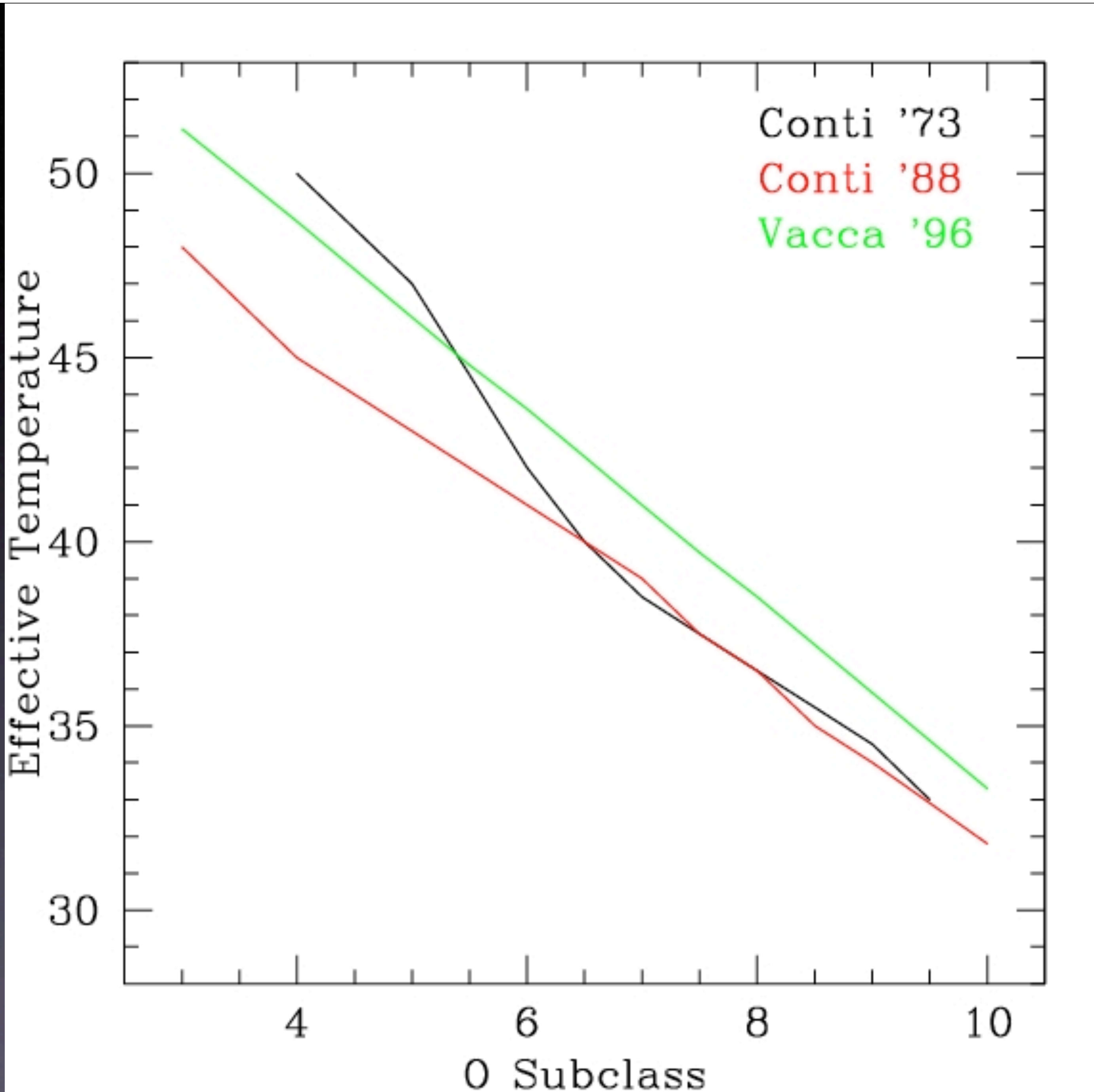
# Full Line Blanketing

- CMFGEN (Hillier & Miller 1998; Hillier 2003)
  - gold standard
- WM-basic (Pauldrach et al. 2001)
  - lacks Stark broadening and co-moving frame treatment but useful in the UV
- FASTWIND (Puls et al. 2005)
  - "approximate---but highly realistic" treatment of line blocking.

# $T_{effs}$ need to be lowered at least at Galactic metallicities

- Martins et al (2002)
- Bianchi & Garcia (2002); Garcia & Bianchi (2004)
- Herrero et al. (2002)
- Repolust et al. (2004)



Conti '73
Conti '88
Vacca '96
Effective Temperature
50
45
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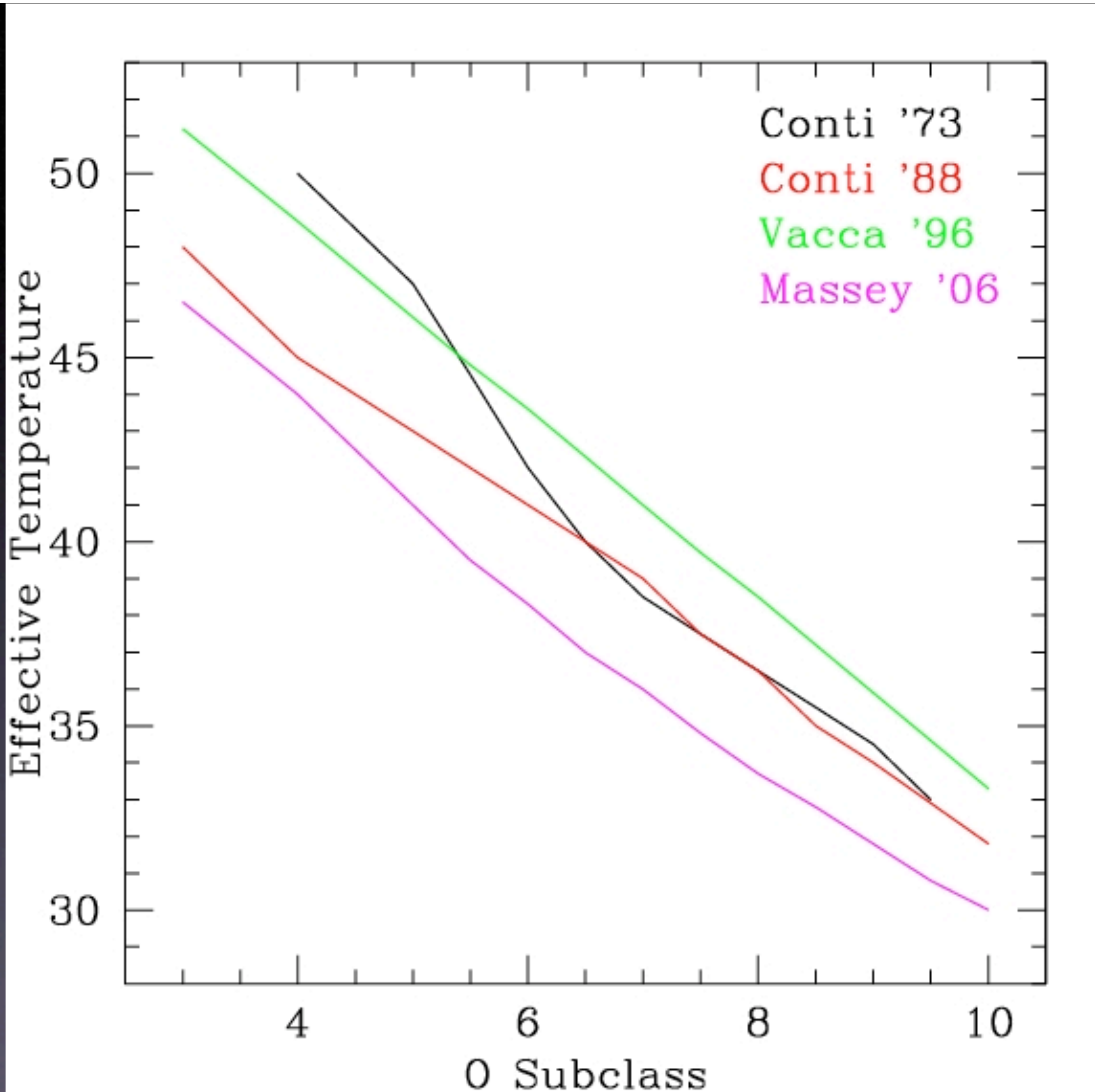
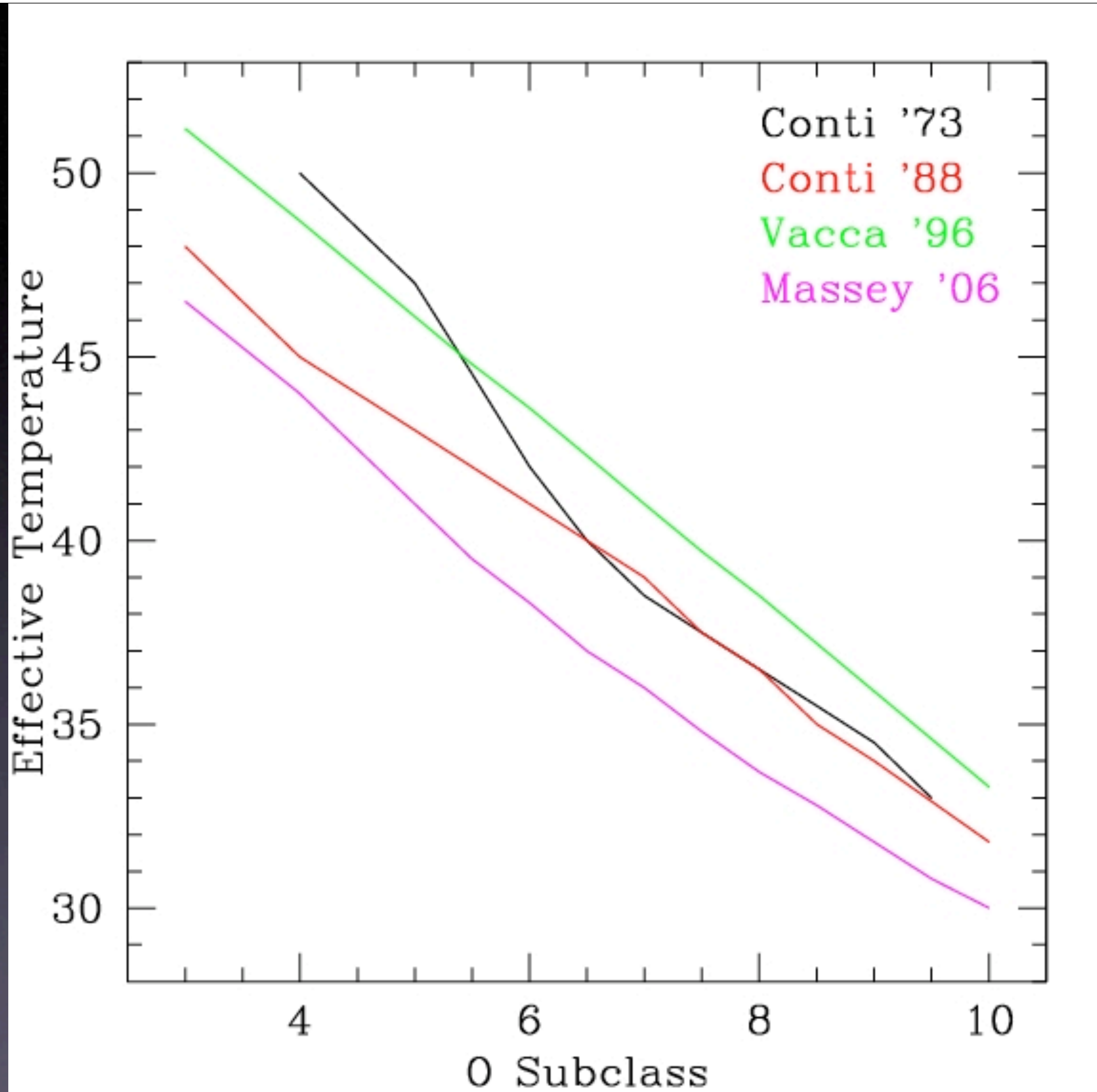
O Subclass

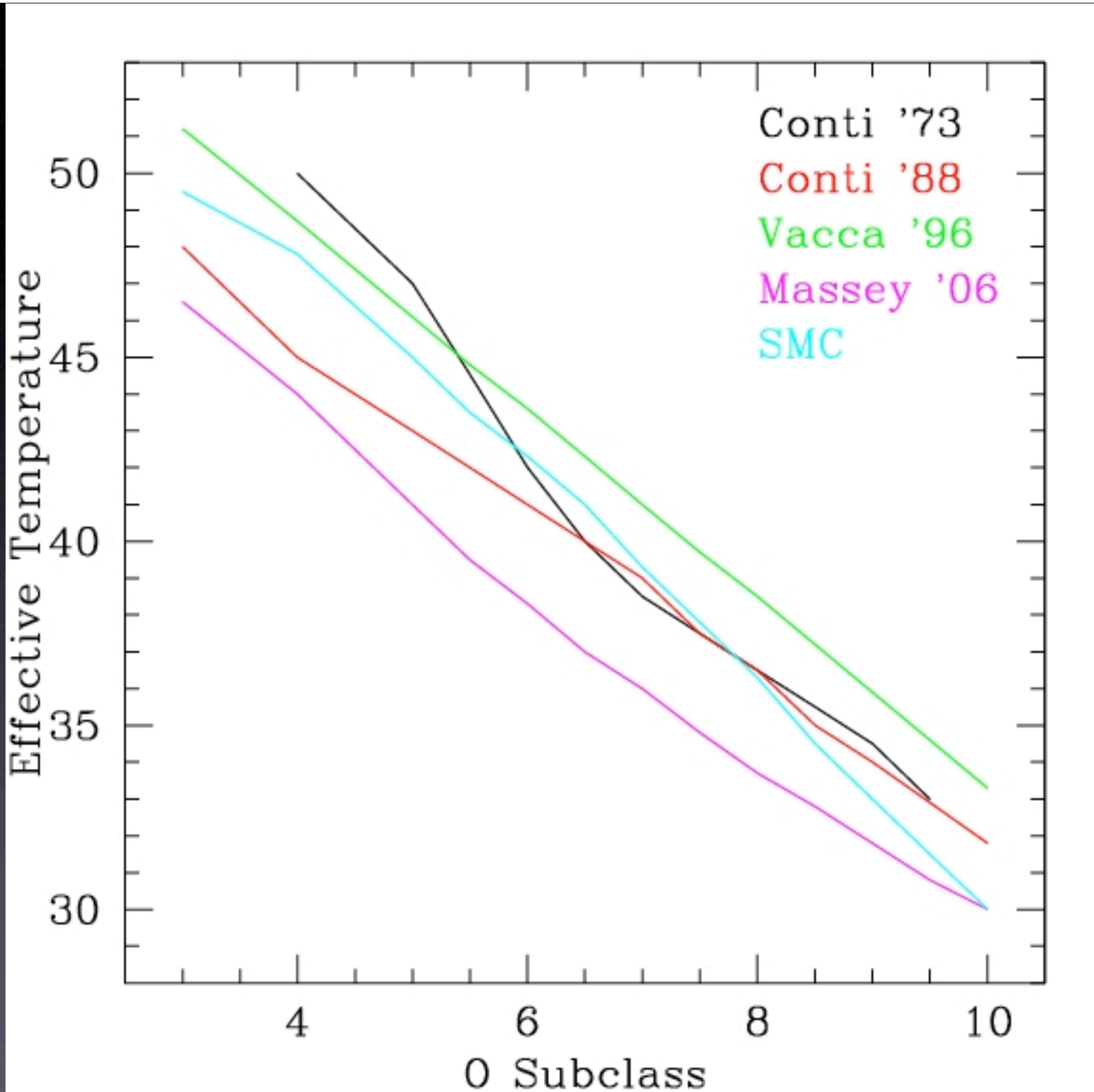


Conti '73
Conti '88
Vacca '96
Massey '06
Effective Temperature
30
35
40
45
50
4
6
8
10
O Subclass

# But what is the effect of metallicity on the scale?

- Massey et al (2004, 2005, 2009) have analyzed sample of 66 Magellanic Cloud O stars using FASTWIND. We were able to find acceptable fits for about 41 (60%); believe the rest to be composites.
- FLAMES (see poster by Lennon et al)
- Heap et al. (2006)


Conti '73
Conti '88
Vacca '96
Massey '06
50
45
40
35
30
Effective Temperature
4
6
8
10
O Subclass



Conti '73
Conti '88
Vacca '96
Massey '06
SMC
50
45
40
35
30
Effective Temperature
4
6
8
10
O Subclass

# Humorous notes

- SMC (metal-poor) scale is not too different than original Conti (1973, 1988) scales, based on pure H, He NLTE models!
- Maximum differences (Vacca-Massey) about 5000 K out of 41K (12%).

*"My best current estimate of Teff for miain-sequence O stars is...to +/- 10 percent. Better models will ultimately help considerably."*

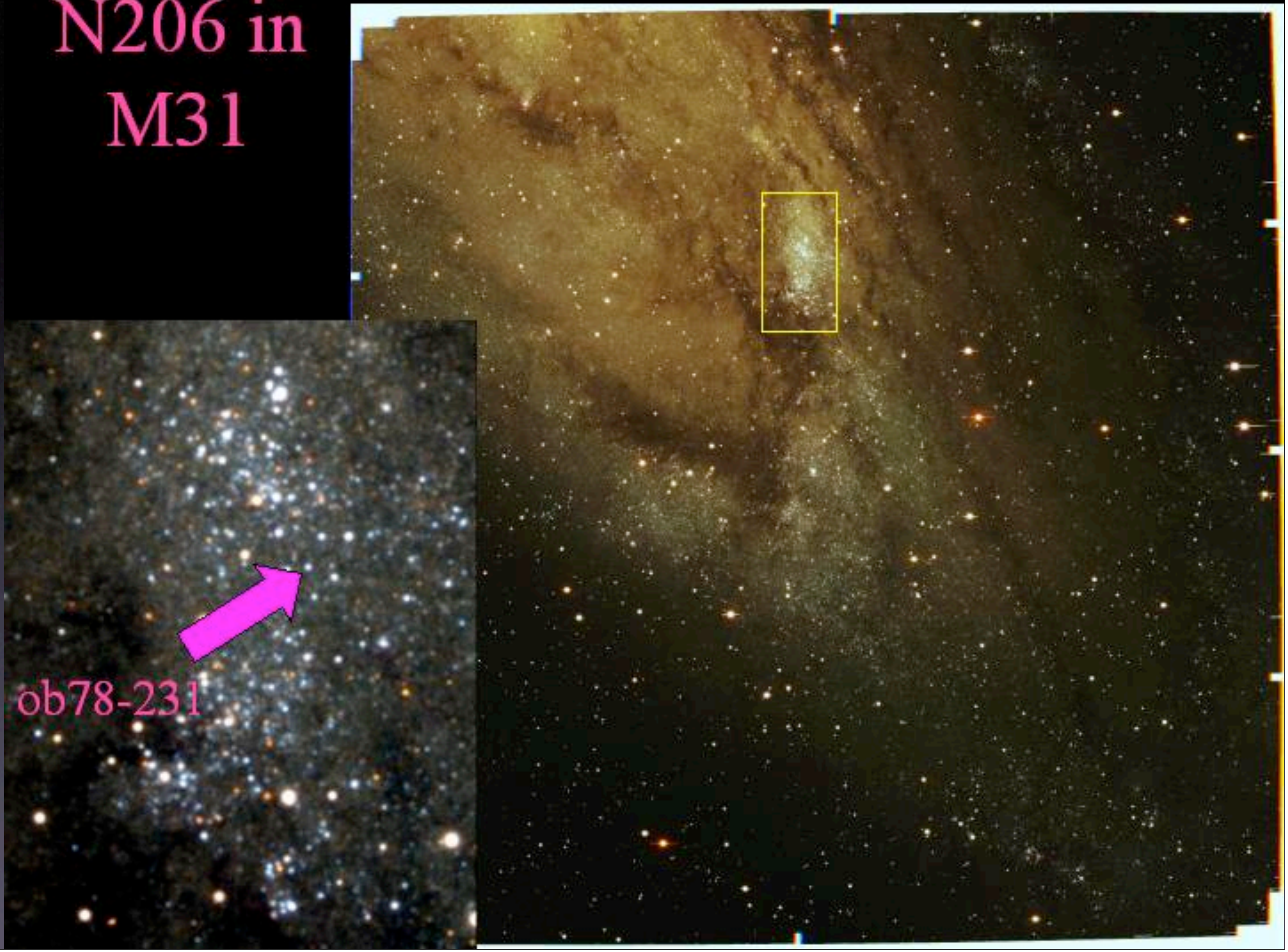
*---Peter S. Conti (1988, p 127)*

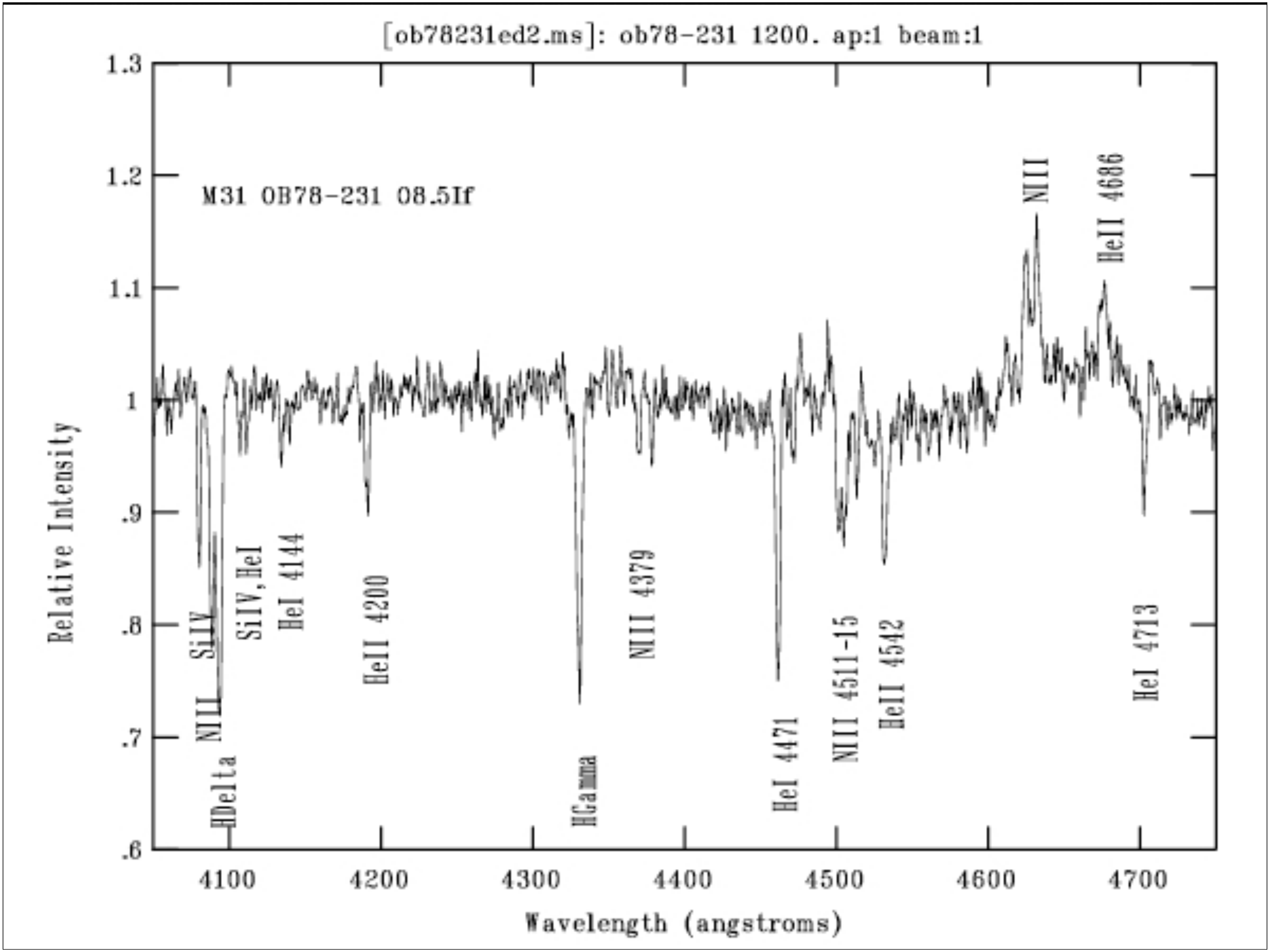
# What's Next?

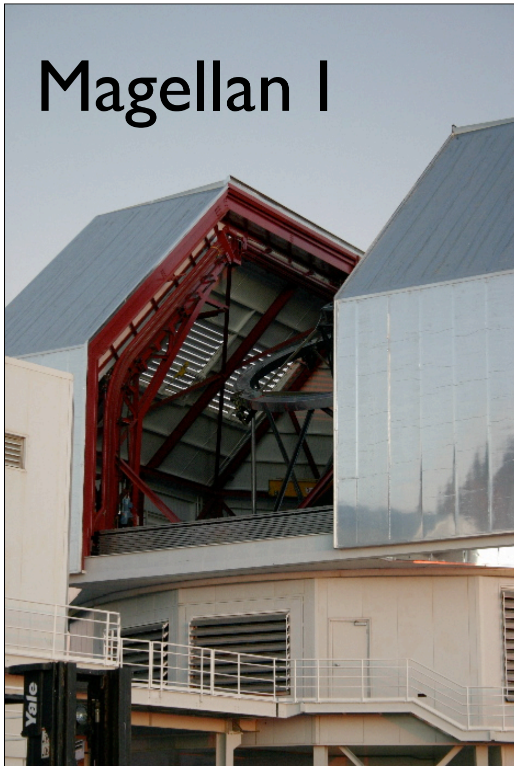
- Wind clumping in models
- Resolve certain controversies
  - UV vs optical
  - He I triplets vs He I singlets
  - Program A vs Program B
- Try it in higher and lower metallicity environments

M31
Z~2Zo

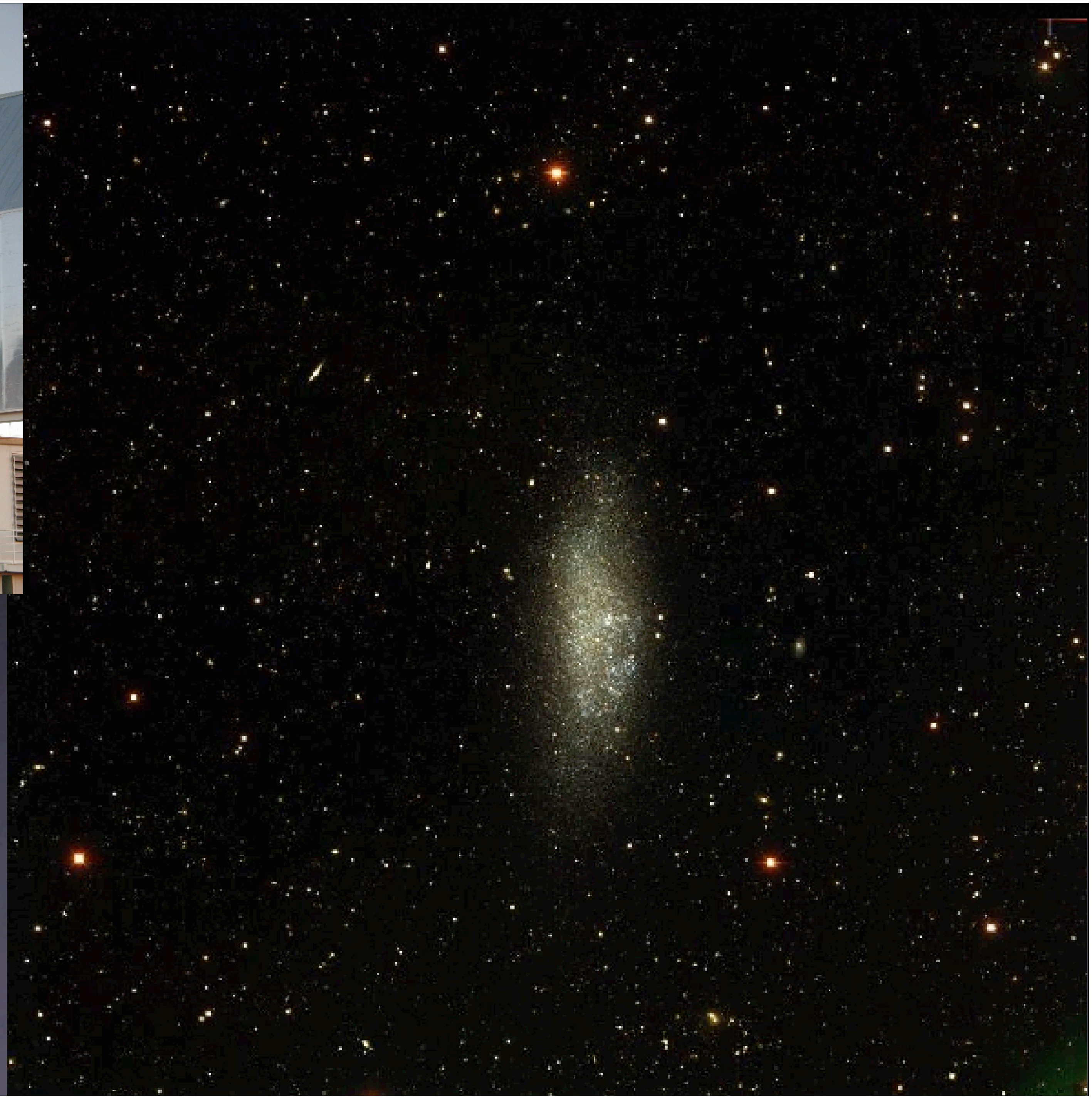
# N206 in M31




[ob78231ed2.ms]: ob78-231 1200. ap:1 beam:1
M31 OB78-231 O8.5If
Relative Intensity
Wavelength (angstroms)
1.3
1.2
1.1
1
.9
.8
.7
.6
4100
4200
4300
4400
4500
4600
4700
SiIV
NIII
HDelta
SiIV,HeI
HeI 4144
HeII 4200
HGamma
NIII 4379
HeI 4471
NIII 4511-15
HeII 4542
NIII
HeII 4686
HeI 4713



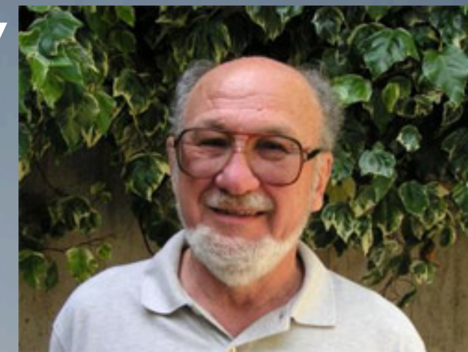
Magellan I



WLM: lowest metallicity of any LG star-forming galaxy (1/10th solar)

*Moonrise over the Andes*

# …so there's still plenty of fun to be had



*Moonrise over the Andes*