A grid of MARCS model atmospheres for stars with 0.5 < C/O ≤ 1

= S and SC stars

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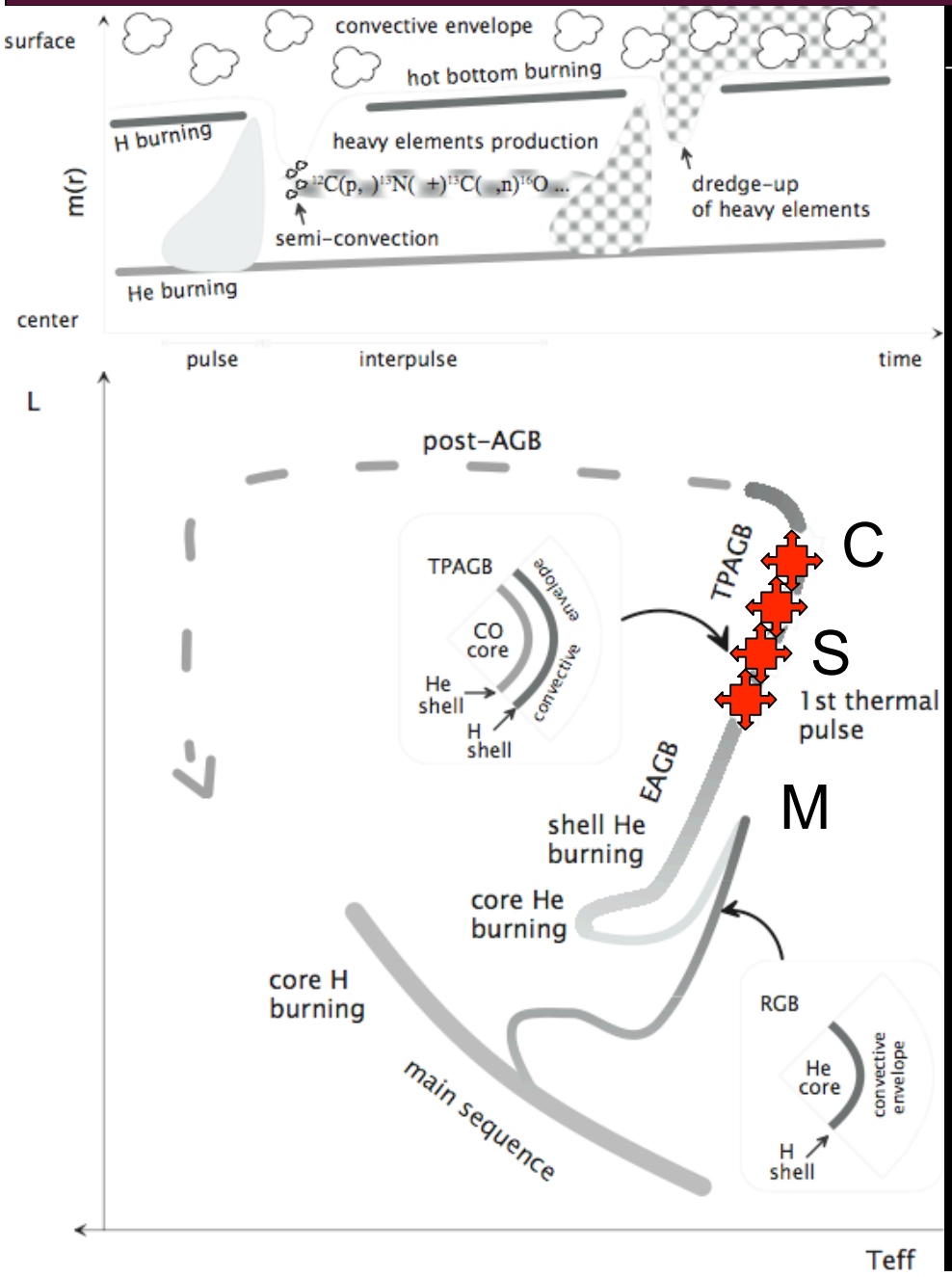
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Ake Nordlund

GCDS

Nice, Nov 3, 2010

AGB evolution sketch



Stars	C/O	spectrum
C	>1	CH, CN, C_2
SC	1	
S	0.54...0.99	(TiO),ZrO,LaO
M	0.54	TiO

From the 1st « 3rd dredge-up » on: carbon + s-process elements (Ba, La, Zr, Tc, ...) dredged up to the surface

S stars fact sheet

• Spectral characteristics:
TiO, VO bands
ZrO bands
« pure » S stars: without TiO



• S stars have 0.5<C/O<1 (not only C/O=1!)

•Some S stars are technetium-rich (Merrill 1952): intrinsic (TPAGB) ~ 50%

•The others are technetium-poor: extrinsic (polluted binary) ~ 50%



• All S stars are s-process enriched
(Smith et al. 1987, Vanture et al. 2002, Vanture & Wallerstein 2003, ...)

• Classification challenge
(Keenan 1954, Keenan & McNeil 1976, Ake 1979, Keenan & Boeshaar 1980, Piccirillo 1980)

Teff, C/O and s-process enrichment deeply entangled

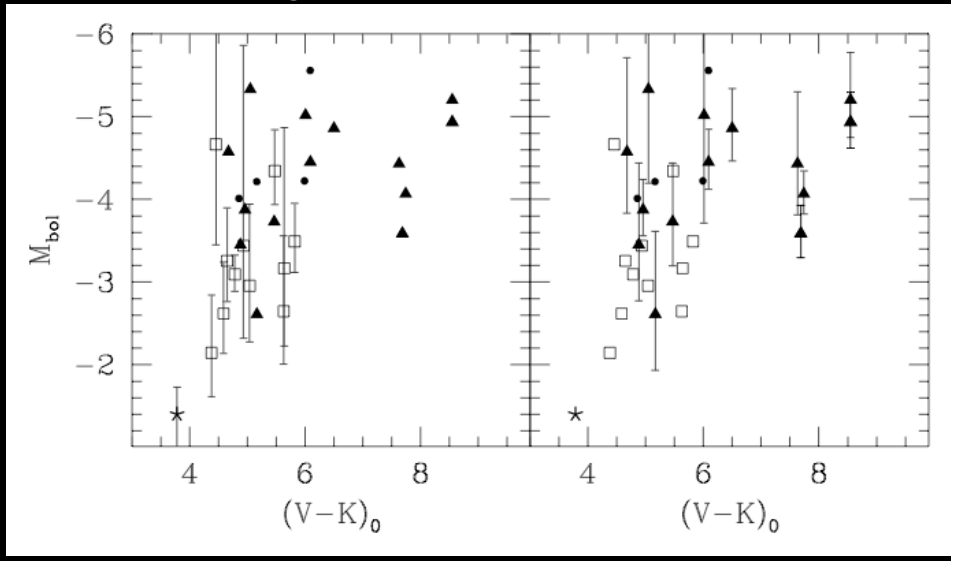
until now: S stars abundances derived with solar composition model atmospheres

Why studying AGB stars in the GCDS context?

- Good galactic and extragalactic tracers
- Intrinsically bright
- Direct constraints on s-process nucleosynthesis, dredge ups and stellar evolution ($N_{C\text{-rich}}/N_{O\text{-rich}}$, abundances, timescales)
- Key contributors to the chemical enrichment of their host galaxy

But:
- very crowded spectra at solar metallicities

HR diagram of S stars from HIPPARCOS



VIM problem (Variability Induced Movers)
Not anymore a big problem for GAIA
(Pasquato, Chiavassa, Jorissen)

S stars (very rough) statistics

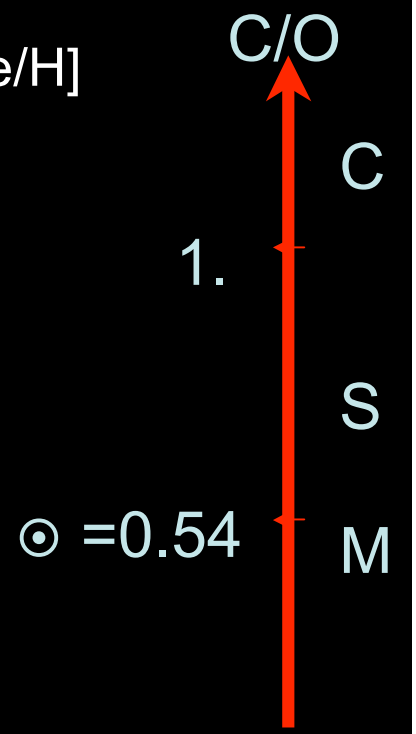
S stars are not statistically insignificant:

•Timescales from L. Siess stellar evolutionary code, at solar [Fe/H]

Weighted by Kroupa (2005) IMF

Fraction of C stars versus INTRINSIC S stars:

$$\frac{\Sigma_i \; n_i \; \Delta t_{i\,(C/O>1)}}{\Sigma_i \; n_i \; \Delta t_{i\,(0.6<C/O<1)}} \qquad i=1..4\ M_\odot$$



➔ C / INTRINSIC S ~ 4.5

very sensitive to timescales at the end of the TPAGB

(adopted mass loss rate: Vassiliadis & Wood 93)

• C / total S stars ~ 2 (since 50% of S stars are extrinsic)

S stars (very rough) statistics

- Fraction of C to S stars from L. Siess evolutionary tracks: C/S ~ 2

- Blanco 1983: in the LMC= Fraction of C to M stars = 2.2

- Iwanowska, 1967: statistics from catalogues
  - Red giants = 4%
  - M = 98.5% of red giants
  - S=0.5%
  - C=1% C/S ~ 2

- Statistics from galactic catalogs of :
  - C stars: GCGC (Alknis 2001)
  - S stars: GCSS 2 (Stephenson 1984)

whatever mag cut for V in [8.. 10]

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S stars (very rough) statistics

In the GAIA context

In the subsample where atmospheric parameters and abundances are to be determined: $5.6 < V < 12$

you expect roughly

1500 C stars

and

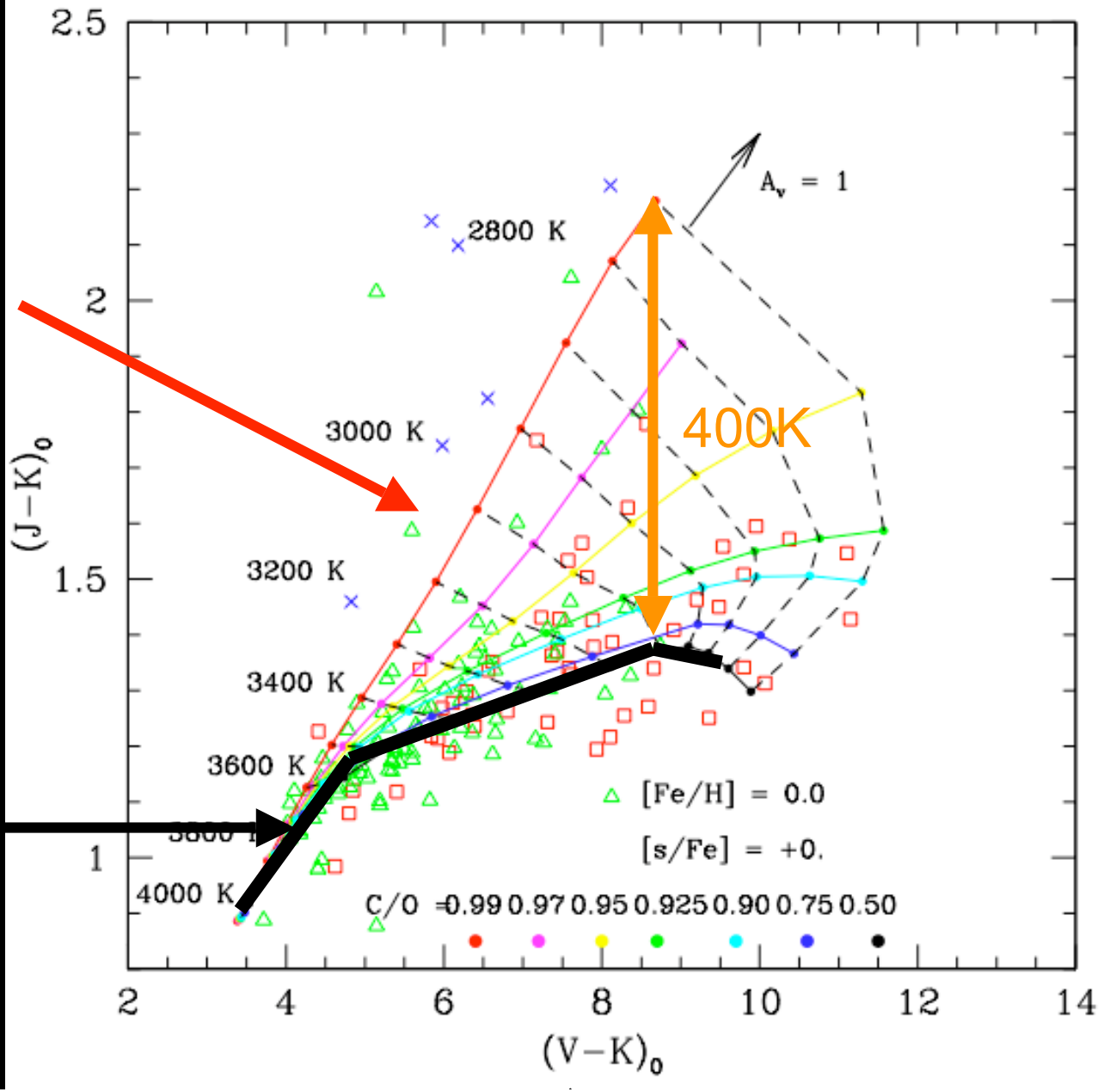
750 S stars

that cannot be analyzed with solar-composition model atmospheres

Inadequate model atmospheres can lead to large temperature errors

color-Teff relation for S giants with C/O=0.991

color-Teff relation for M giants



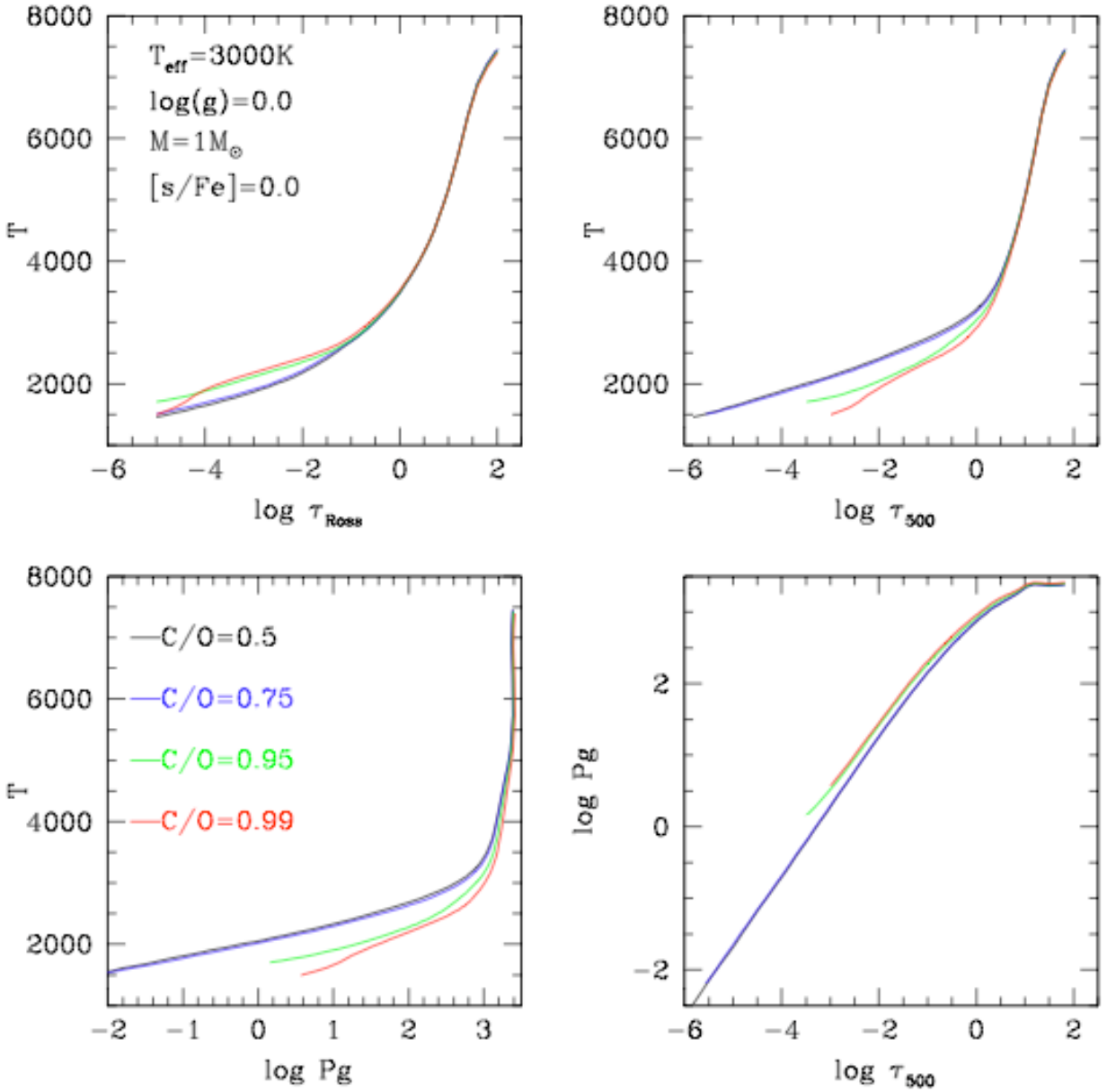
Models: fact sheet

- MARCS model atmospheres for late-type stars:
  see Gustafsson, Edvardsson, Eriksson, Jorgensen, Nordlund & Plez, 2008, A&A 486, 951

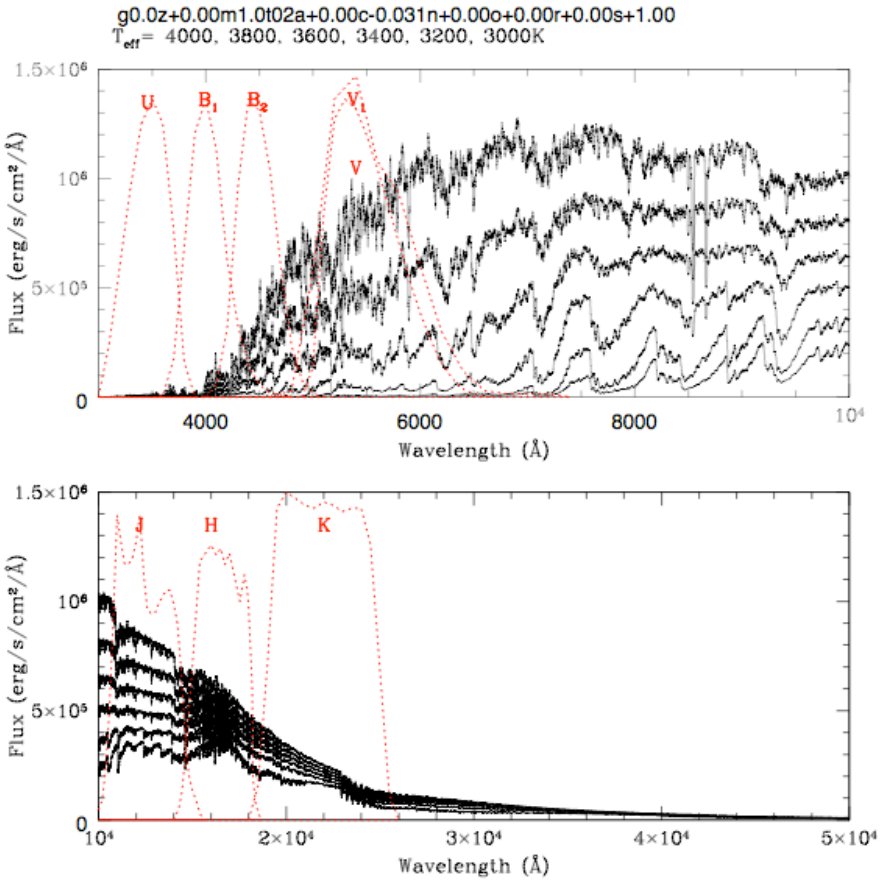
- MARCS model atmospheres for S and SC stars:
  hydrostatic equilibrium, LTE, convection: MLT
  Spherical symmetry for log g < 2, plane-parallel otherwise
  Updated ZrO linelist
  Opacity sampling > 10^5 wavelength points

  2700K < Teff < 4000K (step 100K)
  C/O = 0.5, 0.750, 0.899, 0.925, 0.951, 0.971, 0.991
  [s/Fe] = 0.,+1.,+2.
  [Fe/H] = 0., -0.5 ; [α/Fe] = -0.4 x [Fe/H]
  Log(g) = 0, 1 , 2 , 3 , 4 , 5
  M = $1M_{\odot}$
  ➔3522 converged model atmospheres

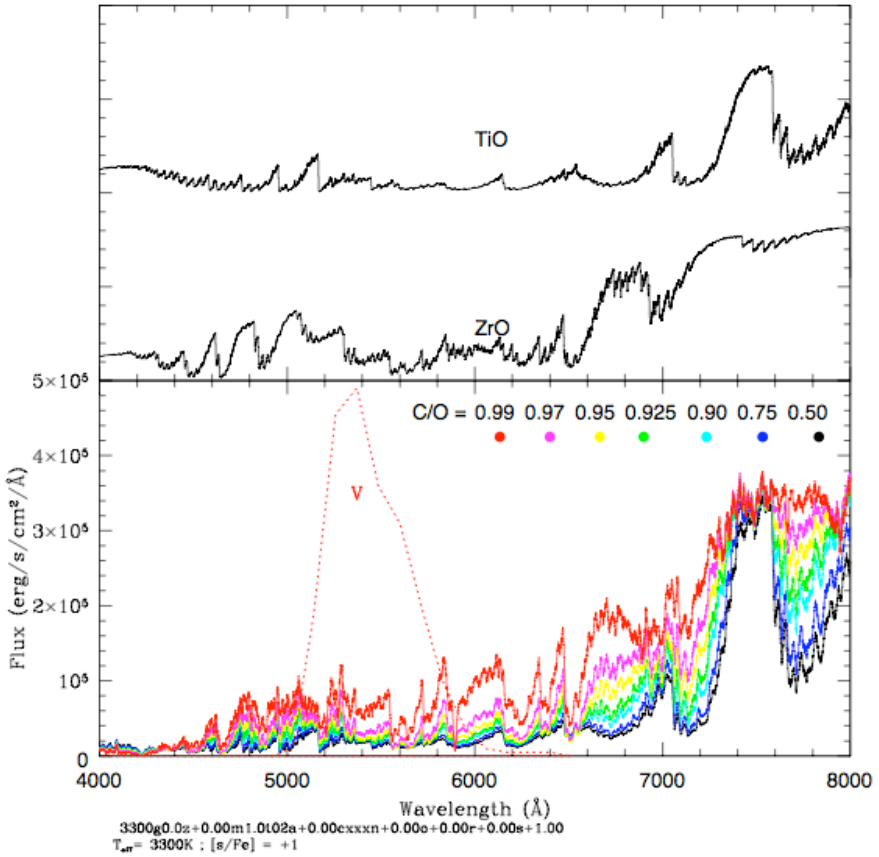
Model structure

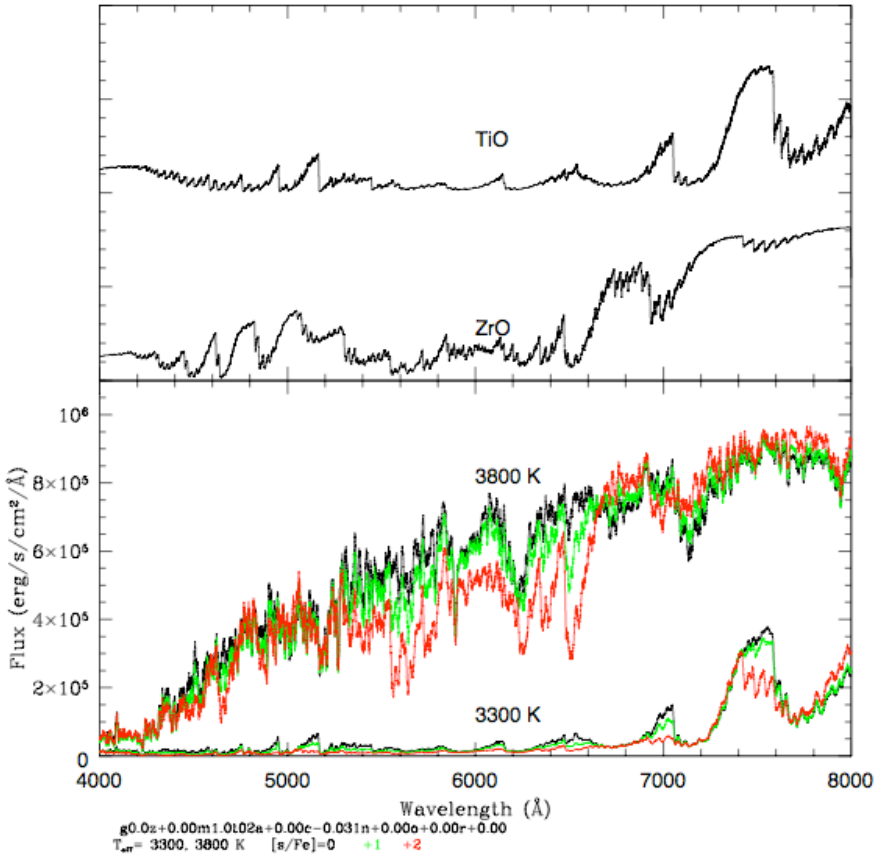


Model spectra of S stars: impact of Teff



Model spectra of S stars: impact of C/O and [s/Fe]





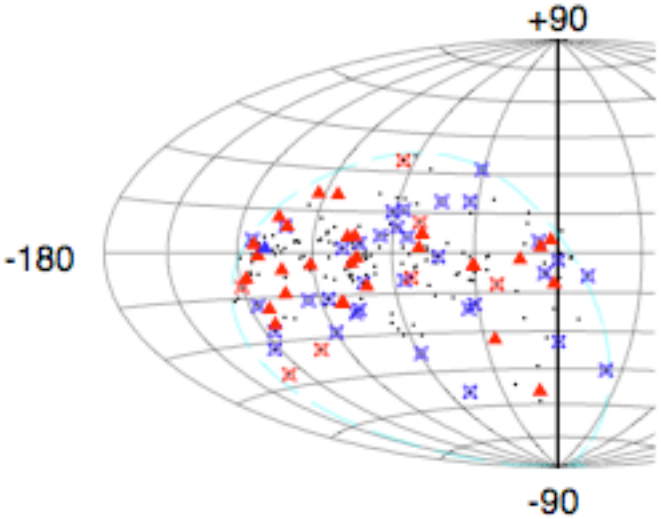
The Henize sample of S stars

Dichotomy:
~ 50% of intrinsic S stars:
genuine TP-AGB, Tc-rich
~ 50% of extrinsic S stars:
polluted binary, Tc-poor

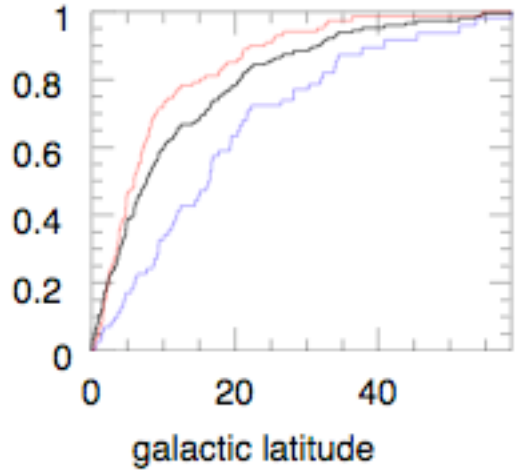
Henize sample of 205 S stars:
R < 10.5, δ < -25°
(Van Eck & Jorissen, 2000)

Available data:
- Geneva UBV B1 B2 V1 G photometry
- SAAO JHKL photometry

Colours dereddened according to Drimmel et al. (2003)



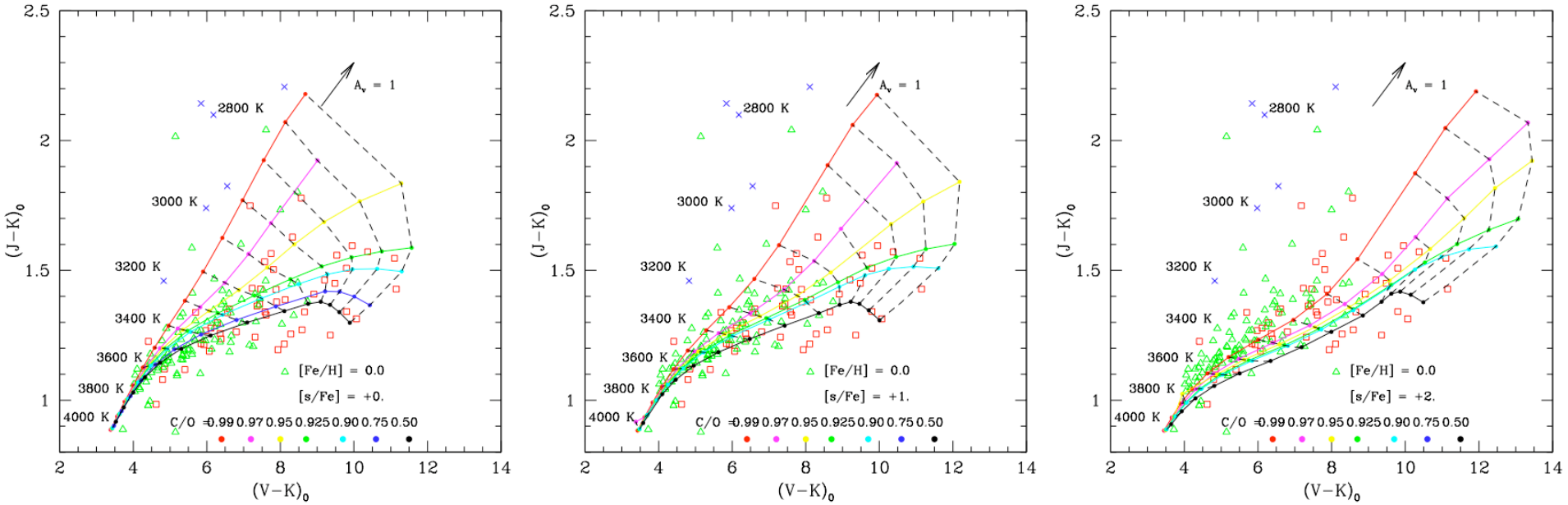
triangle: Tc−rich
cross : Tc−poor



- 160 low resolution spectra: $\Delta\lambda$= 3 Å , 4400-8400 Å , ESO Boller & Chivens
- 70 high-resolution spectra (ESO CAT, R=30 000 -60 000) centered on the Tc lines around 4250 Å

A grid of MARCS model atmospheres for S stars

Photometry: comparison with observations



[s/Fe] = 0 [s/Fe] = +1 [s/Fe] = +2

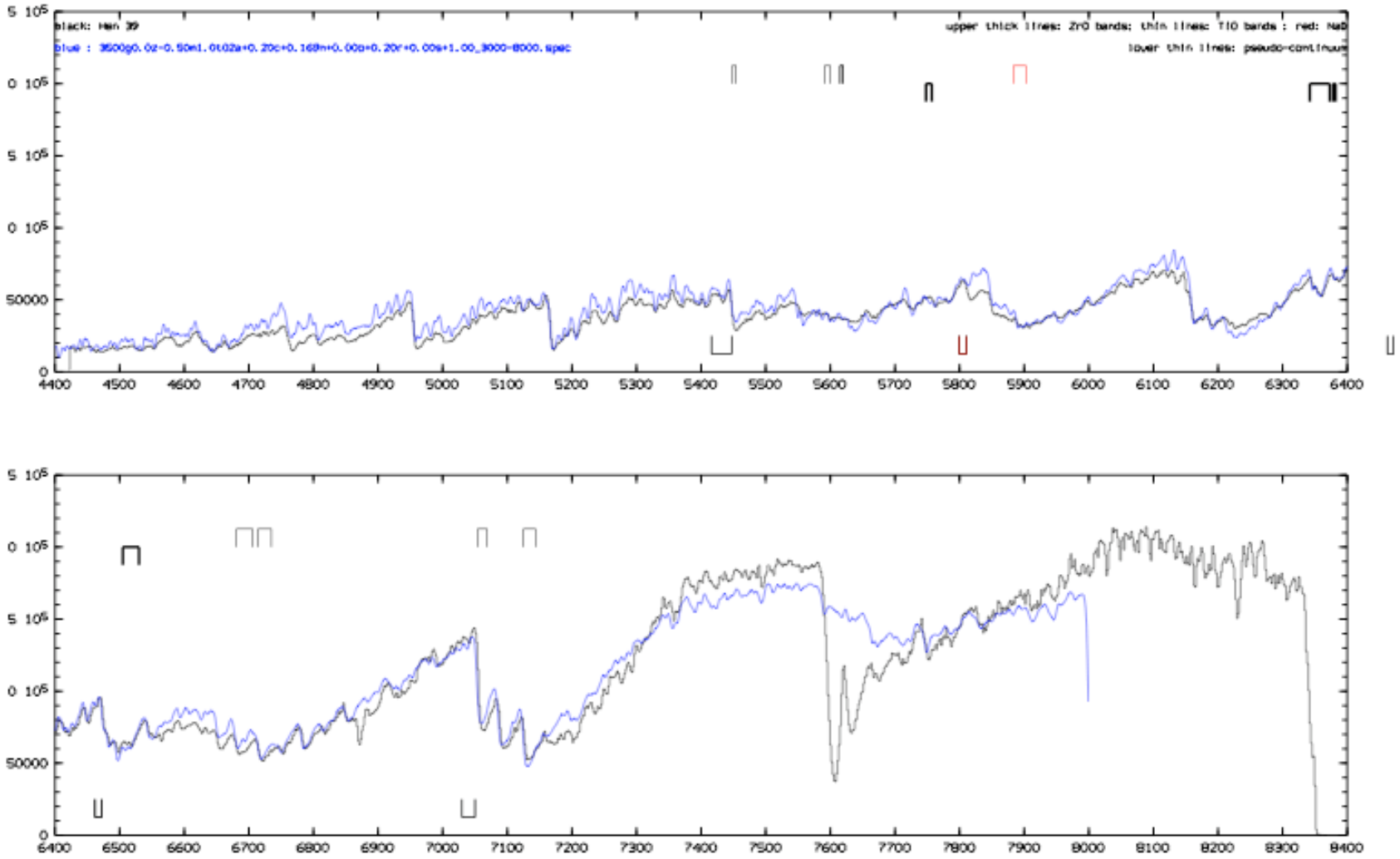
[Fe/H] = 0.
Teff = 2700...4000K
C/O = 0.5...0.991
log g = 0.

M giants
S stars
C stars

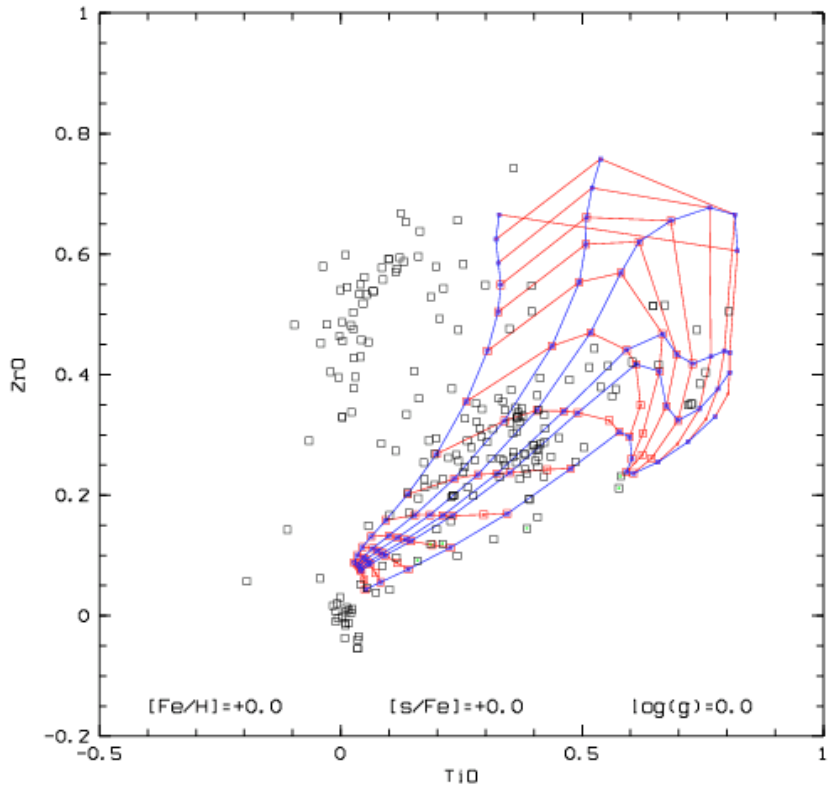
- Teff and C/O effects disentangled
- the M-star temperature scale (based solely on V-K) is NOT VALID for S stars (errors up to 400K)

Spectra: comparison with observations

Teff=3500K,log g=0, C/O=0.5, [s/Fe]= +1



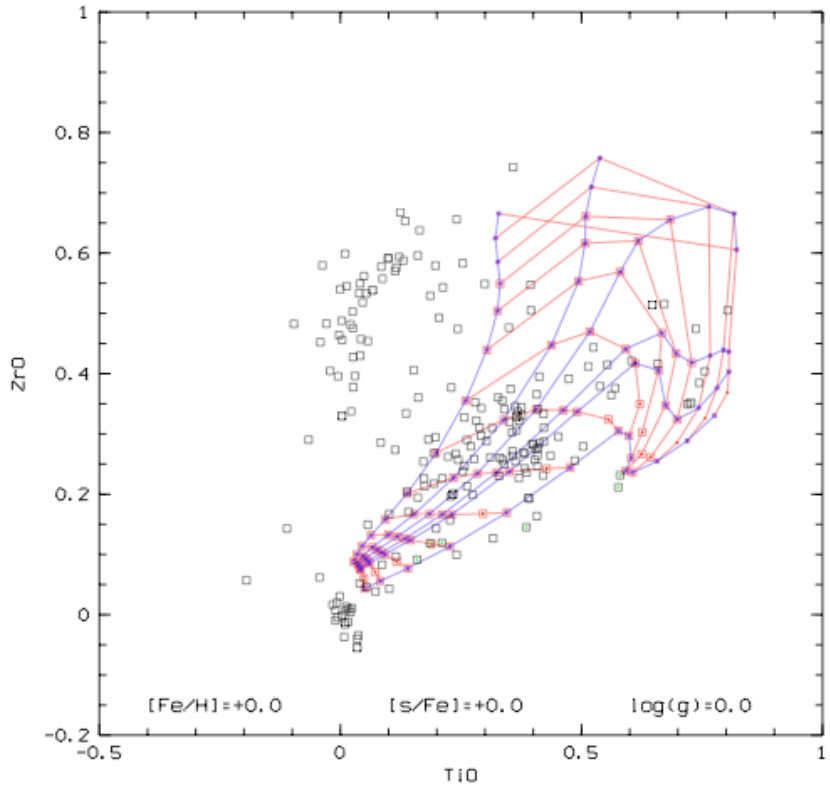
Band strengths: comparison with observations



[Fe/H] = 0.
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Band strengths: comparison with observations

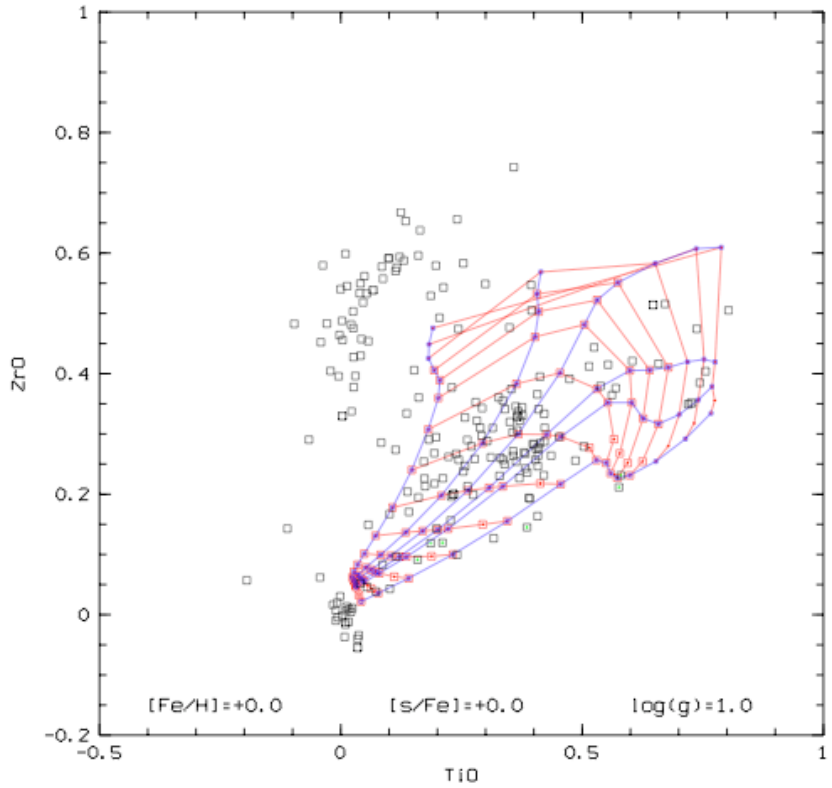


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Increasing gravity

Band strengths: comparison with observations

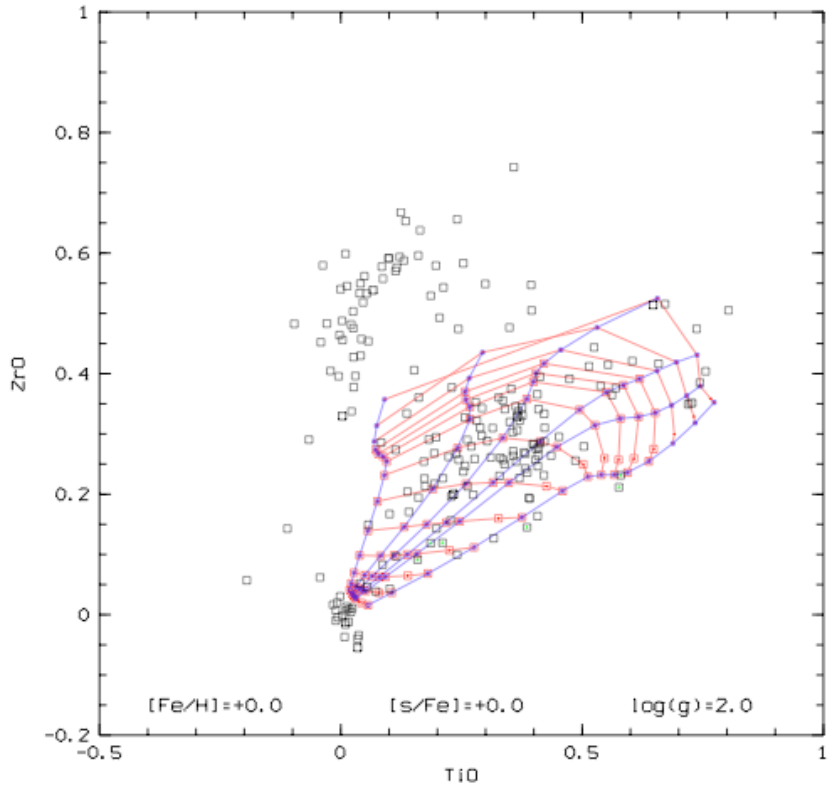


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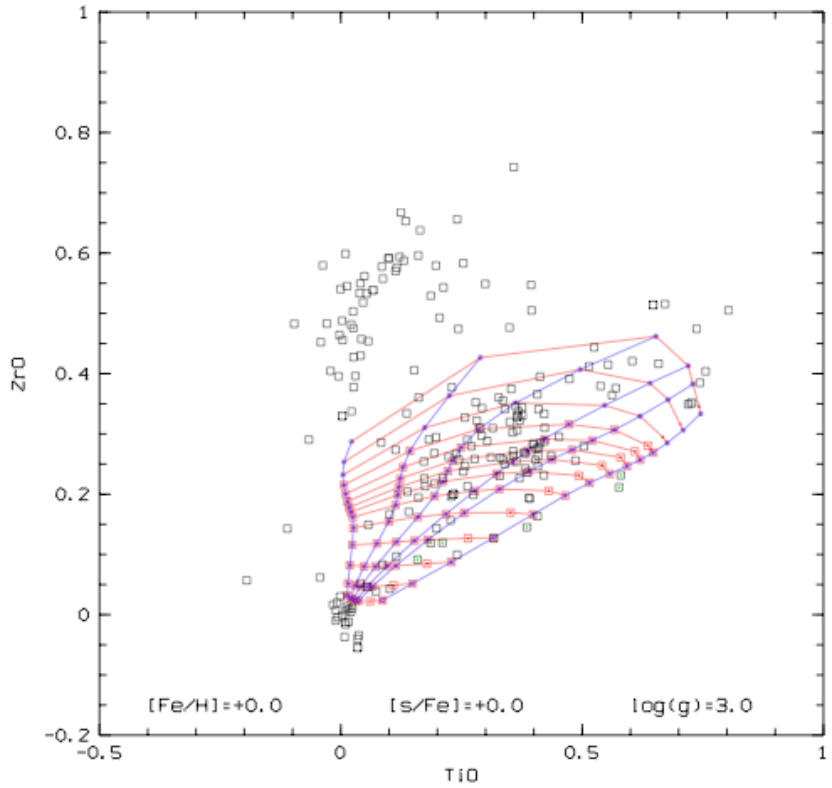


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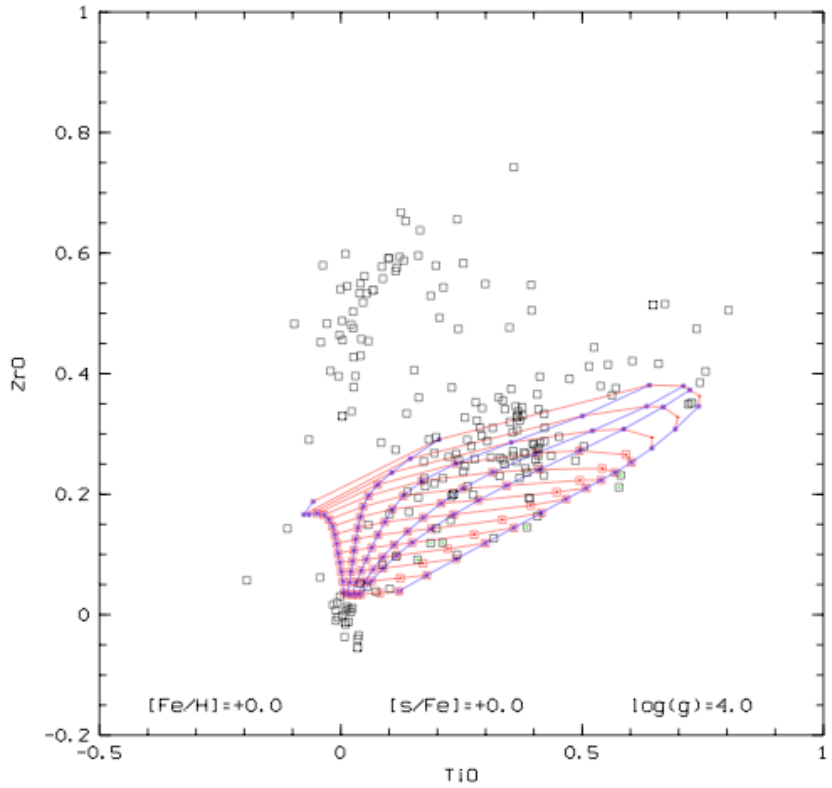


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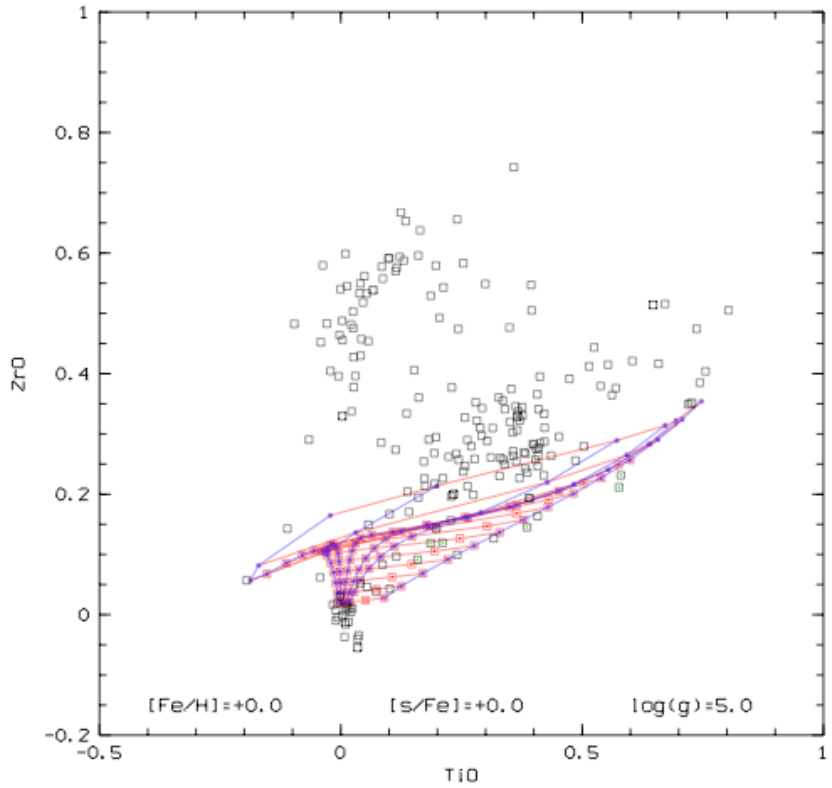


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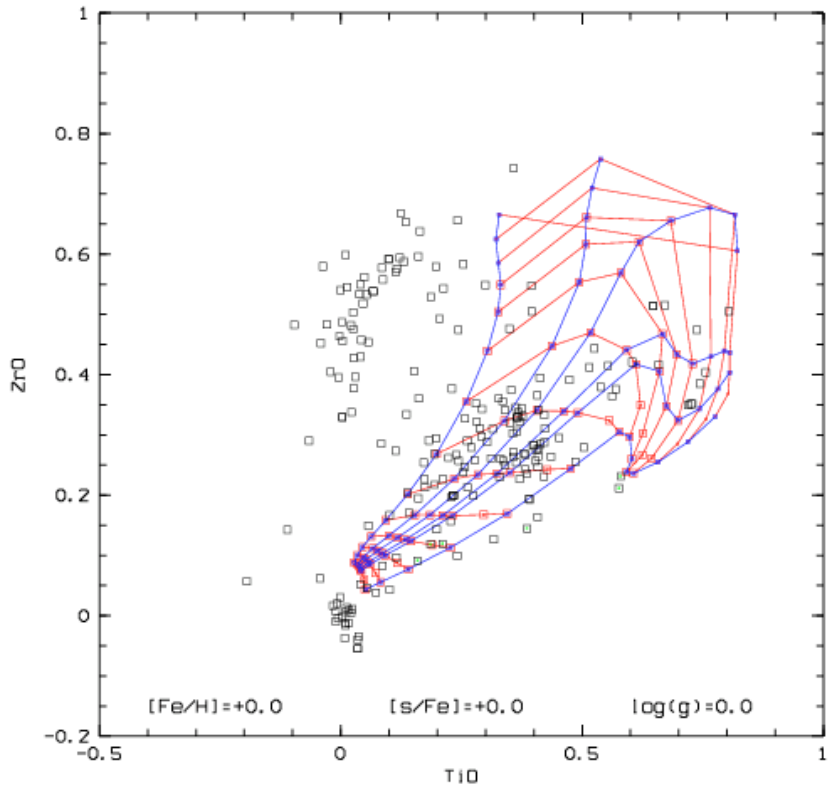


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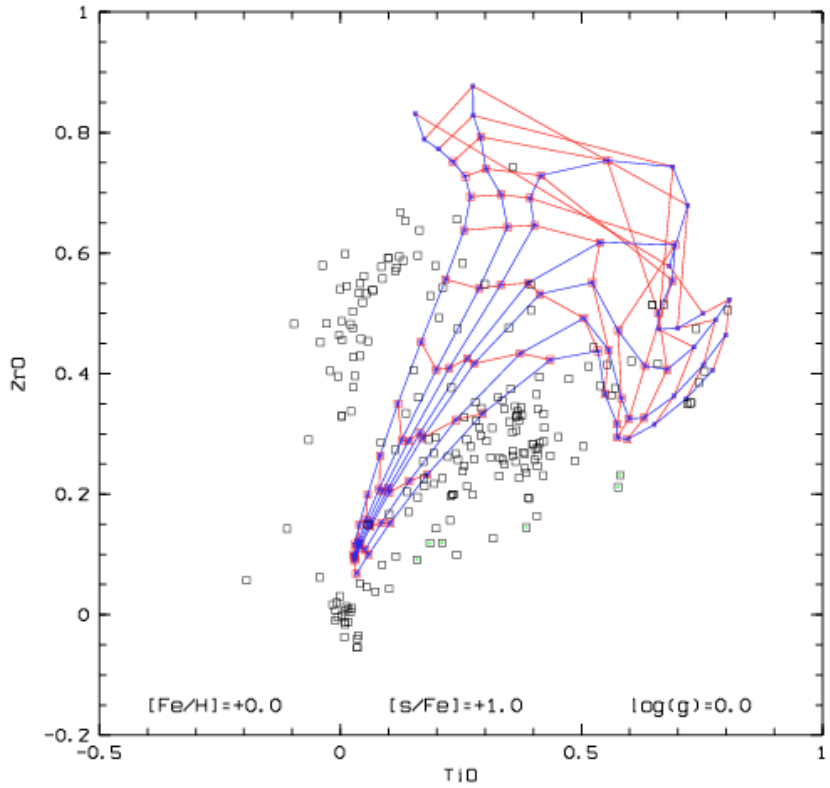
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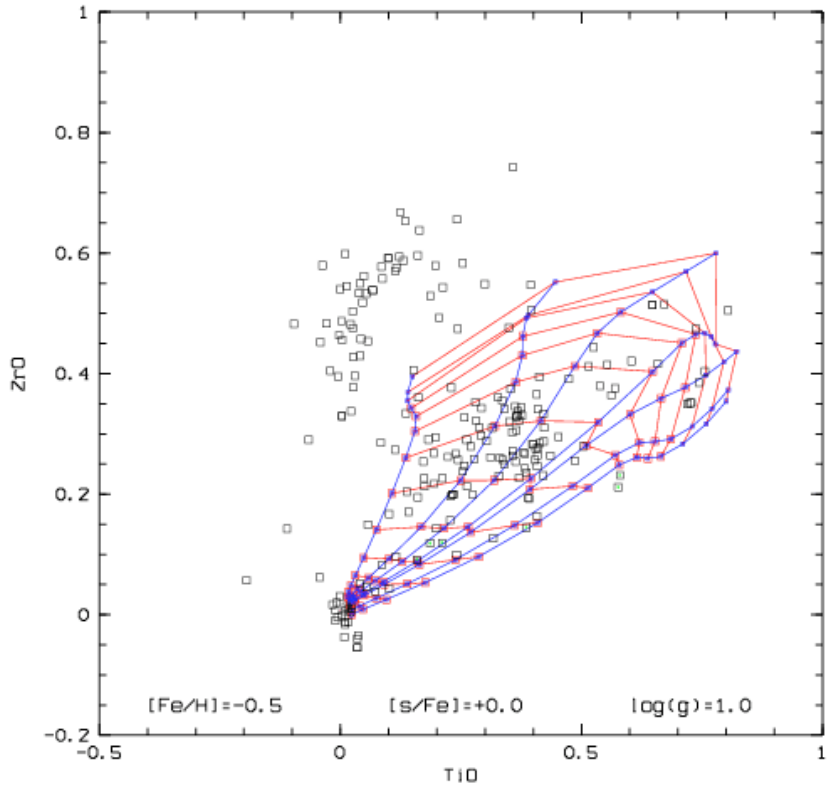
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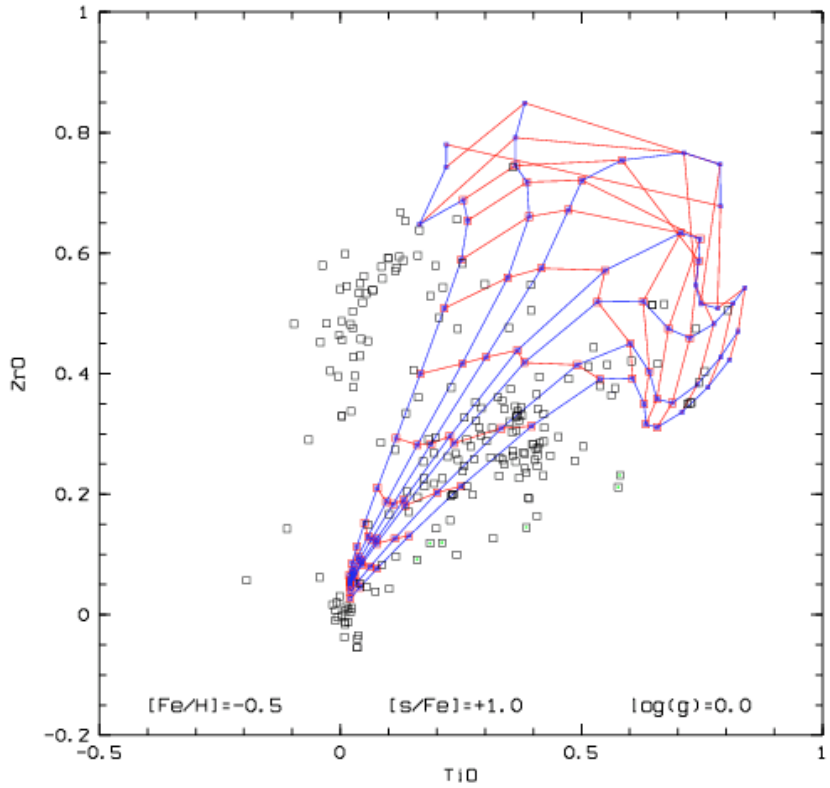
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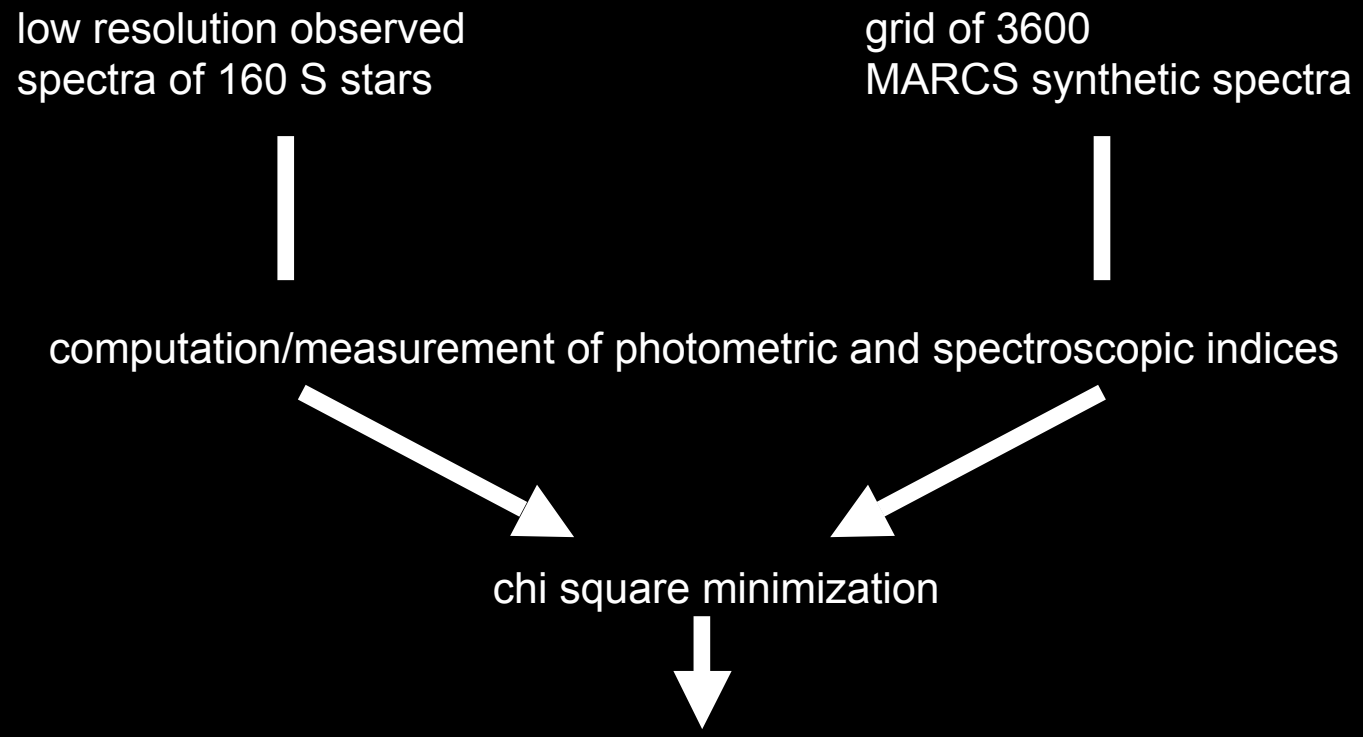


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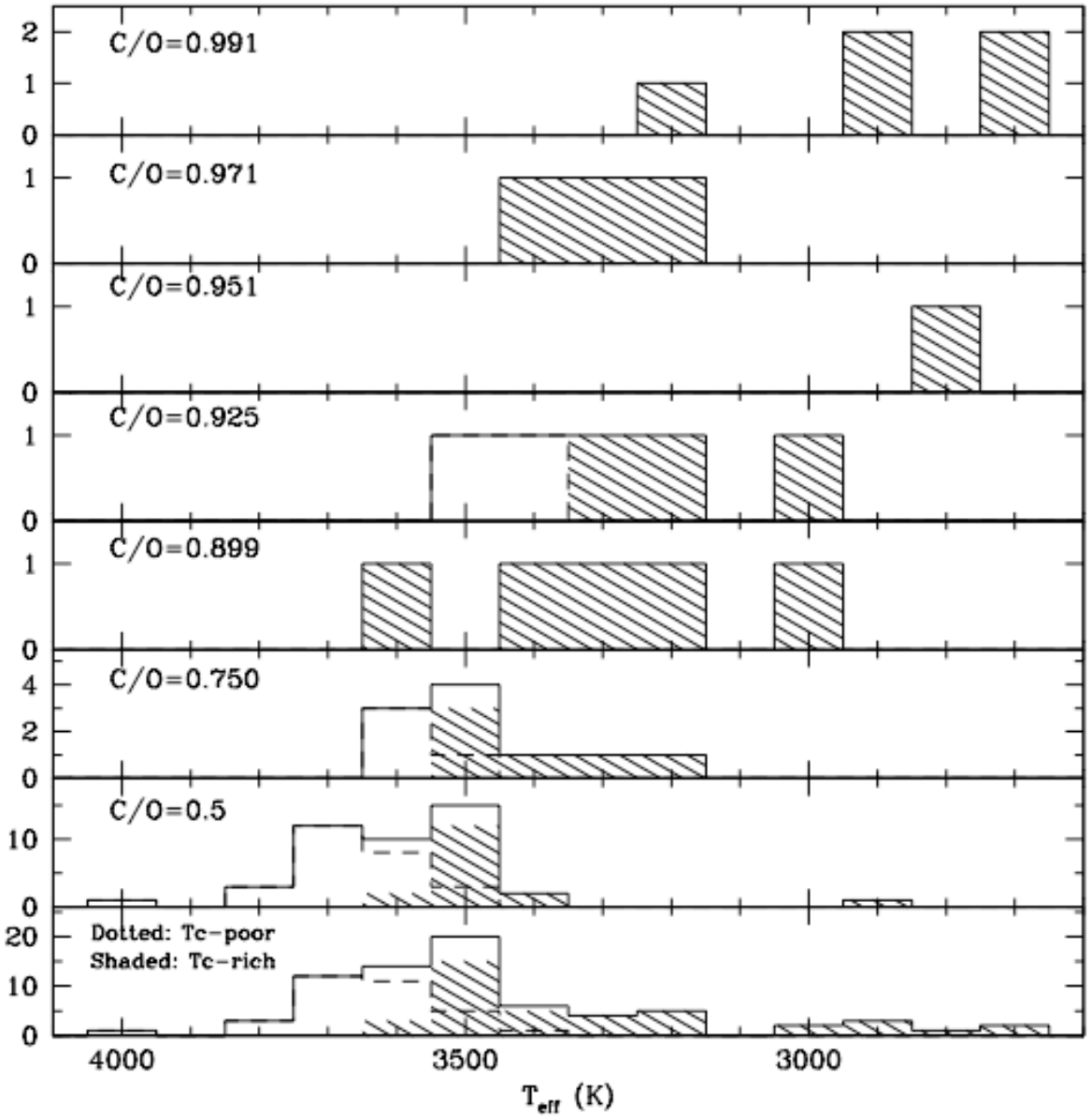
Spectra: comparison with observations

- Spectroscopic indices: TiO and ZrO band strengths, and NaD line strength
- Photometric indices:
  - Geneva photometry: $(U-B1)_0$, $(B2-V1)_0$,
  - Johnson photometry: $(V-K)_0$, $(J-K)_0$, $(H-K)_0$,

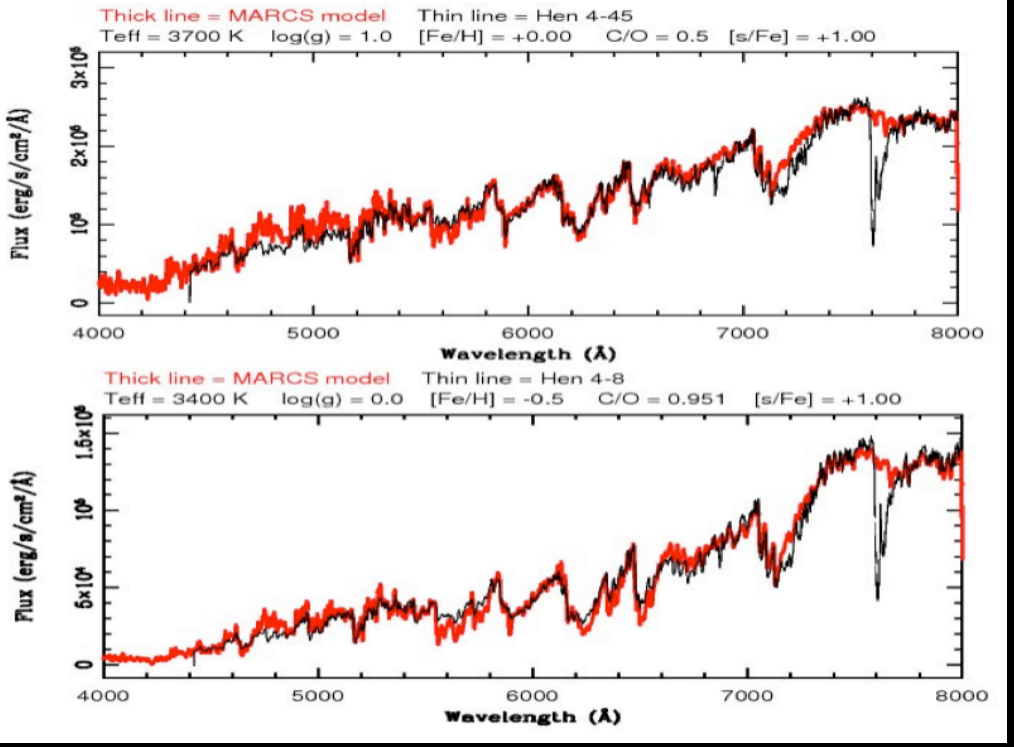


For the moment: post-check still necessary, but we will get fully-automated procedure very soon

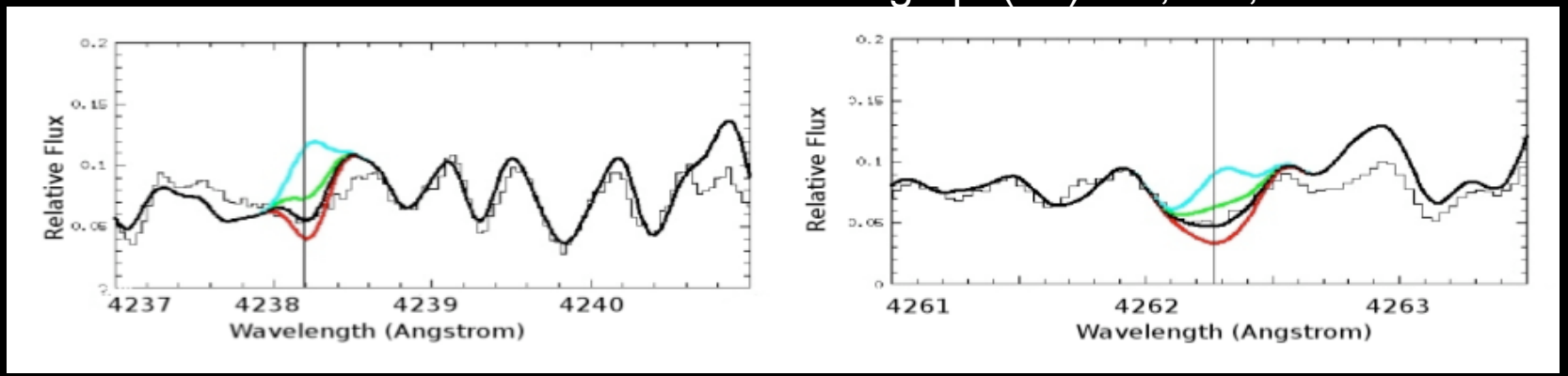
The effective temperature and C/O of S stars



Abundance determinations in key s-process elements



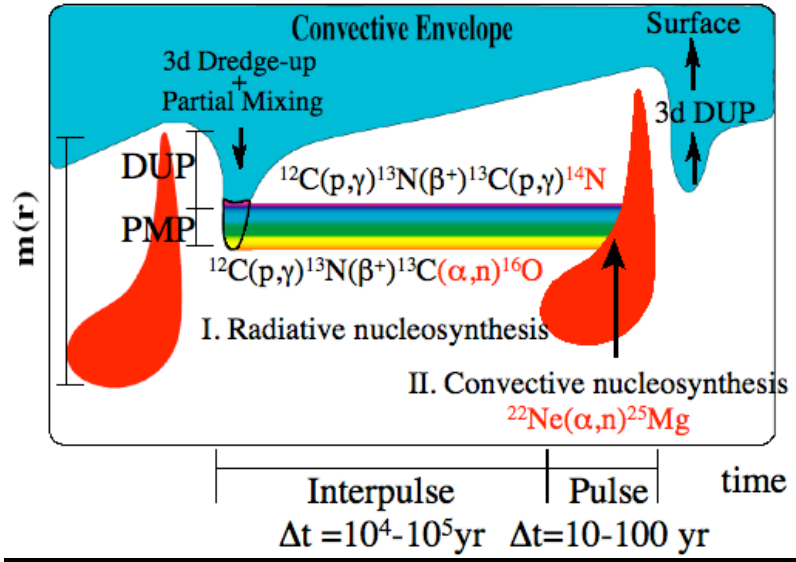
Log eps(Tc) = 0, 0.3, 0.6 and no Tc



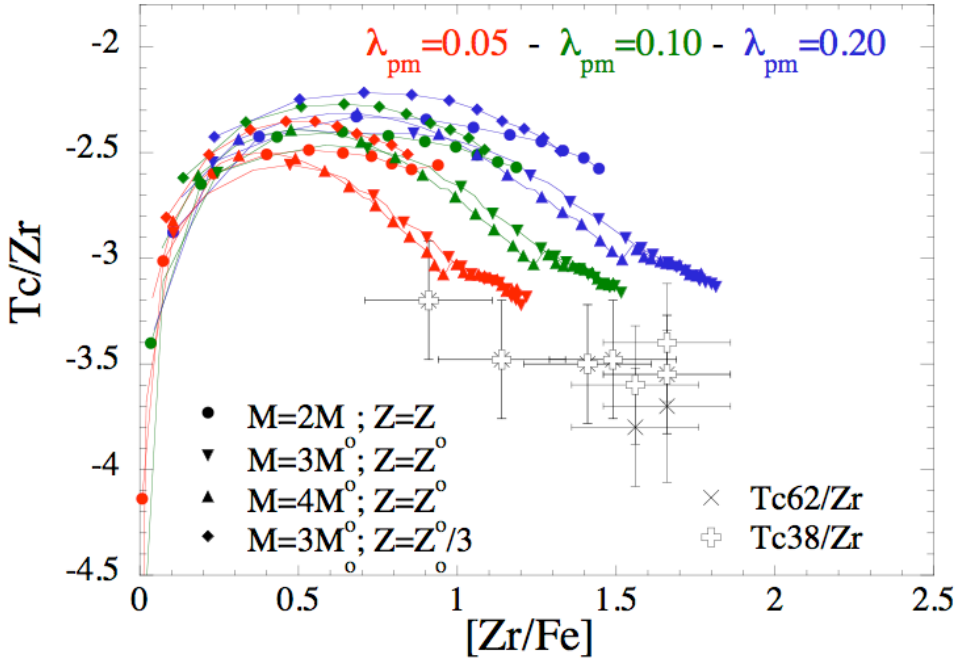
2 lines give compatible abundances

Constraining stellar evolution and nucleosynthesis

The most popular model for the s-process in AGB stars
the partial mixing of protons at the time of the 3d DUP



Recent computations from Siess & Goriely



λ_{pm} = mass of the partial mixing zone / max mass of the thermal pulse

Too low Tc/Zr:
- longer interpulse phases?
- hotter thermal pulses?

Concluding remarks

S and C stars are not insignificant objects (6.5<V<12: 1500 C, 750 S)

Nucleosynthesis through s-process + significant mass loss
Huge contributors to the chemical enrichment of the galaxy

Key-targets for GCDS

S and C stars need dedicated stellar-parameter finding-tools and model atmospheres

First grid of S stars model atmospheres covering the whole range of admissible physical parameters

Checked on visible and IR photometry, and on band-strength indices
Soon checked against infrared spectra
Comparison with 3D model atmospheres

Efficient procedure to determine the physical parameters (Teff, C/O, [s/Fe]) of observed S star and abundances - S stars have 0.5 < C/O < 1 (not only ~ 1!)

Good fit of high-resolution observed spectra of S stars, strong constaints on stellar evolution and nucleosynthesis

A grid of MARCS model atmospheres for S stars