Constraining mixing processes in 16CygA using Kepler data and seismic inversion techniques

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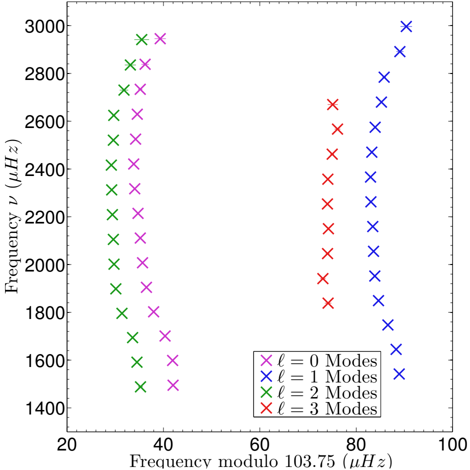
June 2015

General structure of the presentation

1. State of the art;
2. Forward modelling of 16CygA (Seismic, spectro, interfero);
3. Inversions to further constrain 16CygA? (Mass and age);
4. Conclusions and perspectives.

THE 16CYG BINARY SYSTEM (A & B (+C+Bb) - 16CYGA

Kepler's best in class! Solar-like binary system.



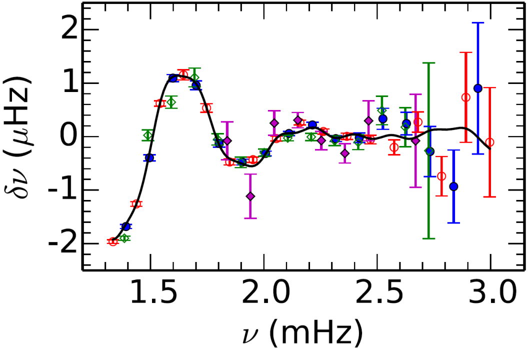
16CygA properties

$< \Delta\nu >$ (μHz)	103.78
T_{eff} (K)	5830 ± 50
Y_f (dex)	0.24 ± 0.01
$\frac{Fe}{H}$ (dex)	0.096 ± 0.026
$\log g$ (dex)	4.33 ± 0.07
R $(R_\odot)$	1.22 ± 0.02

Extensively studied: Metcalfe et al. 2012, Ramirez et al. 2009, Verma et al. 2014, Tucci-Maia et al. 2014, White et al. 2013, Davies et al. 2015, ...

Chemical composition problem:

- Metcalfe et al. 2012 (AMP): $Y_0 = 0.25 \pm 0.01$ ($Y_f \approx 0.20$);
- Verma et al. 2014 (Glitches): $Y_f = 0.24 \pm 0.01$
  $\Rightarrow Y_0 \approx 0.28 - 0.30$.



Verma et al. 2014, ApJ, 790, 138.

We consider:

- $Y_f \in [0.23, 0.25]$ (Verma et al. 2014)
- $\left(\frac{Z}{X}\right)_f \in [0.0209, 0.0235]$ (AGSS09 with Ramirez et al. 2009)

Modelling strategy

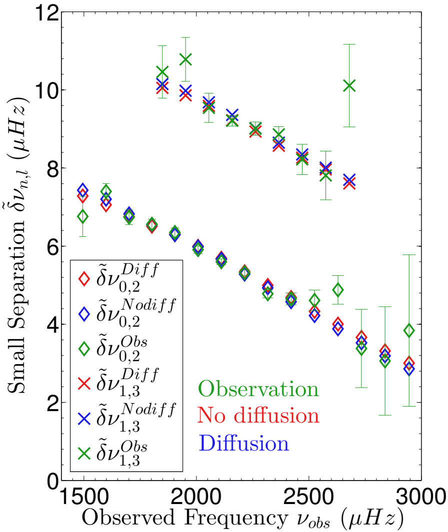
Five-step process

1. Compute reference models (Levenberg-Marquardt algorithm);
2. Carry out inversions of acoustic radius and mean density;
3. Improve the models - compute new reference models;
4. Carry out inversions for core conditions;
5. Build models fitting this additional constraint.

A few comments...

- Local minimization algorithm;
- Dependency on solar mixture (here AGSS09) for $\frac{Z}{X}$;
- Dependency of mass and age on the physical ingredients of the models.

Local behaviour assessed by starting from various initial conditions...



Free parameters

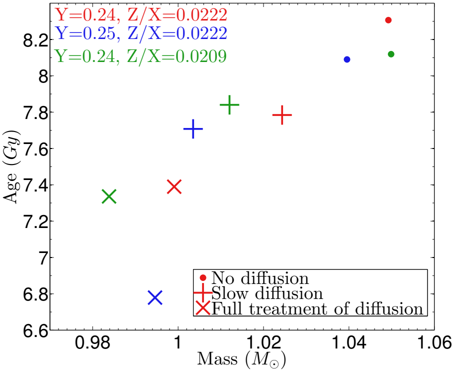
- M, age, α_{MLT}, X_0, Z_0.

Diffusion treatment (Thoul et al. 1994)

Constraints

- $< \Delta\nu >$, $\tilde{\delta}\nu_{n,l}$, T_{eff}, Y_f, $\left(\frac{Z}{X}\right)_f$.

+ check the values of R, $\log g$ and L after the fit.



Impact of mixing + chemical composition!

Results:

- M between 0.97 and 1.07 $M_\odot$;
- Age between 6.8 and 8.3 Gy;
- α_{MLT} around 1.6 ≈ 1.7 (solar).

Origin of the difference with Metcalfe et al. 2012?

$\Rightarrow Y_f$

	Metcalfe et al. 2012	Us
M ($M_\odot$)	1.11	1.09
Age (*Gy*)	6.9	7.1

Impact of Y_f on mass and age!

Starting point: integral relations

$$\frac{\delta\nu^i}{\nu^i} = \int_0^R K^i_{s_1,s_2}\frac{\delta s_1}{s_1}dr + \int_0^R K^i_{s_2,s_1}\frac{\delta s_2}{s_2}dr$$

Structure - Frequency relations
(Gough & Thompson 1991)

Sola Method

Fit of a target using linear combinations of kernels

$$\mathcal{T} = \sum_i c_i K^i_{s_1,s_2}$$

(Pijpers & Thompson1994)

In helioseismology

$\mathcal{T}$= Localized function (Gaussian) to obtain structural profiles

In asteroseismology

$\mathcal{T}$= Related to corrections of an integrated quantity

$$\frac{\delta A}{A} = \int_0^R \mathcal{T}_A \frac{\delta s_1}{s_1}dr$$

$$\bar{\rho} = \frac{3M}{4\pi R^3}$$

$$\tau = \int_0^R \frac{dr}{c}$$

$$t = \int_0^R \frac{1}{r}\frac{dc}{dr}dr$$

$$t_u = \int_0^R f(r)\left(\frac{du_0}{dr}\right)^2 dr$$

(Reese et al. 2012)
(Buldgen et al. 2015)

Inversion Results - Acoustic Radius and Mean Density

Reference Values

$\tau = 4687 \pm 20 \; s$

$\bar{\rho} = 0.778 \pm 0.02 \; g/cm^3$

Inverted results

$\tau = 4592 \pm 15 \; s$

$\bar{\rho} = 0.83 \pm 0.007 \; g/cm^3$

Inversion

Inversion for the acoustic radius, τ and the mean density $\bar{\rho}$

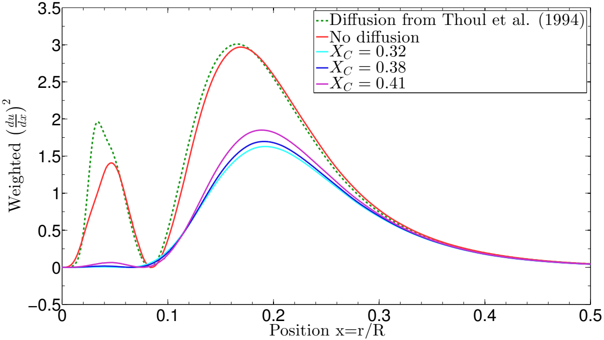
- Good kernel fit;
- Small Dispersion of the results;
- Unable to reduce the dispersion of mass and age.

But: $\Rightarrow$ **Can be used as supplementary constraints!**

Result: Improved reference models by also fitting τ and $\bar{\rho}$.

INVERSION TECHNIQUE - CORE CONDITIONS INDICATOR

Goal: probing the core by probing the $u_0 = \frac{P_0}{\rho_0} \propto \frac{T}{\mu}$ gradient.



Definition:

$$t_u = \int_0^R f(r) \left(\frac{du_0}{dr}\right)^2 dr$$

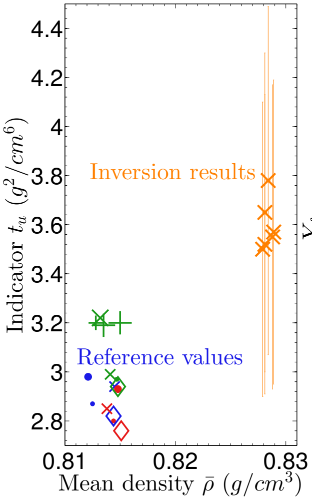
- Very sensitive to changes in core conditions.

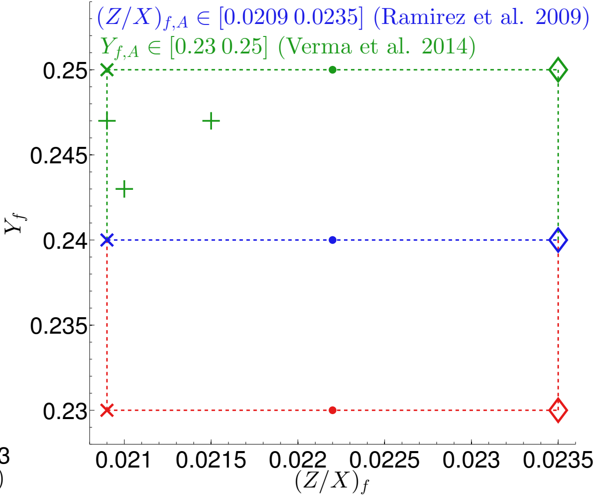
See Buldgen et al. (submitted).

Improving models ⇒ Improving fundamental parameters!

Inversion results - Core conditions indicator

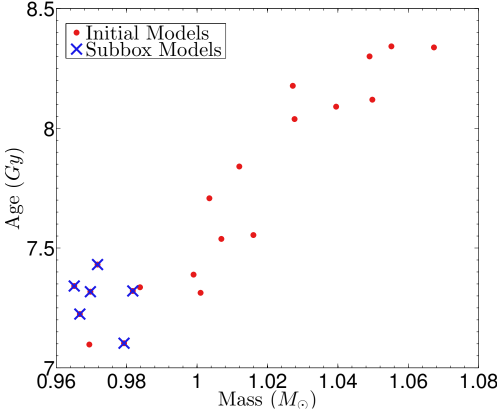
The sensitivity of the indicator allows us to constrain chemical composition and diffusion!





INVERSION RESULTS - CORE CONDITIONS INDICATOR

How does it constrain **mass** and **age**?



M $(M_\odot)$	$0.96 - 1.0$
Age (Gy)	$7.0 - 7.4$
Y_0 (dex)	$0.30 - 0.31$
Z_0 (dex)	$0.0194 - 0.0199$
L $(L_\odot)$	$1.49 - 1.56$
R $(R_\odot)$	$1.19 - 1.20$

Solar values:
$Y_0 = 0.2703$,
$Z_0 = 0.0142$

From 5% to 2% in mass and 8% to 3% in age! (Also 3% to 1% in radius, between 1.19 and 1.20 $R_\odot$).

In conclusion:

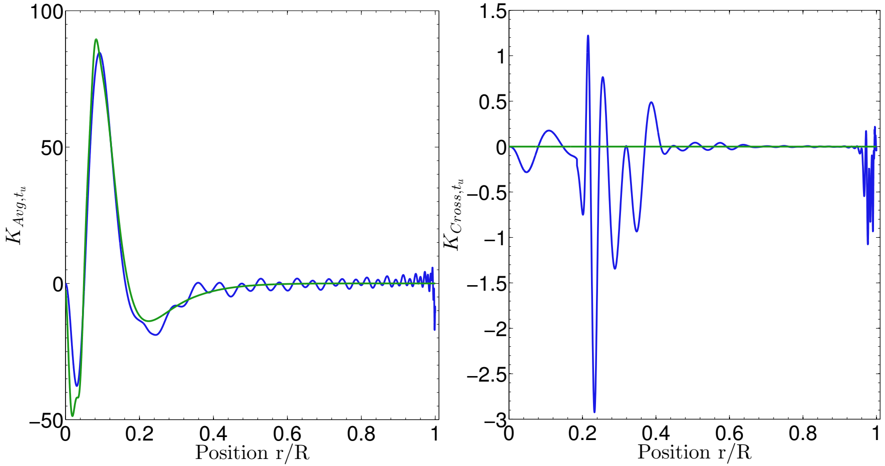
- Strong constraints on chemical mixing and composition;
- Reduction of mass and age dispersion ⇒ crucial for PLATO;
- Importance of Y constraints and incompatibility with GN93;
- Consistent independent modelling of 16CygB.

But let us not be mistaken:

- Age is model-dependent (3% ⇒ Internal error!);
- We need additional indicators (Convection, Opacity,...).

Philosophy: Inversions are a tool using seismic information that will, through synergies with stellar modellers, help us build more physically accurate descriptions of stellar structure.

Thank you for your attention!

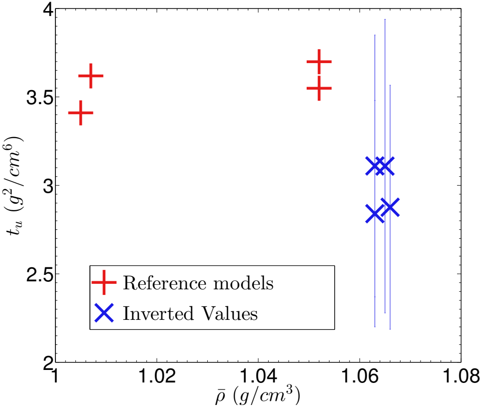

100
50
0
−50
K_{Avg,t_u}
0
0.2
0.4
0.6
0.8
1
Position r/R
1.5
1
0.5
0
−0.5
−1
−1.5
−2
−2.5
−3
K_{Cross,t_u}
0
0.2
0.4
0.6
0.8
1
Position r/R

APPENDICES

With $Y_f = 0.24$, $(Z/X)_f = 0.0204$

- $M = 0.96 M_{\odot}$
- $Age = 7.23 Gy$

Depending on the assumed chemical composition, always less massive than 16CygA. t_u serves as a consistency check but no gain in accuracy.



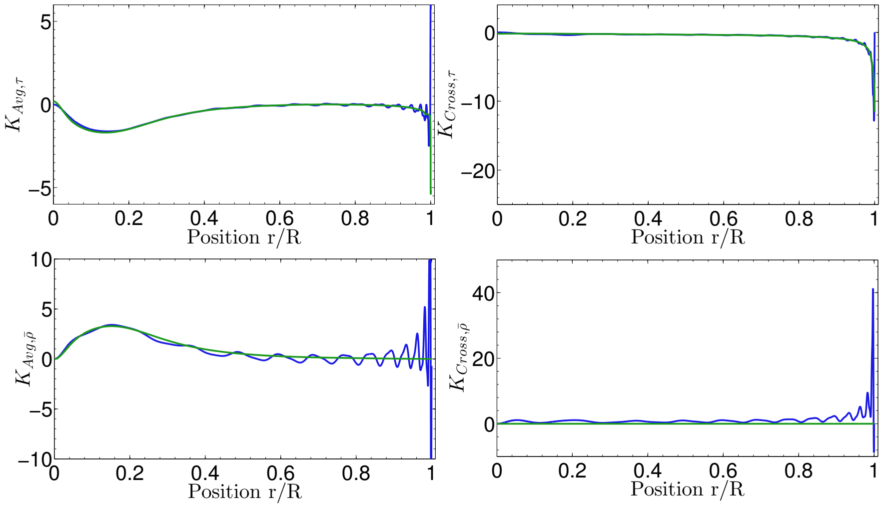
GN93 MIXTURE

If one considers GN93, we obtain $\left(\frac{Z}{X}\right)_f \in [0.0287, 0.0316]$, the box is simply around different Z/X values.

- slightly higher masses ($1.03M_\odot$), slightly higher radii;
- slightly lower ages (around $6.8\,Gy$);

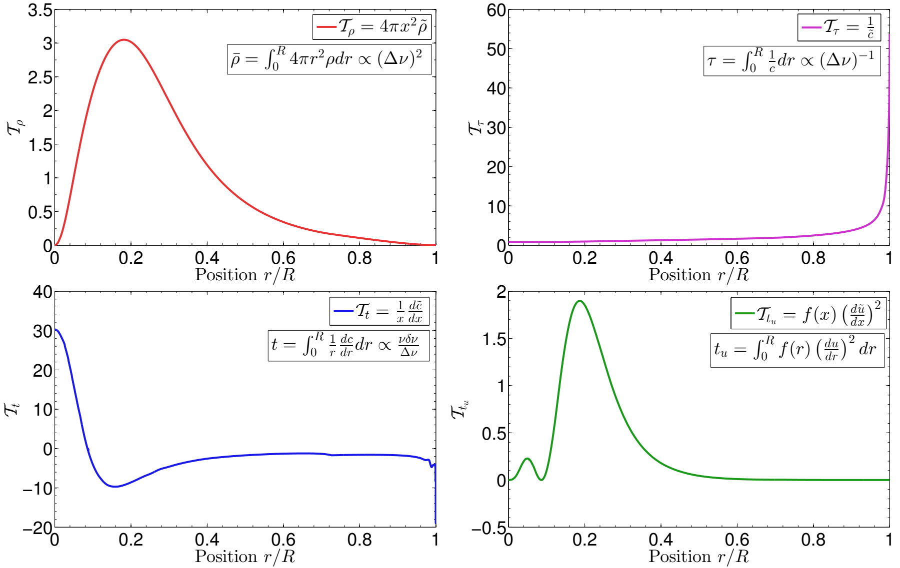
Using t_u :
The models reach values of $t_u = 3.01g^2/cm^6$ if one considers the **lowest metallicity with the higher helium content and diffusion.**

Appendices



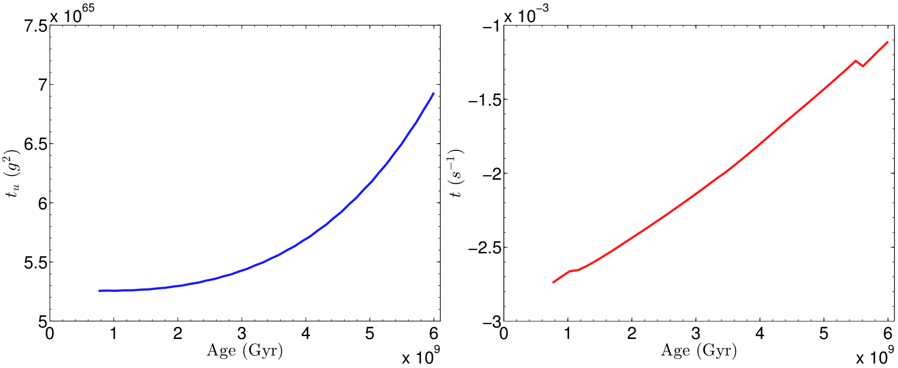
$K_{Avg,\tau}$
5
0
−5
0 0.2 0.4 0.6 0.8 1
Position r/R
$K_{Cross,\tau}$
0
−10
−20
0 0.2 0.4 0.6 0.8 1
Position r/R
$K_{Avg,\bar{\rho}}$
10
5
0
−5
−10
0 0.2 0.4 0.6 0.8 1
Position r/R
$K_{Cross,\bar{\rho}}$
40
20
0
0 0.2 0.4 0.6 0.8 1
Position r/R

APPENDICES



$\mathcal{T}_\rho = 4\pi x^2 \tilde{\rho}$
$\bar{\rho} = \int_0^R 4\pi r^2 \rho dr \propto (\Delta\nu)^2$
$\mathcal{T}_\rho$
Position r/R
$\mathcal{T}_\tau = \frac{1}{\tilde{c}}$
$\tau = \int_0^R \frac{1}{c} dr \propto (\Delta\nu)^{-1}$
$\mathcal{T}_\tau$
Position r/R
$\mathcal{T}_t = \frac{1}{x}\frac{d\tilde{c}}{dx}$
$t = \int_0^R \frac{1}{r}\frac{dc}{dr} dr \propto \frac{\nu\delta\nu}{\Delta\nu}$
$\mathcal{T}_t$
Position r/R
$\mathcal{T}_{t_u} = f(x)\left(\frac{d\tilde{u}}{dx}\right)^2$
$t_u = \int_0^R f(r)\left(\frac{du}{dr}\right)^2 dr$
$\mathcal{T}_{t_u}$
Position r/R

APPENDICES



x 10^65
7.5
7
6.5
6
5.5
5
$t_u\ (g^2)$
0
1
2
3
4
5
6
Age (Gyr)
x 10^9
x 10^−3
−1
−1.5
−2
−2.5
−3
$t\ (s^{-1})$
0
1
2
3
4
5
6
Age (Gyr)
x 10^9