Probing Convective Mixing in Stellar Interiors with α Centauri A and B

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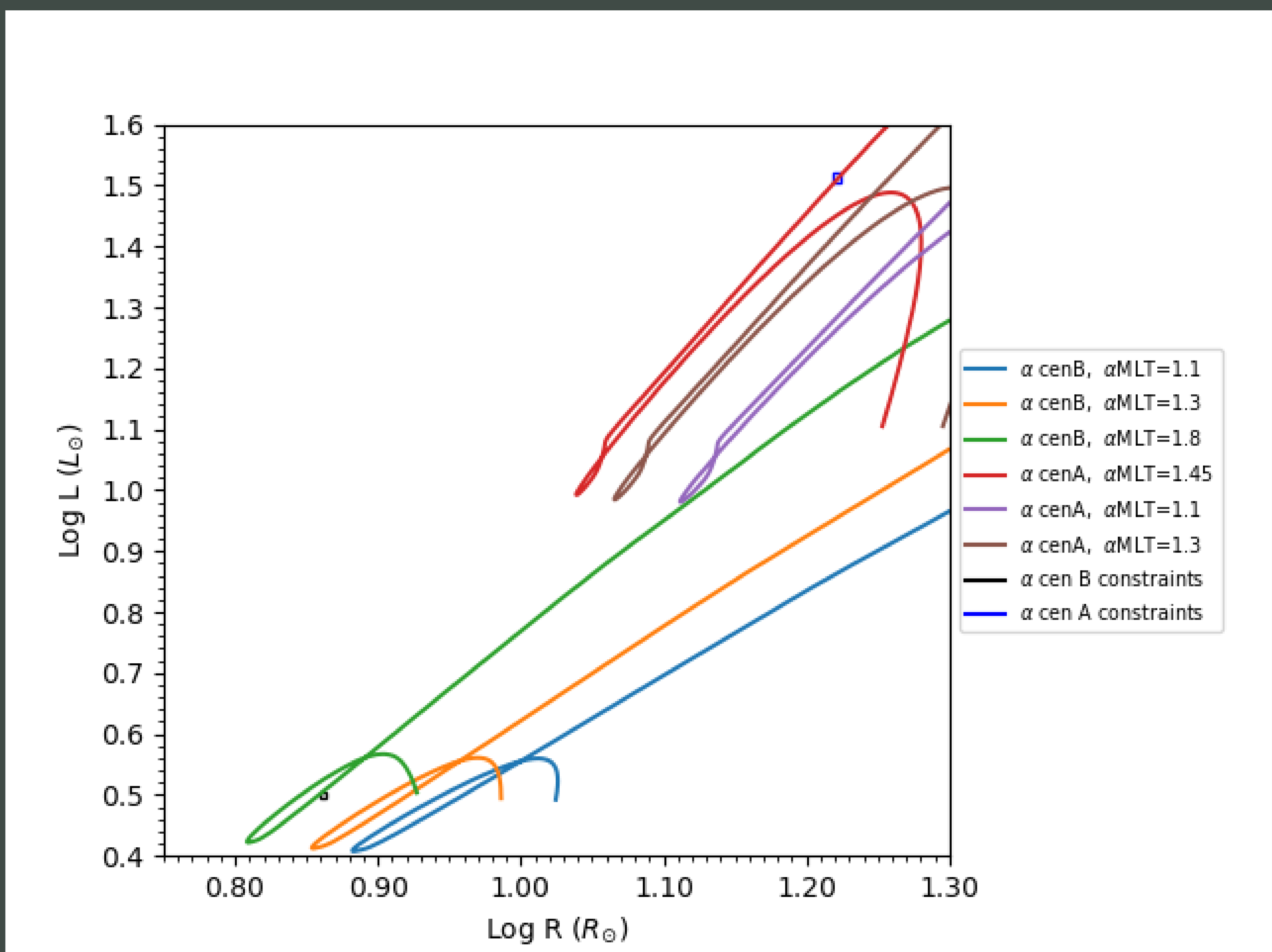
ABSTRACT

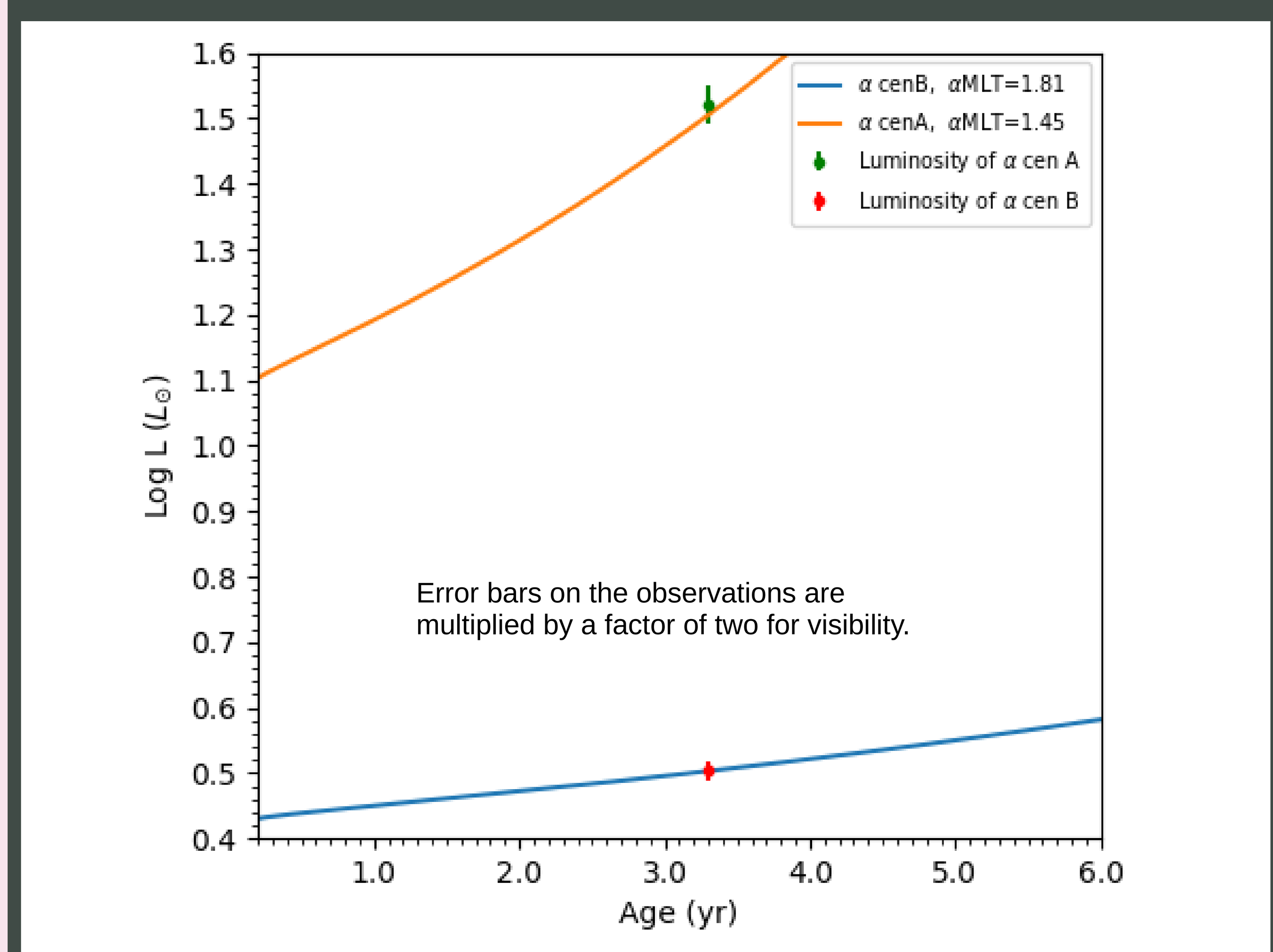
The bright, nearby binary Alpha Centauri provides an excellent laboratory for testing stellar evolution models. The mass, radius, and luminosity of Alpha Cen A and B are known to better than 1% accuracy thanks to recent interferometric and adaptive optical observations (Kervella et al., 2017), and p-mode oscillations have been observed in both stars. We present new stellar models which simultaneously fit the classical and seismic observations, with particular emphasis on the convective mixing length parameter $\alpha_{\rm MLT}$—the adaptivity of which is necessary to fit the models to observations. The oscillation data provide an important constraint on the models: the small frequency separation is sensitive to the composition gradient in the core of the stars, while the large frequency separation constrains the mean density of the stars, providing an independent check on the mass and radius.

SATISFYING OBSERVATIONAL CONSTRAINTS



All models shown were generated using the Dartmouth Stellar Evolution Program (DSEP) code (Dotter et al. 2008), using initial abundances of $X_{\rm in} = 0.025$, $Y_{\rm in} = 0.29$ for α cen A and $X_{\rm in} = 0.026$, $Y_{\rm in} = 0.28$ for α cen B. Mixing lengths $\alpha_{\rm MLT}$ are varied as shown. Boxed regions indicate observational constraints on radius and luminosity from Kervella et al. (2017).

FINDING A COMMON AGE



A matching pair $S_{p,A}$, $S_{p,B}$ satisfies the following criteria:

- consistency of both model stars' luminosity, radius, and mass within the error bars reported by [4]
- consistency between the surface abundances Z/X for both stars and with the value reported by [6]; this will necessarily require that $Z_{\rm in}$ and $Y_{\rm in}$ are similar
- the above conditions are met at a common age, but restricting to ages above 600 Myr to ensure we are extracting parameters at the relevant evolutionary phase

Importance of a Common Age

Because α cen A and B are members of the same system, models must satisfy their respective observational constraints at a common age. We run a series of grids, with increasing refinement, over a parameter space consisting of variations in initial metallicity and helium abundances (Z, Y, respectively), mass, and mixing length $\alpha_{\rm MLT}$. We search for distinct sets of input parameters $S_p = \{Z, Y, M, \alpha_{\rm MLT}\}$ for each star which produce a match at any common age.

Fits were found at a common age of 3.3 Gyr, as indicated to the left. This age is somewhat lower than what has been reported in previous work (see e.g. ~ 5 to 6 Gyr, Kim 1999).

MODEL GRID AND PARAMETERS

The input parameter spaces S_p are sampled at the following initial resolutions:

α Cen A mass: 1.10 or 1.11 ($M_\odot$)
α Cen B mass: 0.93 or 0.94 ($M_\odot$)
$\alpha_{\rm MLT}$: 1.3 to 2.0, $\delta_{\rm step} = 0.05$
$Z_{\rm in}$: 0.01 to 0.046, $\delta_{\rm step} = 0.005$
$Y_{\rm in}$: 0.25 to 0.045, $\delta_{\rm step} = 0.01$

From these data, we iteratively isolate local minima and increase resolution on those regions until a match within specified tolerances is found.

Table 1: Parameter sets S_p

Star	Mass $M_\odot$	$\alpha_{\rm MLT}$	Initial Z_{in}	Initial Y_{in}	Age (Gyr)	Surf Z/X
α Cen A	1.11	1.45	0.025	0.29	3.311	0.0347
α Cen B	0.93	1.8	0.026	0.28	3.236	0.0375
α Cen A	1.11	1.45	0.025	0.29	3.311	0.0347
α Cen B	0.93	1.805	0.026	0.28	3.260	0.0375
α Cen A	1.11	1.45	0.025	0.29	3.311	0.0347
α Cen B	0.93	1.81	0.026	0.28	3.294	0.0375

Parameter combinations S_p which fit all observational considerations as well as produce common ages between α Cen A & B.

NEED FOR ADAPTIVE MIXING LENGTH

We find that, in order to produce any viable solution, we must invoke sub-solar mixing lengths ($\alpha_\odot = 1.9258$) for both stars! This conclusion supports a growing body of evidence suggesting that the use of a solar-calibrated mixing length is insufficient for modeling stars with non-solar chemical compositions (Joyce & Chaboyer, 2017).

OBSERVATIONAL SYSTEM PARAMETERS

Table 2: Known System Parameters

	α Cen A	α Cen B	Reference
Mass $M_\odot$	1.1055 ± 0.004	0.9373 ± 0.003	Kervella et al. 2017
Radius $R_\odot$	1.2234 ± 0.0053	0.8632 ± 0.004	Kervella et al. 2017
Luminosity $L_\odot$	1.521 ± 0.015	0.503 ± 0.007	Kervella et al. 2017
Z/X	0.039 ± 0.006	0.039 ± 0.006	Thoul et al. 2003

Data Collection

Observations for α Cen B were collected in 2003 using the UVES spectrograph on the VLT at ESO, Chile, and using the UCLES spectrograph at the Anglo-Australian Telescope. At the VLT, 3379 spectra were obtained and at the AAT, 1642 were obtained [5]. Observations for α Cen A were likewise collected using UVES and UCLES over the course of 5 nights [1]. The luminosity of the system is inferred via direct observation. The mass is inferred from the binary solution, and the radius is inferred from interferometry. The surface abundance Z/X is obtained via high resolution spectroscopy.

ASTEROSEISMIC ANALYSIS

Integrating high-resolution evolutionary models from DSEP with the GYRE stellar oscillation code (Townsend & Teitler, 2013), we determine the resonant oscillation modes and frequency spacing for models of α Cen A and B generated using parameter sets $S_{p,A}$, $S_{p,B}$ (values listed in columns 2–5 of Table 1) at the uncovered common age of 3.3 Gyr.

GYRE can determine both the resonant acoustic/pressure modes, known as p modes, as well as those induced by internal gravity waves (g modes) of an evolutionary model. We are interested in p modes because pressure waves are sensitive to the outer convective envelope, and it is turbulence in this region which excites these modes.

From our models of the system, we extract parameters known as the large (eqn. 1) and small (eqn. 2) frequency spacings, defined as follows:

$$\Delta\nu_{n,l} = \nu_{n+1,l} - \nu_{n,l} \quad (1)$$

$$\delta\nu_{n,l} = \nu_{n,l} - \nu_{n-1,l+2} \quad (2)$$

where n refers to radial order, or the number of nodal surfaces in the radial direction. Parameter l refers to the harmonic degree, which, along with azimuthal order m, characterizes the behavior of the mode over the surface of the star. We validate against known solar values of $\Delta\nu_{n,l}$ and $\delta\nu_{n,l}$ by generating a solar model with DSEP and processing it with GYRE.

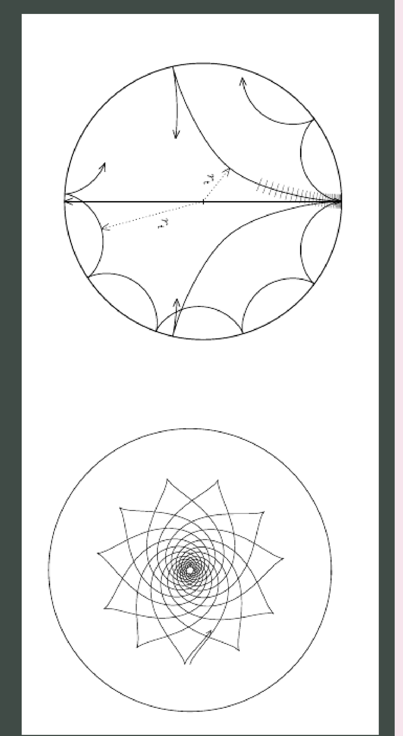


Diagram taken from Figure 2 of M. P. Di Mauro (2017)'s asteroseismology review [3]. Propogation of the p modes is shown above, g modes below.

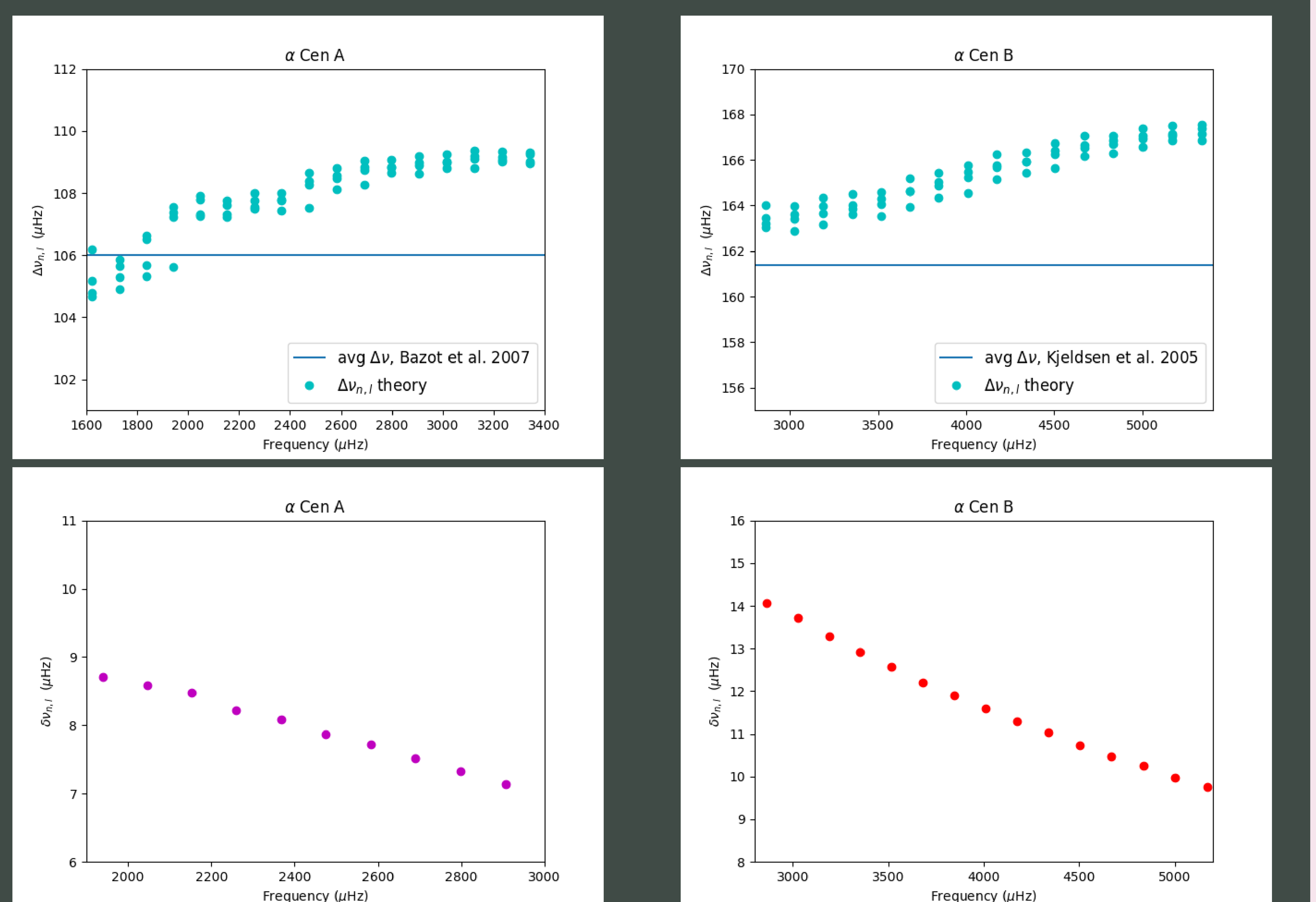
ASTEROSEISMIC PARAMETERS: LITERATURE vs. DSEP

Table 3: Frequency Spacing

Object	$\Delta\nu_{n,l}$ (DSEP)	$\delta\nu_{n,l}$ (DSEP)	$\Delta\nu_{n,l}$ (Lit)	$\delta\nu_{n,l}$ (Lit)	$\alpha_{\rm MLT}$ (DSEP)	Reference (Lit)
Sun	137	9	136	8	1.9258	Broomhall et al. 2009
α Cen A	108.4	8	106	7	1.45	Bazot et al. 2007
α Cen B	165.7	11.5	161.4	10	1.81	Kjeldsen et al. 2005

All frequencies given in μHz. Large frequency averages are computed for $l = 0, 1, 2$ and 3. Small frequency averages are presented for $l = 0$ only. DSEP models used to generate these data are the last pair listed in Table 1.

FREQUENCY SEPARATIONS



Large ($\Delta\nu_{n,l}$) and small ($\delta\nu_{n,l}$) frequency spacings as determined by DSEP and GYRE are shown for α Cen A and B over radial orders $n = 17 - 35$, a similar range used in the analyses of [1] and [5]. The emergence of multiple large frequency spacing values at a given frequency is caused by considering multiple mode numbers simultaneously, in this case $l = 0, 1, 2, 3$ and 4. These are averaged in computing the average $\Delta\nu_{n,l}$ values reported in Table 3. This preliminary work indicates the power of the seismic data to further constrain the physics used in the stellar models. We plan on examining other variations in the input physics (such as convective overshoot) in the future to determine if we can better fit these observations.

REFERENCES

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[1] M. Bazot et al. Asteroseismology of α Centauri A. Evidence of rotational splitting. *A&A*, 470:295–302, July 2007.
[2] A.-M. Broomhall et al. Corrections of Sun-as-a-star p-mode frequencies for effects of the solar cycle, August 2009.
[3] M. P. Di Mauro. A review on Asteroseismology. *ArXiv e-prints*, March 2017.
[4] P. Kervella, L. Bigot, A. Gallenne, and F. Thévenin. The radii and limb darkenings of α Centauri A and B Interferometric measurements with VLTI/PIONIER. *A&A*, 597:A137, January 2017.
[5]H. Kjeldsen et al. Solar-like Oscillations in α Centauri B. *ApJ*, 635:1281–1290, December 2005.
[6] A. Thoul et al. A new seismic analysis of Alpha Centauri. *A&A*, 402:293–297, April 2003.
[7] R. H. D. Townsend and S. A. Teitler.GYRE: an open-source stellar oscillation code based on a new Magnus Multiple Shooting scheme. *MNRAS*, 435:3406–3418, November 2013.
[8] M. Joyce and B. Chaboyer. Not All Stars are the Sun: Empirical Calibration of the Mixing Length for Metal-Poor Stars Using 1-D Stellar Evolution Models, 2017 *ApJ accepted with revisions*, September 2017