Asteroseismic Constraints on the Evolutionary Models of Hot Subdwarfs

Seismology of the Sun and the Distant Stars 2016

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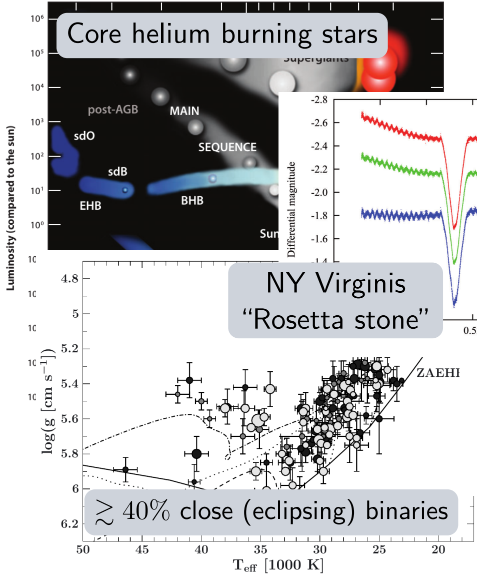
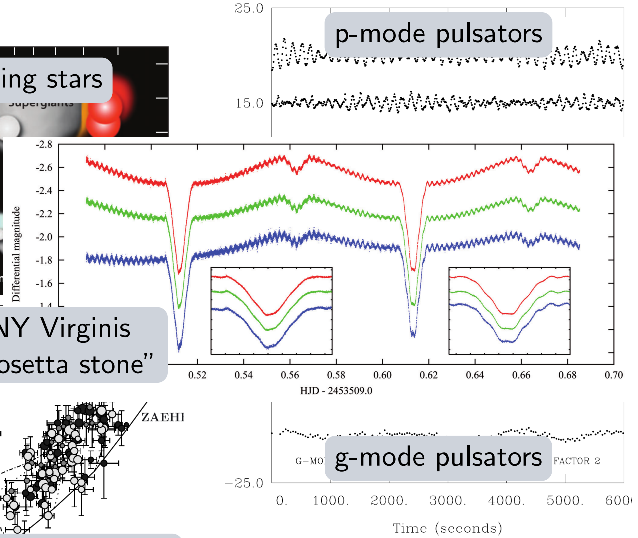
Hot Subdwarfs? Why Subdwarf B Stars?





(Heber (2009); Kupfer et al. (2015); Fontaine et al. (2003); Vučković et al. (2007))

Hot Subdwarf B stars - What do we know?

Spectroscopy

- $T_{\rm eff} = 20000\,{\rm K}{-}40000\,{\rm K}$
- $5.0 < \log(g/({\rm cm/s^2})) < 6.2$
- Helium deficient atmospheres
- Enhanced Fe-group abundances

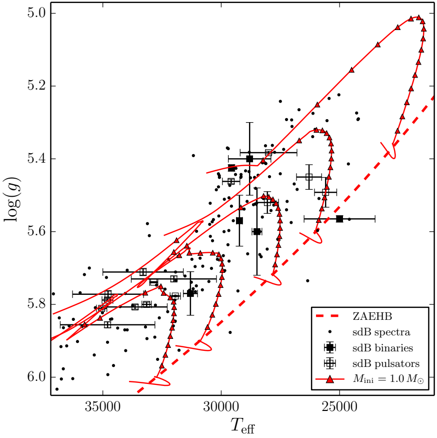
$\Rightarrow$ **Diffusion**

Eclipsing binaries

$\Rightarrow$ $M \approx 0.44{-}0.5 M_\odot$

Pulsations

- g-/p-mode pulsators
- **hybrid pulsators**



Schindler et al. (2015)

sdB stars

are hot, compact helium burning cores of red giants.

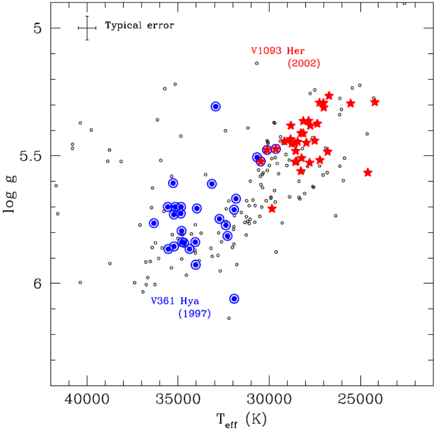
Hot B Subdwarfs - Pulsators

p-mode pulsators Kilkenny et al. (1997)

- $80 - 600\,\mathrm{s}$
- low degree l, low order k
- $\sim 10\%$ pulsating
- ~ 60 known pulsators

g-mode pulsators Green et al. (2003)

- $45 - 250\,\mathrm{min}$ or longer
- low degree l, $k \sim 1 - 65$
- $> 70\%$ pulsating
- ~ 50 known pulsators



Charpinet et al. (2013)

Hybrid pulsators Schuh et al. (2006)

- ~ 3 known pulsators

Hot B Subdwarfs - Pulsation driving mechanism

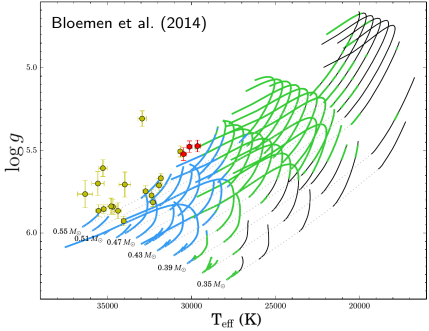
p-mode pulsations

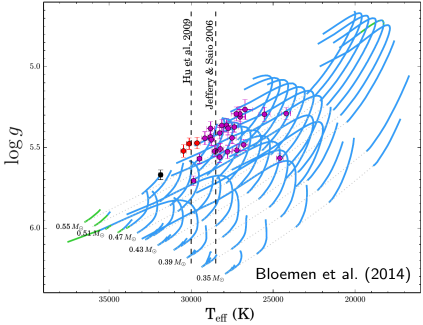
- Diffusion (radiative levitation)

⇒ Iron group opacity bump (mostly **Fe**)

⇒ κ-mechanism

Charpinet et al. (1996, 1997); Fontaine et al. (2003)





g-mode pulsations

- Diffusion (radiative levitation)

⇒ Iron group opacity bump (Fe+**Ni**)

⇒ κ-mechanism

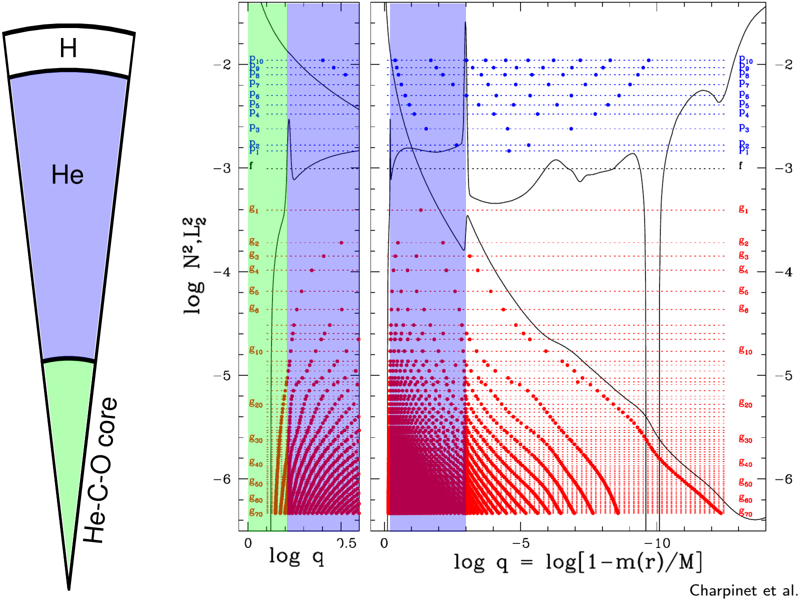
Jeffery & Saio (2006, 2007); Hu et al. (2009); Bloemen et al. (2014)

Conclusions

I

Subdwarf B stars offer a wide variety of observables which make them **excellent probes for asteroseismological analysis.**

Hot B Subdwarfs - Mode structure



Charpinet et al. (2013)

Hot B Subdwarfs - Quantitative Asteroseismology

Results using the Forward Modelling Method

The forward method delivers

- Surface parameters ($\log(g)$,T_{eff})
- ⇒ Test against Spectroscopy
- Radius and Mass estimates
- ⇒ Test against Binaries
- Rotation
- Structural Parameters ($\log(q[H])$,$X(C+O)$,...)

The Rosetta stone: NY Virginis

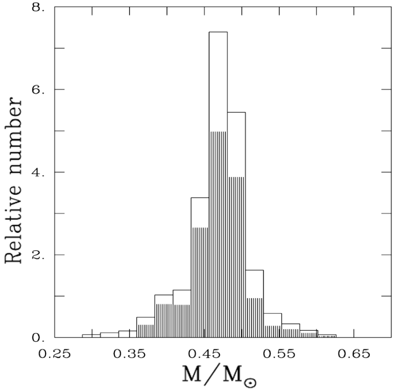
	$M/M_\odot$	$\log(g)$	$R/R_\odot$
OA1[1]	0.389	5.74	0.14
OA2[1]	0.466	5.77	0.15
2.Gen.[2]	0.459	5.739	0.151
3.Gen.[3]	0.471	5.814	0.141

[1]: Vučković et al. (2007),[2]: Charpinet et al. (2008),

[3]: Van Grootel et al. (2013)

Result: sdB mass distribution

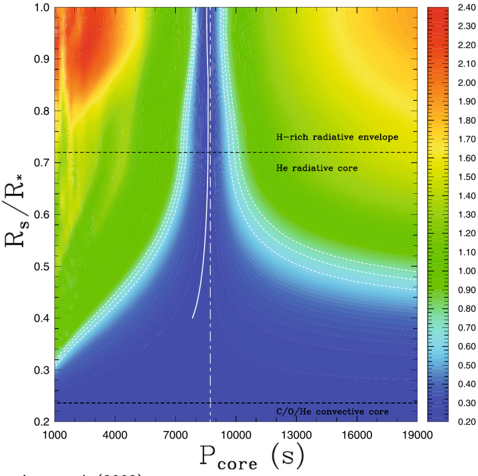
Mean mass of $M = 0.470\,M_\odot$



Fontaine et al. (2012)

Hot B subdwarfs - Quantitative Asteroseismology

Insights into Rotation



Charpinet et al. (2008)

sdB stars in binaries

- 2 synchronized
- 4 unsychronized

⇒ Constraining synchronization timescales

(Charpinet et al., 2008; Van Grootel et al., 2008; Pablo et al., 2011, 2012; Østensen et al., 2014)

Isolated sdB stars

- Periods: mostly $\gtrsim 30\,\mathrm{d}$
- Slow rotation
- Assuming secular evolution

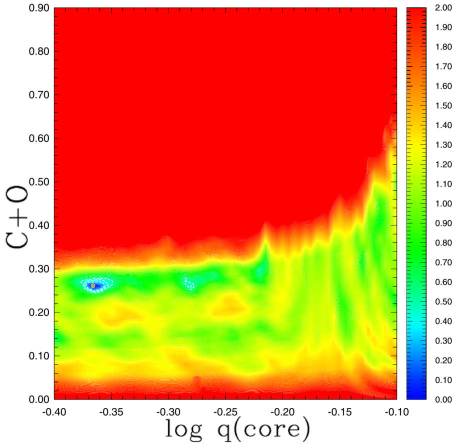
⇒ Connection to red giants

(Baran et al., 2009; Charpinet et al., 2011a; Baran, 2013; Foster et al., 2015)

Hot B Subdwarfs - Quantitative Asteroseismology

Insights into the deep interior - The convective core

Observed trapped g-modes are sensitive to COHe-core boundary



Van Grootel et al. (2010b)

Convective core sizes

- Van Grootel et al. (2010a)
  $M_{cc}/M_\odot = \mathbf{0.22 \pm 0.01}$
  KPD 0629-0016
- Van Grootel et al. (2010b)
  $M_{cc}/M_\odot = \mathbf{0.28 \pm 0.01}$
  KPD 1943+4058
- Charpinet et al. (2011b)
  $M_{cc}/M_\odot = \mathbf{0.274^{+0.008}_{-0.010}/0.225^{+0.011}_{-0.016}}$
  KIC 02697388

"Standard" stellar evolution

$$M_{cc}/M_\odot \approx \mathbf{0.10 - 0.15}$$

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I

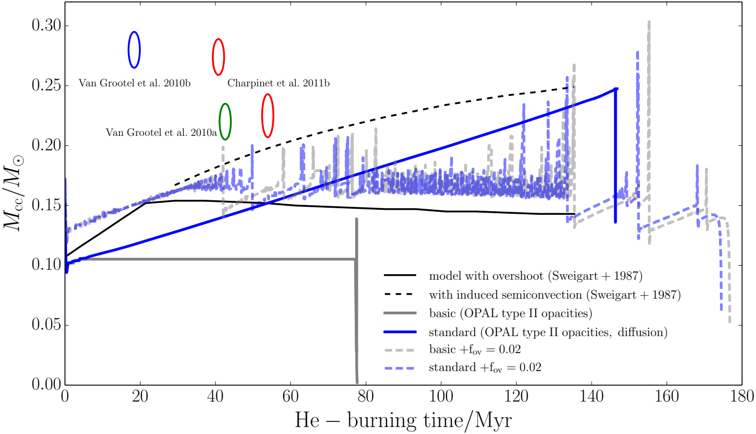
Subdwarf B stars offer a wide variety of observables which make them **excellent probes for asteroseismological analysis.**

II

Quantitative asteroseismological analysis of sdB stars provides an **exceptional view into the structure of core helium burning stars.**

Hot B Subdwarfs - Constraints on Convection

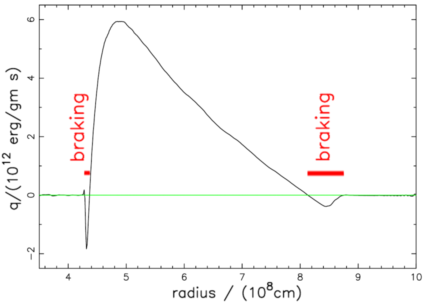
Stellar evolution vs. Asteroseismic analysis



Schindler et al. (2015)

Conventional convection algorithms seem **not** to be sufficient !

Convection - 3D to 1D (Arnett et al., 2015)



Advection

Nonlinear Sink term (Drag)

$$\frac{\partial}{\partial t}u + u \cdot \frac{\partial}{\partial x}u = \beta g \Delta \nabla - \frac{u^2}{l_d}$$

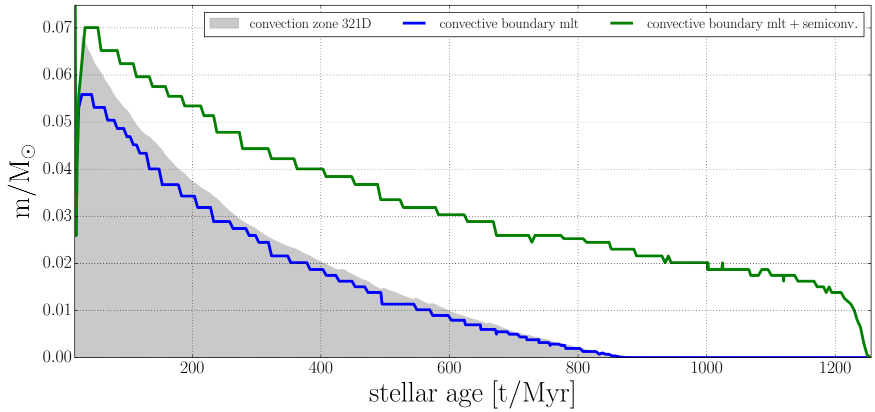
Source term (Buoyancy)

A first sanity check without advection (Preliminary!)

$$u = -\frac{l_d}{2\delta t} + \sqrt{\left(\frac{l_d}{2\delta t}\right) + \frac{u_0 l_d}{\delta t} + (g\beta l_d)^2 \,\delta\nabla}$$

Preliminary! MESA using 321D without advection

$1.5\,M_\odot$ star using the Ledoux criterion



Conclusions

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II

Quantitative asteroseismological analysis of sdB stars provides an **exceptional view into the structure of core helium burning stars.**

III

The results of asteroseismological analysis of sdB stars **challenge our understanding of the physics that shape the structure of stars**.

The road towards 321D

- Sanity test of 321D without advection against MLT (✓)
- We are working on including the advection term ⇒ Stay tuned!

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