A theorist looks at a new age for stellar physics

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summary

• precision photometry enables precision asteroseismology
• fundamental physics questions can find answers
• equation-of-state in extreme conditions
• end-to-end test of nuclear reaction rates and networks
• stellar physics phenomena can be probed
  • diffusion in stellar envelopes
  • radiative levitation (below the surface)
  • effects of tidal stresses on stellar interiors
  • backtracking evolution to the common envelope phase
• harmonious stars can upset the false harmony of our models

A brief ideosynchratic itinerary

• Basic stellar structure/physics and areas where improvement would help
• Examples of precision photometry to the rescue

asteroseismic

A brief ideosynchratic itinerary

• Basic stellar structure/physics and areas where improvement would help
• Examples of precision photometry to the rescue

• nonideal effects in equation of state - crystallization
• nuclear fusion cross sections
• ‘thermal’ neutrino emission
• radiative levitation and diffusion

• Beyond single spherical stars:
  Mechanisms of tidal synchronization

Pulsating stars in the HR diagram
stellar structure in a nutshell
• a “reminder” of basic stellar structure and evolution

Dependent / Independent variables
• Independent variable - a measure of position
  -or-
  • mass fraction within - \( M_r \)

the basic equations
• Continuity
  \[
  \frac{dM_r}{dr} = 4\pi r^2 \rho (r)
  \]
• HSE
  \[
  \frac{dP}{dM_r} = -\frac{GM_r}{4\pi r^2}
  \]
• Energy conservation
  \[
  \frac{dL_r}{dM_r} = -T\frac{dS}{dt}
  \]
• Energy transport
  \[
  \frac{dT}{dM_r} = \frac{GM_r}{4\pi r^2} \frac{T}{P}
  \]
• Equation of state
  - \( \rho (P, T, \mu) \)
  - \( \mu (P, T, X_i) \)
  - \( S (P, T, \mu) \)
• Energy generation
  - \( \varepsilon_{\text{nucl}} (P, T, X_i) \)
  - \( \varepsilon (P, T, X_i) \)
• Energy transport
  - \( \nabla_{\text{rad}} \rightarrow \kappa_{\text{rad}} (P, T, X_i) \)
  - \( \nabla_{\text{cond}} \rightarrow \kappa_{\text{cond}} (P, T, X_i) \)
  - \( \nabla_{\text{convective}} \rightarrow ??? \)

input physics questions
(that asteroseismology can address)
• Equation of State
  - non-ideal effects
  - Coulomb crystallization - pulsating cool, massive WDs
• Nuclear processes
  - difficult cross-sections - chemical profiles in WD interiors
  - neutrino emission - evolution rates in hot WD pulsators
• Radiative transport - opacities
  - Cepheid masses, driving, and the iron bump
  - sdB driving (with diffusion thrown in)
  - B star pulsations
• the convective flux
  - white dwarf driving and harmonics
  - solar-like oscillations

other issues (non-coefficient)
• time evolution of abundance
  • composition changes via nuclear burning
    - direct impact through \( dS/dt \) term
  • composition changes via chemical diffusion
    - diffusion coefficients via atomic physics
    - radiative levitation
  • composition changes via turbulence
    - instantaneous mixing via convection
    - convective overshoot
    - partial mixing via semiconvection, other processes
    - rotational mixing
• mass loss / accretion
• rotation
• magnetic fields
• tidal interaction and other effects of companions

Pulsating stars in the HR diagram
proximity effects - Coulomb interactions between ions
- Coulomb potential between two ions: $Z^2e^2/a$,
- Coulomb effects are expected to become important when $Z^2e^2/a \sim kT$. Thus form the ratio
  \[
  \Gamma_C = \frac{Z^2e^2}{\alpha kT} = 2.27 Z^2 \left( \frac{\rho}{10^9 \text{g cm}^{-3}} \right)^{1/3} \left( \frac{T}{10^7 \text{K}} \right)^{-1} \left( \frac{A}{12} \right)^{-1/3}
  \]
- when $\Gamma_C = 1$, effects begin to be felt
- solar interior: $\Gamma_C = 0.1$
- if $\Gamma_C >> 1$, effects are strong (mutual ion repulsion)
  - $\Gamma_C = 175$ : ion-ion forces can cause crystallization (first proposed by Salpeter 1961)
  \[
  T_{\text{final}} = 3.4 \times 10^6 Z^2 \left( \frac{A}{12} \right)^{-1/3} \left( \frac{\rho}{10^9 \text{g cm}^{-3}} \right)^{1/3} K
  \]
- white dwarf interior $\Gamma_C = 150$ to 250 or more

late stages: crystallization

crystalline white dwarfs?
- at sufficient pressure, fully ionized metals can lock into a crystalline lattice
- conditions realized within cores of massive white dwarfs while surface still warm
- nonradial pulsations can reveal the crystallization boundary

"Twinkle, twinkle, little star,
How I wonder what you are!
Up above the world so high,
Like a diamond in the sky!"

Jane Taylor (1783-1824)

Credit: Travis Metcalfe and Ruth Bazinet
Harvard-Smithsonian Center for Astrophysics
Montgomery & Winget 1999

period spacing vs. crystallization fraction

Dependence on $T_{\text{eff}}$

Montgomery & Winget 1999

BPM 37093: “the diamond star”

- 8 modes, unknown $l, n$
- period range 511 s to 636 s
- M,T spectroscopy constraints on models:
  - 12 available modes, $l=1,2$

Metcalfe et al. 2004, Kanaan et al. 2005

BPM 37093: “the diamond star”

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the basic equations

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  $$\frac{dM_r}{dr} = 4\pi r^2 \rho(r)$$
- HSE
  $$\frac{dP}{dM_r} = \frac{GM_r}{4\pi^2}$$
- Energy conservation
  $$\frac{dL_r}{dM_r} = -T \frac{\partial S}{\partial t} + \epsilon$$
- Energy transport
  $$\frac{dT}{dM_r} = -\nabla \frac{GM_r T}{4\pi^2 r^2}$$
- Equation of state
  - $\rho (P, T, \mu)$
  - $\mu (P, T, X_i)$
  - $S (P, T, \mu)$
- Energy generation
  - $\epsilon_{\text{nuc}} (P, T, X_i)$
  - $\epsilon \rho (P, T, X_i)$
- Energy transport
  - $\nabla_{\text{rad}} \rightarrow \kappa_{\text{rad}} (P, T, X_i)$
  - $\nabla_{\text{cond}} \rightarrow \kappa_{\text{cond}} (P, T, X_i)$
  - $\nabla_{\text{convective}} \rightarrow ???$
non-resonant reaction rates
- simplest general form
  \[ \langle \sigma v \rangle_0 = \frac{K_0 S(0)}{Z_i Z_j} T^{-2/3} e^{K_3 T^{-1/3}} \]
- \( S(0) \) is a quantity (related to the cross section at 0 energy) extrapolated from measurements at higher energy (why?)

\[ \begin{align*}
  v_{ij} &= K_0 S(0) Z_i Z_j T^{2/3} e^{K_3 T^{1/3}} \\
  T &= 15,000,000 \text{K} \\
  kT &= 1.3 \text{ keV}
\end{align*} \]

\[ T = 15,000,000 \text{K} \\
E(\text{Gamow}) = 25 \text{ keV} \]

from Everett Lipman

core helium burning
- \( ^3\text{He} \rightarrow ^{12}\text{C} \) (triple alpha)
- as temperature increases, see more \( ^{12}\text{C} + ^4\text{He} \rightarrow ^{16}\text{O} \)
- final \( ^{16}\text{O}/^{12}\text{C} \) depends on the reaction rate of \( \uparrow \)

\( ^{12}\text{C} + ^4\text{He} \rightarrow ^{16}\text{O} \) : rate poorly known

C/O WD core (Metcalfe et al. 2002)
post-helium burning core abundance profiles

DB pulsator fits - core C/O profile
(Metcalfe 2003)
- compositional stratification in two DB pulsators
- period spacings - composition transition zones
- periods - composition 'calibration' given external constraints on \( T_{\text{eff}} \) and \( \log g \)

From John Lattanzio's online stellar evolution tutorial

From Metcalfe 2003
DB pulsator fits - core C/O profile
(Metcalf 2003)

other issues (non-coefficient)
- time evolution of abundance
- composition changes via nuclear burning
  - direct impact through $dS/dt$ term
- composition changes via chemical diffusion
  - diffusion coefficients via atomic physics
  - radiative levitation
- composition changes via turbulence
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  - partial mixing via semiconvection, other processes
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- rotation
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- tidal interaction and other effects of companions

a DB pulsator in the Kepler field
Østensen et al. 2011
- a rare type of pulsator
- identified in the Kepler field
- Ground-based confirmation of pulsation
- Director's Discretionary Observations

a DB pulsator in the Kepler field
Østensen et al. 2011
- multiple triplets
- 3.3 µHz splitting
- rotation period of 1.75 days (?)

a DB pulsator in the Kepler field
Østensen et al. 2011
- asymptotic g-mode pulsator
- 36.3s period spacing
- $M \sim 0.56 \, M_{\odot}$

DB seismic modeling
Bischoff-Kim & Østensen 2011
- Best fit mass
- $0.570 \, M_{\odot}$
- Best fit $T_{\text{eff}}$
- 29,200K
- much hotter than spectroscopic value
DB seismic modeling

Best fit mass
• 0.570 M$_{\odot}$

C/O core size
• 0.36 M$_{\odot}$

Central O abund.
• 0.6 - 0.65

Bischoff-Kim & Østensen 2011

a DB pulsator in the Kepler field

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Energy Transport - radiative

As posed, it is contained in $\nabla$: $\frac{dT}{dM_r} = -\nabla \frac{GM_r}{4\pi r^2} \frac{T}{P}$

photons diffusion (‘radiative’ heat transport): $\nabla = \nabla_{\text{rad}}$

$\nabla_{\text{rad}} = \frac{L_r}{4\pi r^2 T^4} \frac{\kappa_r}{16\pi^4 \pi T^4} \frac{GM_r}{P}$

$\kappa_r$ - the radiative opacity:

- flux: $F_r = -\frac{4\pi}{3} \frac{1}{\rho c_r} \frac{dT}{dr}$
- integrate: $F_{\text{rad}} = \int_0^\infty F_r dv = -\frac{4\pi}{3} \frac{1}{\rho c_r} \int_0^\infty \frac{dT}{dr} dv$
- where $\frac{1}{\kappa_r} = \int_0^\infty \frac{dt}{\rho c_r} dv = \frac{acT^3}{\pi}$

so $F_r = \frac{4ac}{3\kappa_r} \frac{dT}{dr}$
about that $\kappa$V

- atomic processes
  - electron scattering (easy...)
  - free-free scattering
  - bound-free absorption
  - bound-bound absorption - the messiest of all
- molecular absorption - also messy!
  - H
  - CO, OH, H$_2$O, CH$_4$, ...

the kappa mechanism

$$W_{\text{rad}} = \int \frac{dT}{T} \left\{ \left( \frac{\ln \frac{T}{T_{\text{ref}}}}{\kappa_T} \right) + \frac{1}{3} \left( \frac{\ln \frac{T}{T_{\text{ref}}}}{\kappa_\rho} \right) \right\}$$

- if the integrand is $> 0$, then that region contributes to a positive value of $W_{\text{rad}}$ and therefore pulsation driving
- typical values for power law opacity:
  $\kappa_T \sim -3.5$ ; $\kappa_\rho \sim 1.0$ ; $\Gamma_3 \sim 5/3$ so $(\kappa_T/\kappa_\rho) \sim 0$
- Damping or driving when thermal response time of the layer is comparable to the pulsation period:

$$\tau_{\text{therm}} \equiv \int \frac{M_r c_v T \rho dm}{L} \approx P_{\text{puls}}$$

the kappa mechanism

- 'normal' situation
  - compression cycle:
    - $T, \rho$ increase, $\kappa$ decreases:
    - region becomes 'leakier' to radiation
    - Flux can increase, so energy is not 'bottled up'
  - $W_{\text{rad}} < 0$
- 'unstable' situation (partial ionization)
  - compression cycle:
    - $T, \rho$ increase
    - $\kappa$ does not decrease
    - (energy goes into ionization)
    - Flux 'bottled up'
  - can only release energy on 'downstroke' when $T$ falls
- GENERAL CONDITION - partial ionization

an example of pure kappa

Pulsating stars in the HR diagram
non-adiabatic pulsation:
driving, damping, and the convective flux

- Radiative energy transport - opacities and driving
  - Cepheid masses, driving, and the iron bump
  - (massive pulsators and the iron bump)
  - sdB driving (with diffusion thrown in)
- the convective flux
  - white dwarf driving and harmonics

sdB stars and standard models

instability regions

red/green = short period
purple = long-period

anatomy of an sdB evolutionary track

Diffusion in hot HB stars

- when sufficiently hot (i.e. thin-enough envelope)
- helium settles down through atmosphere
- radiation levitates metals
- abundance peculiarities appear for $T_{\text{eff}} > 11,000$K

gravitational settling of He

i.e. Unglaub & Bues 2001

H. Hu et al. 2010
gravitational settling of He

Driving Mechanism:
opacity effect with levitated Iron
(Charpinet et al. 1996-2002)

Charpinet, Fontaine, & Brassard 2009:
“nonadiabatic asteroseismology” of sdB stars

- kappa mechanism is robust in sdB stars
- predictive
- observed pulsations (given Teff, log g) require levitated iron
- use observed period ranges to place strong constraints on subsurface Fe (and on processes that would dilute the driving)

Charpinet et al. (2007)

other issues (non-coefficient)
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Testing tidal synchronization

- tight binaries = tides
- are spins of stars slowed / sped up by tidal interaction?
- pulsations measure the stellar rotation rate
A "reflection binary" - light from the hot star reflecting off of a dimmer companion: Stellar (not lunar) phases!

Testing tidal synchronization
- tight binaries = tides
- are spins of stars slowed / sped up by tidal interaction?
- pulsations measure the stellar rotation rate
Testing tidal synchronization

- tight binaries = tides
- are spins of stars slowed / sped up by tidal interaction?
- pulsations measure the stellar rotation rate
- B4 - no tidal synchronization
- Is this something 'normal'?

Two more examples

Pablo et al. (KASC WG11) 2012

G-mode asymptotics

KIC 11179657

Rotationally split multiplets:

\( P_{\text{rot}} = 9.63 \, \text{d}, \, P_{\text{orb}} = 0.40 \, \text{d} \)

\( \sim \Omega_{\text{rot}} \)

Rotationally split multiplets:

\( P_{\text{rot}} = 10.3 \, \text{d}, \, P_{\text{orb}} = 0.44 \, \text{d} \)

\( \sim \Omega_{\text{rot}} \)
tidal synchronization... or not?

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</table>

- internal rotation profile may be accessible
- slow rotation of sdBs seems to be the rule - constraint on RGB angular momentum evolution?

synch mechanisms

- J.-P. Zahn: tidal theory (1975)
  - tidal forcing drives evanescent waves
  - 'friction' of waves transports angular momentum from spin to orbit
  - spin down/up time:
    \[
    \frac{1}{t_{\text{syn}}} = 3(2)^{\frac{1}{3}} \left( \frac{R_s}{R} \right) \left( \frac{M R^2}{I} \right) q^2 (1 + q)^{\frac{1}{2}} \left( \frac{B}{|\dot{B}|} \right)^{\frac{1}{2}}
    \]
  - more usefully, $t_{\text{syn}} \sim P^{0.5}$
  - meridional circulation transport of angular momentum
  - spin down/up time: $t_{\text{syn}} \sim P^4$
- for sdB binaries, Tassoul much faster than Zahn

slow rotation of sdBs

- non-synchronous sdB pulsators in binaries
  - rotation period of 7-20+ days
- 'single' sdB pulsators
  - rotation periods from 20 to 40+ days
- suggests that sdB formation channels (single/binary) produce sdB stars that rotate at the same rate
- possible constraint on Common Envelope ejection process?
- what about differential spin-up?
summary

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