Advanced astrophysics notes

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1 Introduction

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1.1 Topics

They are selected topics in stellar physics.

1. Stellar pulsations and Astroseismiology (dr. Michele Trabucchi);
2. stellar winds (dr. Paola Marigo);
3. final fates of massive & very massive stars (dr. Paola Marigo).

Basics in Stellar Physics: "astrophysics II" inside the bachelor's degree in astronomy (second semester). It can be taken as an optional course.

Material:

1. *Introduction to stellar winds* by Lamers, Cassinelli.
2. *Stellar Atmospheres: Theory and observations* (lecture notes from 1996).

and more on Paola Marigo's site.

1.1.1 Stellar Winds

Moving flows of materials ejected by stars. 20 to 2×10^3 km/s.

See *Bubble Nebula* in Cassiopea, there is a $45M_\odot$ star ejecting stellar wind at 1700 km/s.

Diagram: luminosity vs effective temperature. We see the *main sequence*. We can also plot the *mass loss rate*, $\dot{M} > 0$ in solar masses/year. An other important parameter is v_∞.

Diagram: mass loss (or gain) rate vs age of star.

Stellar winds affect stellar evolution, the dynamics of the interstellar medium, the chemical evolution of galaxies.

Momentum is approximately injected with $\dot{M}v$, kinetic energy with $\frac{[}{i}]12\dot{M}v^2$. Within 1×10^8 yr around half of the infalling matter is reemitted.

1.1.2 Contents

We will start with the basic theory of stellar winds, and then: *coronal*, *line-driven* and *dust-driven* winds.

1.2 Final fates of massive & very massive stars

Masses over $10 M_\odot$.

1.3 Stellar oscillations

…see slides.

Material: slides on moodle or Marigo's page.

1. *Pulsating stars* by Catelan & Smith (introductory);
2. *Theory of stellar pulsation* by Cox (harder).

Written exam, partial exam on stellar pulsation.

2 Variability in Astronomy

First observations of variable stars: $\sim$ 1600, omicron-Ceti. It changes in magnitude by 6 orders of magnitude.

Others are found from the 1600 onwards, but since the XX century the reason is unknown. Is it *rotation*, *eclipses*?

For some it sure are eclipses, but the Cepheids are different. See δ-Cephei, asymmetric continuous curve. What if stars *pulsate*?

The *light curve* is the luminosity curve over time.

We can also look at the *phased* light curve. Of course we need the period: the phase is

$$\varphi = \frac{(t - t_0) \bmod \Pi}{\Pi} \tag{1}$$

where Π is the period. $E(t) = \lfloor (t - t_0)/\Pi \rfloor$ is the epoch.

We can then measure the period, but if the light curve is multiperiodic we can subtract the model from the curve to see if there are additional periods: this is *prewhitening*.

We can also look at the luminosity in Fourier space.

Of course there are issues with observational gaps (day-night, full moon): aliases; accuracy, duration of observations…

Also, the period can change in time.

Things have improved a great deal with large-scale surveys and space suveys.

2.1 Classification

By variability type: regular, semi-regular or irregular.

By intrinsic variability: extrinsic, external to the star: eclipses, transits, microlensing, rotation; intrinsic: rotation, eclipses (self-occultation), eruptive and explosive variables, oscillations, secular variations (?).

Whether rotation is to be considered intrinsic or extrinsic is a matter of taste.

Oscillations can be classified by several criteria.

The geometry can be radial (classical pulsators) or non-radial.

The restoring force can be the pressure gradient or the gravitational force (bouyancy, not gravitational waves).

The excitation mechanism can be ***.

The evolutionary phase and mass of the star can also be different.

3 Summary of stellar structure & evolution

Eulerian: properties of a gas are fields, the position is the position of an observer. To differentiate position with respect to time is meaningless: position is an independent variable. $f = f(r^i, t)$.

Lagrangian: we follow an element of fluid: $\mathrm{d}r^i \big/ \mathrm{d}t = v^i$. We can identify univocally these fluid elements.

When treating stellar structure & evolution, we look at mass layers $\mathrm{d}m$. $f = f(m, t)$.

In the lagrangian case, we use the convective derivative $\mathrm{d} \big/ \mathrm{d}t = \partial_t + v^i \partial_i$ where v^i is the velocity defined before.

3.1 Equations of stellar structure

In the spherically symmetric case.

Continuity equation:

$$\frac{\partial r}{\partial m} = \frac{1}{4\pi r^2 \rho} \tag{2}$$

Momentum conservation:

$$\frac{\mathrm{d}P}{\mathrm{d}m} = -\frac{Gm}{4\pi r^4} \tag{3}$$

Energy conservation:

$$\frac{\mathrm{d}L}{\mathrm{d}m} = \varepsilon - \varepsilon_\nu - \varepsilon_g \tag{4}$$

where ε is the rate of nuclear enery generation per unit mass, while ε_ν is the rate of energy loss due to neutrino emission per unit mass, and ε_g is the work done by the gas per unit mass & time.

Energy transfer equation:

$$\frac{\partial T}{\partial m} = -\frac{GmT}{4\pi r^4 P}\nabla \tag{5}$$

where $\nabla = \partial \log T / \partial \log P$ is the temperature gradient, which has contributions from radiation, conduction, convection...

With the diffusion approximation,

$$\nabla = \nabla_{\mathrm{rad}} = \frac{3}{16\pi acG}\frac{\kappa_R LP}{mT^4} \tag{6}$$

where κ_R is the Rosseland mean opacity, given by

$$\frac{1}{\kappa_R} = \frac{\displaystyle\int_0^\infty \frac{\mathrm{d}B_\nu}{\mathrm{d}T}\frac{1}{\kappa_\nu}\,\mathrm{d}\nu}{\displaystyle\int_0^\infty \frac{\mathrm{d}B_\nu}{\mathrm{d}T}\,\mathrm{d}\nu} \tag{7}$$

and

$$L = -\frac{64\pi^2 ac}{3}r^4\frac{T^3}{\kappa}\frac{\partial T}{\partial m} \tag{8}$$

where κ is a generalized opacity.

If we need to deal with convection, this defies any simple modeling. There are instability criteria: where is it relevant? This is given by Ledoux's crterion,

$$\nabla_{\mathrm{rad}} > \nabla_{\mathrm{ad}} - \frac{\chi_\mu}{\chi_T}\nabla_\mu \tag{9}$$

where ∇_μ is the log gradient... (***)

In the convective core, $\nabla \approx \nabla_{\mathrm{ad}}$, but outside of it we need something else.

Mixed-length theory model convection with "bubbles":