Astroseismology: The Key to Probe the Stellar Interiors.

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November 8, 2008

Outline

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- Stars which undergo light variation are called **pulsating** or **variable** stars.
- Reasons to study stellar pulsations: why, and how do stars pulsate.
- The goal is: to understand general properties of stars, microphysics(nuclear reaction rates, neutrinos, etc), macrophysics(convection, radiation fields, stellar winds, etc).

Example

Here is a simple Example:
Harlow Shapley 1914, showed that for a **radial** expansion and contraction of a star the period is approximately given by the dynamical time scale of the star:

$$t_{dyn} \sim \left(\frac{R^3}{GM}\right)^{1/2} \sim (G\bar{\rho})^{-1/2}. \quad (1)$$

$\Longrightarrow$ if you would measure the period of oscillation of a star, you will have an estimate of its mean density $\bar{\rho}$, and it is a great result.
$\Longrightarrow$ observing one mode, returns one piece of information.
What if we had a star with two observable modes. In principle, we expect to understand more details on its structure (like R and M of the previous example) [2].

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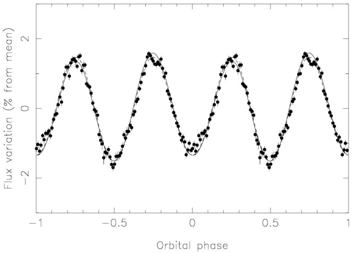

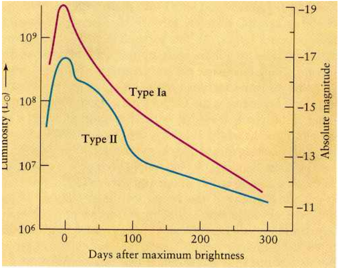

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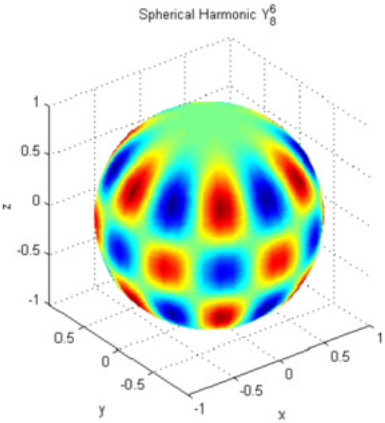
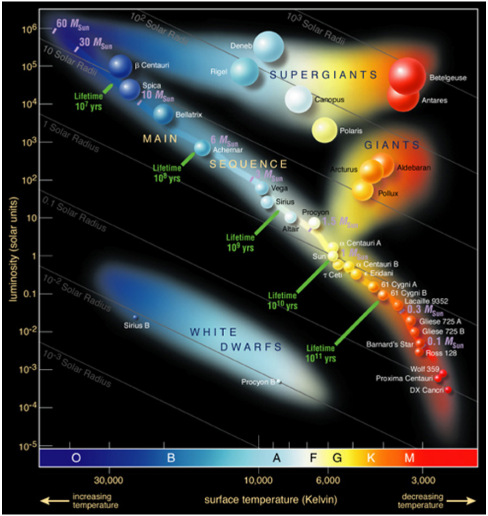
- Nova and Supernova explosions,

Variability in Doppler Line

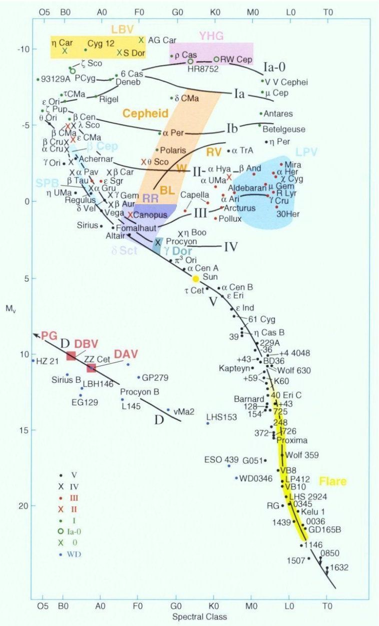
•If stars are observed spectroscopically, then the periodic variation of surface of stars will have a view similar to this. Here, spherical harmonics $Y_\ell^m(\Omega)$ are employed to show regions of receeding/exceeding matter in blue/red.
•Note that, this image shows only a single mode with a characteristic oscillation period.
•The Sun oscillates in superposition of hundreds of modes similar to this. The dominant oscillation periods is of the order of 5 minutes.



Pulsators on the HR diagram



The location of a star on this diagram depends on its mass and luminosity, and it best describes the **evolutionary status** of any star.



General Classes of Pulsators on the HR diagram is listed below. Note that many subclasses also exist that are not mentioned here:

- Solar-like pulsators,
- δ-Scuti stars,
- γ-Dor,
- RR-Lyrae,
- Cepheids,
- **S**lowly **P**pulsating **B** stars,
- Irregulars,
- Mira and red giants,
- β-Cep,
- ZZ-Ceti, DOV, DBV, DAV.

Our Target Star: α Hercules

We aim at IASBS to study this star through seismic techniques. The most uptodated features of this star are listed below.

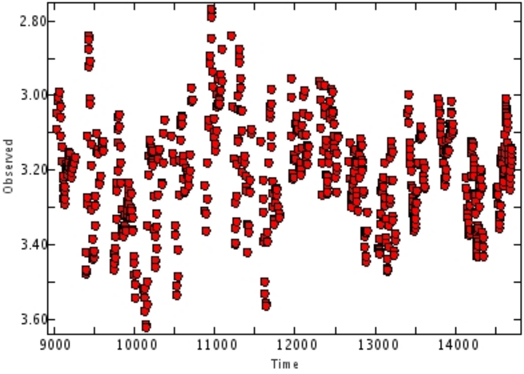
- Catalogue Name: α-Her, 64 Her, HD 156014,
- Apparent Visual Magnitude: [2.8,3.6],
- Variability type: Semiregular (???),
- Spectral type: M5Ib-II $\longrightarrow$ bright red giant,
- Mass $\sim 14M_\odot$,
- Radius $\sim 400R_\odot \sim 1.9$ AU,
- $B - V \sim 1.44$
- Distance$\sim$ 380 ly = 120 parsec,

Other features:
Evolved, massive star, showing complicated semi-regular light variations. Circumstellar envelope extending > 90 AU. Bright member of a triple star system with G5III+F2V components.

Outline

Observations

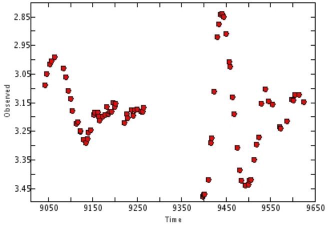
The data is supplied from Dr. E. F. Guinan from Villanova University, and were collected by R. Wasatonic using a 25cm telescope. They span for 15 years (1993-2008), and constitute 681 data points observed in V-band.

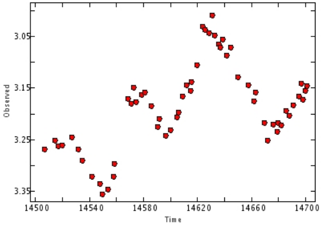


The abscissa is the Julian date -2440000, and the ordinate is the apparent visual magnitude. Note that the data are not collected evenly in time, and there exist gaps of random size in the data. The gap size varies from a minimum of one day to a maximum of 170 days. The presence of gaps give rise to **aliasing**, i.e., extra peaks in the power spectrum.

Observations

The Light curve as seen here seems to be complicated, and evidently, more than one mode must be present simultaneously in the star. These two figures show the first and the last set of data.





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•Their structure is dominated by **convection**,
•Their study helps understanding convection better.
•The Radius of such stars is not well defined, and varies in different bands. It is largest in the V-band (TiO), and smallest in the Ir-band. The amplitude of variations is also more pronounced in V-band.

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- More than %50 of PRGs have long secondary periods (typically ten times the primary period). The reason is yet undiscovered.

Classifying Giants and SuperGiants

As seen in the table, there are many uncertainties in properties of Giants.

Type	Class	$M/M_{\odot}$	Amplitude	Period (d)	Periodicity
Giants:	Mira	1-3	$>$2.5 mag	80-1000	well-pronounced
Giants:	SRa	1-3	$<$2.5 mag	$>$35	persistent
Giants:	SRb	1-3	$<$2.5 mag	$>$20	poorly expressed
Giants:	Lb	1-3	?	long	Irregular
SuperGiants:	SRc	5-20	?	long	Semi-regular
SuperGiants:	Lc	5-20	?	long	Irregular

Study of PRGs in the Local Group: Multiperiodicity

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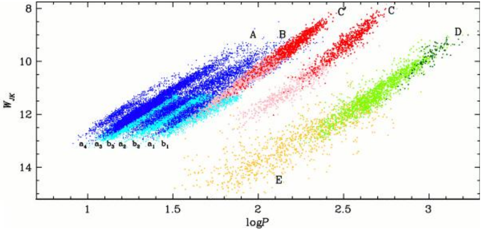

P-L diagram for: AGB stars (red), and Red Giant stars (blue).
Note: Existence of a secondary long periods (orange and green).
B&C: Fundamental, A&C': First overtone, D&E: Long secondary periods, a&b: Fundamental and overtones.

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Red Supergiants: SRc variables

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7. Ideally, they are semi-regular, but characteristic time scales of 250-1000 days exist,
8. Semi-theoretical P-L relation (LMC and SMC):

$$M_{\rm bol} = -8.6 \log P + 16.4 \qquad (2)$$

Variability and Characters

What is the origin of the short and long-period variations?

•Initially, people thought that's the effect of rotation, and the fact that the bright and dark convetion cells in its outer layers are few and large.

•Recently, it is suggested that they are fundamental, and first overtone pulsations, though their ratio is too large.

•The challenge in their understanding is the long time scales involved (decades of monitoring required), and their light curve irregularity.

SRc variables are:

Spectral Type	Temperature	M_V	M_{bol}	Initial Mass	Final Mass
M1-M4	3000-3500K	-5 to -7	-7 to -9	15-30 $M_\odot$	5-20 $M_\odot$

Mass Loss

•The **mass loss** is very intense in SRc stars. Radiation pressure is in charge of this mechanism. Actually, this is a very wise decision, to moderate the catastrophe of their fate.
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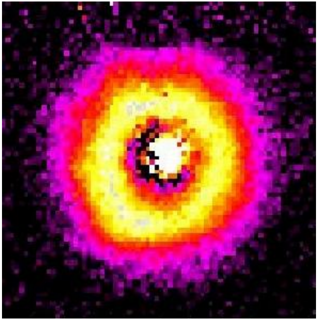

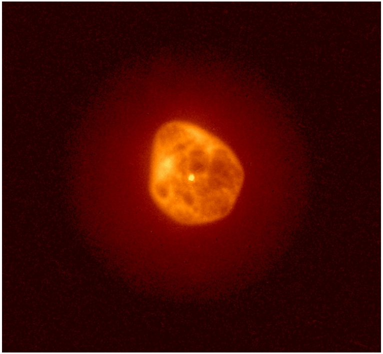

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DFT

•For any function of time $f(t)$ which is the observed magnitude of the variable star in this case, the Fourier transform is performed over the observation time $[0, T]$. The power spectrum $P(\omega)$ is then defined to be:

$$f(\omega) = \int_0^T dt\ f(t)e^{i\omega t}, \qquad \Longrightarrow P(\omega) = |f(\omega)|^2. \tag{3}$$

•Now, to simulate the observation of a **double-mode** star with sinusoidal time variations, I write the amplitude as a superposition of two (or more) simple harmonic oscillators. But most astronomical data strings have gaps, so I have inserted two random and regular gaps, with a moderate degree of white noise. The synthetic data string is plotted here.

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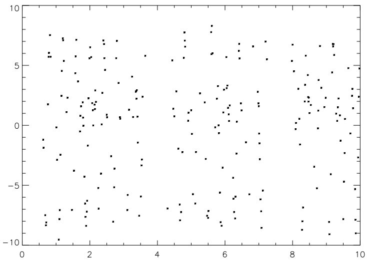

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•Note that the amplitude is the square root of the power.

•I have tested this routine for many different number of modes present, and in all cases, the results were reasonable, except the power level of a mode with an amplitlude comparable to that of the noise, in which case the noise sheds a shadow on that mode.

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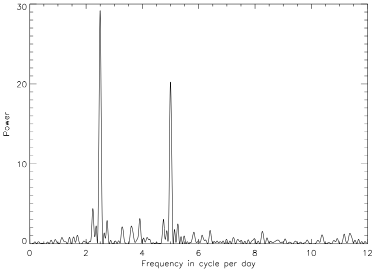

Power Spectrum for Solar Oscillations

•As we know, the Sun oscillates dominantly in pressure modes with 5-min period. If the whole disk of the sun is observed spectroscopically, then the absorption lines vary in time, and the sun shows this rich spectrum of modes.
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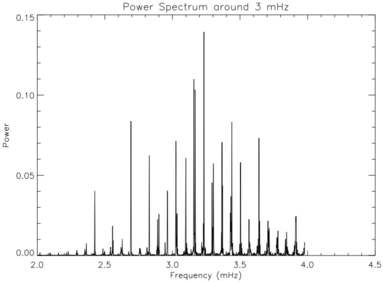

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CLEAN Spectrum

A very efficient routine is the CLEAN. For those power spectrum that more than one mode are present, CLEAN computes the period and amplitude of each mode very reasonably. The algorithm is simple:

1. Perfrom a DFT of the data string, and find the frequency and amplitude of the dominant mode. This is the first mode of oscillation ω_1.
2. Subtract this dominant mode from the whole data set, and call it Residual(I).

$$\text{Redisual}_1 = m_v(t) - a_1 \sin(\omega_1 t),$$

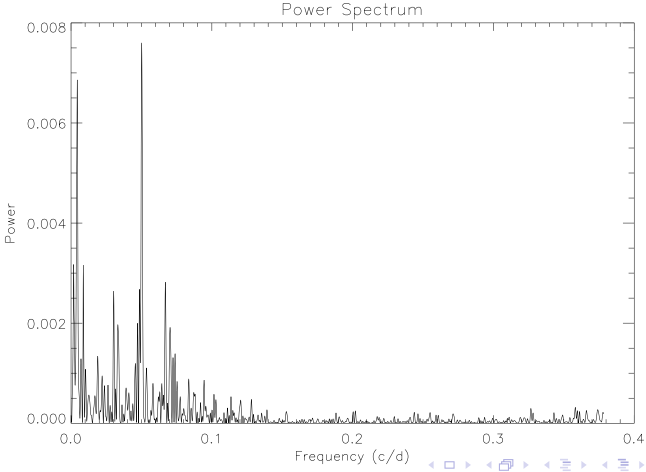
3. Perform a DFT on this residuals and find the dominant mode of the residuals, this is the second mode of oscillation ω_2.
4. subtract the ω_2 mode from Residual(I), and call it Residual(II).

$$\text{Redisual}_2 = \text{Residual}_1 - a_2 \sin(\omega_2 t),$$

5. Go on, until the power spectrum shows no primary peak, or say, it is **clean**.

CLEAN Spectrum for α Hercules

I have performed the CLEAN algorithm to α-Her data, and the result is plotted.



CLEAN Spectrum for α Hercules

mode	Frequency (c/d)	Period (d)	Amplitude
τ_1	.0080	125.29	0.0873
τ_2	.0007	1411.95	0.0821
τ_3	.0003	3490.66	0.0641
τ_4	.0112	89.50	0.0435
τ_5	.0014	722.21	0.0440
τ_6	.0054	185.07	0.0389
τ_7	.0075	133.40	0.0321
τ_8	.0078	127.58	0.0287
τ_9	.0058	173.33	0.0293
τ_{10}	.0106	94.20	0.0293

As we expected from an SRc supergiant:

•The star is multiperiodic, and both short-period and long-period modes are present.

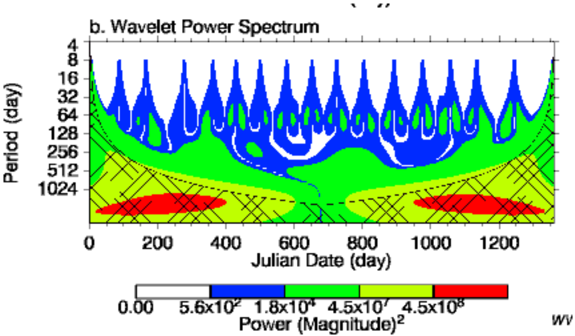
•The long periods or one order of magnitude longer than the primary mode (τ_2, τ_3, τ_5).

•Seven modes are close in frequency:(τ_1, τ_7, τ_8), (τ_4, τ_{10}), (τ_6, τ_9). It is not expected that they are excited and present simultaneously. **Probably**, each of them were active for some limited duration of time, and then has faded away. At some later time, a mode similar to that in frequency is excited once again.

Outline

'Preliminary' Wavelet Analysis

The **gassian** wavelet is employed here. Contour plots represent the power of each mode. A growing and decaying $\sim$ 1024-day mode seems to dominate the power spectrum (τ_2, τ_5), while the 125-day mode seems to vary in strength ($\tau_1, \tau_4, \tau_7, \tau_8, \tau_{10}$). Therefore, α Hercules switches between modes during the time. This is the origin of an **intermediate degree of chaos** in the light curve of SRc stars [3], [4]. In this way, the evolution of such stars can be traced out *live*.



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   - p-mode?
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3. Why are the two dominant modes transient?
4. What is the origin of long term variations?
5. A full seismic test to reveal the details of the structure of this star, such as
   - the internal rotation profile $\Omega(r)$,
   - sound speed profile $c(r)$,
   - stratification in chemical elements $\nabla\mu(r)$,
   - the extent of the convection layer.

   As a result, the mass M and radius R are found with an improved accuracy.

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Thanks for you attention.