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LA-UR -83-784

CONF-830337--1

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LA-UR--83-784

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TITLE: MYTHICAL MAIA, ULTRASHORT AND 53 PSC VARIABLES, Lecture 4

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SUBMITTED TO: Swiss Society of Astrophysics and Astronomy
Saas Fee, Switzerland, March 21-26, 1983

March 14, 1983

Los Alamos

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FORM NO. 836 R4
ST. NO. 2629 5/81

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MYTHICAL MAIA, ULTRASHORT AND 53 PSC VARIABLES

Moving down the main sequence from the β Cephei variables, we come to later B-type stars. The suspicion of variability for these stars goes back to Vogel in 1891 who studied the radial velocities of Vega. Since that time there have been numerous studies of Vega (Wisniewski and Johnson 1979, Fernie 1981) and other B and early A stars which hint at variability in both radial velocity and light. Since Struve (1955) discussed these stars 28 years ago, they have been called the Maia stars after the Pleiades star that he thought was the prototype. The uncertainty in their actual variability has led Breger (1980) to call them the mythical Maia variables.

The complete list of these stars is given in Table 1, ordered in decreasing luminosity which probably would be the decreasing order of their periods if they all are seen in the same pulsation mode. The Pleiades rotation velocities come from Anderson, Stoeckly, and Kraft (1966). Luminosities come from the Crawford (1978) c_0, β photometry for the Pleiades and Vega. Bolometric corrections to the Crawford absolute visual magnitudes are obtained from the Code et al. (1976) calibration. The Crawford c_0 values are converted for these four stars to T_e using the Sterken and Jerzykeiwicz formula given in the first lecture. The γ Gem data come directly from Code et al.

TABLE 1
MAIA VARIABLES

Star Name	Spectral Type	Period	vsini	Velocity Amplitude	$\log(L/L_\odot)$	$\log T_e$
η Ori Ab	B1	.2	·160			
Alcyone	B7III	.27	220	20	3.28	4 091
Maia	B7III	.10	40	51	3.02	4.128
Taygeta	B6V	.27	135	18	2.87	4.148
γ Gem	A0IV	.13			2.01	3.967
Vega	A0V	.19		8	1.78	3.985
O Vir A	A1V	.15	·40			
γ UMi	A3II-III	0.10				

Variability of these stars has been championed by Beardsley and his collaborators. Periods in the table except that for γ UMi all come from Beardsley, Worek, and King (1980) and from Beardsley and Zizka (1980).

The γ UMi period comes from Struve (1955). Joshi, Gurti and Joshi think it is a δ Sct star at 0.14 day.

Figure 1 displays perhaps the best case of radial velocity variations, that for Maia, from data published by Henroteau (1921). The presumed orbital motion is shown by the mean amplitude changing over a eight-month period. The scatter in this data, and the even larger scatter in the data for the other Maia stars, leads one to suspect that these variations are not real.

Percy (1978) observed 20 stars some of which are in our window of spectral class B6 to A3. Those of even later spectral type, and perhaps even γ UMi, fall into the region of the δ Scuti variables which will be discussed in a later lecture. His 12 possible Maia variable candidates, including Maia and Taygeta, showed no variations in light generally greater than 0.01 magnitude. However, if one looks at the details of

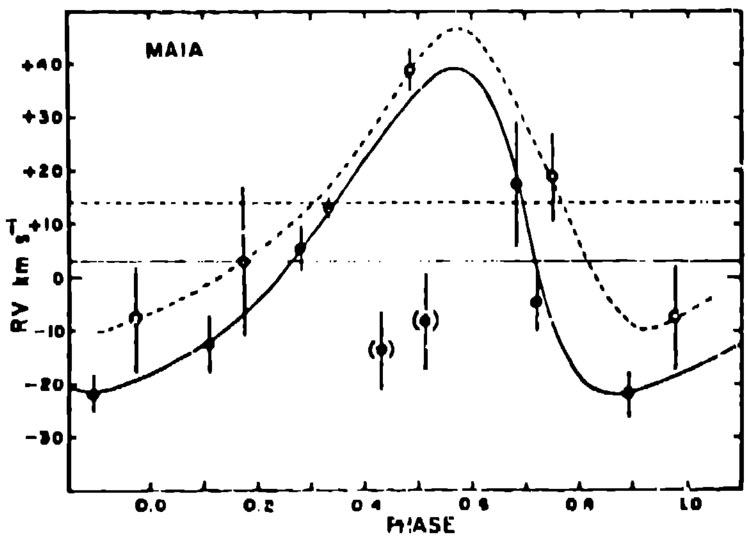

Fig. 3.--A phase plot of the published radial velocities by Henroteau obtained on two separate nights. Filled circles represent observations obtained on the night of 16 December 1919 and open circles the night of 16 August 1920. Note the strong shift in systemic velocity due to binary motion. The two rejected velocities at phases 0.4 and 0.5 are possibly the result of blending of separate shock wave component lines, one very positive and one very negative. A similar occurrence has been observed by the authors at about this phase for Taygeta.

Figure 1. The radial velocity observations of Henroteau for Maia as presented by Beardsly, Worek, and King.

Maia-Taygeta comparison, a light amplitude of one or the other might as large as 0.005 magnitude. The reality of the Maia variations probably will depend on reliable data at an accuracy of 0.001 magnitude.

Struve, Sahade, Lynds, and Huang (1957) also questioned the variability of the radial velocity of Maia. Their conclusion was that there is non-periodic variability in the helium line intensities, but none in the radial velocity or light of this star, this latter constant at the level of 0.01 magnitude.

Just as for the β Cephei variables, we can plot these Maia stars on a theoretical H-R diagram. In Figure 2 we show the theoretical evolution tracks for 2.25, 3 and 5 solar masses for a composition thought to be appropriate for these stars, that is, X=0.71 and Y=0.27. These tracks have been given by Iben (1967) in his review article. At one point along each track, the radial fundamental period is indicated along its line of constant period. For the five Maia stars with good luminosities and effective temperatures, their positions are given. Unlike the β Cephei variables, these stars seem to be in their shell

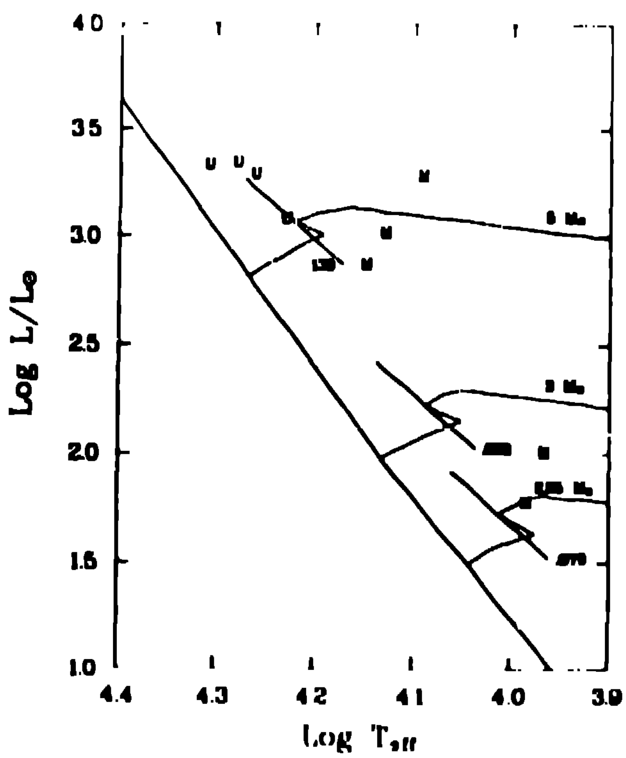

Figure 2. Points for the Maia (M) and ultrashort (U) variables are plotted on the Hertzsprung-Russell diagram which gives three theoretical evolution tracks and lines of constant radial fundamental mode period.

hydrogen burning stages after core hydrogen exhaustion. For these evolved stars, there is an isothermal core interior to a μ-gradient region out to 0.2 of the mass as for the more massive stars considered before, but here the core and μ-gradient zone is smaller in mass and radius. Could it be that the phenomenon for the Maia stars is almost the same as for the β Cephei variables, but the occasional jolt due to occasional semiconvection is not so effective in making the radial and nonradial modes appear, at least at observable amplitudes?

At Los Alamos we decided about two years ago that we would like to try ourselves to detect the Maia pulsations. J. E. Brolley used the Kitt Peak 16-inch telescope for five photometric nights over a two-week period to obtain relative brightnesses of the six brightest stars in the Pleiades. Between 35 and 38 points were obtained for each star. The basic data to be searched for periodicity were the observations of each star compared to the interpolated brightness of the mean of the other five stars at the time of the observation.

Before we present the results of the search for variablitiy, we will review three methods that we have used at Los Alamos to study these data. We first started using the method of Lafler and Kinman (1965). We define a variable Θ and scan over a period range seeking minima. Theta is defined by Lafler and Kinman as

$$\Theta = \frac{\sum_i (m_i - m_{i+1})^2}{\sum_i (m - \bar{M})^2} \quad . \qquad (1)$$

The denominator is just the mean square deviation of the points from the mean magnitude $\bar{M}$. The numerator is the mean square deviation of the adjacent points after being phased according to the chosen period. Theta reaches a minimum when points are correlated and can be shown to be about two when points are totally uncorrelated between cycles of the chosen period.

This autocorrelation method finds the best period that has the phased points follow each other in a smooth curve. When the best period has been found, the actual light curve can be plotted by once again phasing all the data to one cycle of the adopted period. We and many others have then proceeded to fit these data for one cycle with some function such as a cubic spline. Subtraction of this fit function at the phase of each data point from that point gives a set of residual points. These new points, one for each point of the original data, can then be searched for additional periods if multimode behavior is suspected from the data phased with the first period.

While the method is good and has been used widely, the weakness is in the subtraction of, or prewhitening by, the principal variation. A search for periodicity in the residuals depends directly on the accuracy of the prewhitening.

A second method we have used is due to Stellingwerf (1978) who also defines a statistic Θ which reaches a minimum when plotted versus period if the data show any periodicity.

A discrete set of observations can be represented by two vectors, the magnitudes x and the observation times t, where the ith observation is given by (x_i, t_i) and there are N points in all (i = 1, N). Let σ^2 be the variance of x, given by

$$\sigma^2 = \frac{\Sigma(x_i - \bar{x})^2}{N - 1} , \qquad (2)$$

where $\bar{x}$ is the mean; $\bar{x} = \Sigma x_i/N$. For any subset of s_i we define the sample variance s^2 exactly as in Equation (2). Suppose we have chosen M distinct samples, having variances s_j^2 (j = 1, M) and containing n_j data points. The overall variance for all the samples is then given by

$$s^2 = \frac{\Sigma (n_i - 1)s_j^2}{\Sigma n_j - M} \qquad (3)$$

as a consequence of Equation (1).

We wish to minimize the variance of the data with respect to the mean light curve. Let II be a trial period, and compute a phase vector ϕ: $\phi_i = t_i/\Pi - [t_i/\Pi]$; here brackets indicate the integer part. Equivalently, $\phi = t \bmod (\Pi)$. We now pick M samples from x using the criterion that all the members of sample j have similar ϕ_i. Usually the full phase interval (0, 1) is divided into fixed bins, but the samples may be chosen in any way that satisfies the criterion. All points need not be picked, or, alternatively, a point can belong to many samples. The variance of these samples gives a measure of the scatter around the mean light curve defined by the means of the x_i in each sample, considered as a function of ϕ. We define the statistic

$$\Theta = s^2/\sigma^2 , \qquad (4)$$

where s^2 is given by Equation (3) and σ^2 is given by Equation (2). If Π is not a true period, then $s^2 \cong \sigma^2$ and $\Theta \cong 1$, whereas if Π is a correct period, Θ will reach a local minimum compared with neighboring periods, hopefully near zero.

For each bin, in a small range of phase of a trial period, the scatter of the points is minimized. The mimimization of this dispersion for all the chosen bins is the basis of the statistic which is minimized. At any and all phases, the dispersion is minimized leading to the name of the method phase dispersion minimization or PDM. For this method as well as the Lafler-Kinman method, no assumption is made for the form of the variation with time. The final light curve at the best period is merely the mean of the data points in each bin.

The choice of the bins is important. In order to smooth the data somewhat and gain more phase resolution, the basic bins can be split into pairs or triplets or any number n. Allowing for the periodic boundary condition at the end of the cycle, the actual number of bins used in the calculation is increased by that factor by having these new bins of the same size as the basic bins cover the basic bins in n steps. Thus any phased point appears in n bins.

In our period searches at Los Alamos, we have tended to concentrate on a least-squares method discussed by Faulkner (1977). This method has some advantages over the autocorrelation methods if the amplitude is small and naturally sinusoidal as it is for the upper main sequence variables. Instead of looking for maxima in the power spectrum as Wehlau and Leung (1964) have done, we look for minima in the variance of least-squares fits of sinusoidal functions. A scan again in period or frequency is made fitting luminosity L(t) data by the formula

$$\frac{L(t)}{\langle L \rangle} = 1 + \sum_{i=1}^{m} (a_i \sin 2\pi i f t + b_i \cos 2\pi i f t), \qquad (5)$$

where there are m harmonics and the resultant fit quantities are the mean luminosity, and the a and b values for each of these harmonics.

From these linear least-squares fits, residuals can be calculated and a variance obtained. A plot of the standard deviation, the square root of the variance, versus period or frequency will show minima (and aliases!) at the frequencies which occur in the time series data.

First order Fourier series fits, that is, with no higher harmonics included, have been used by Barning (1963) and by Shobbrook, Lomb, and Herbison-Evans (1972). For distorted light curves, we can detect some of this distortion by including any number of harmonics that the number of data points reasonably allows. For a large distortion, however, use of the sinusoidal functions is not efficient because of the large number of harmonics that may be required.

Figure 3 shows the plots of the standard deviation for a range of trial periods. These Fouriergrams for the six Pleiades stars (Brolley et al. 1981) show no strong minima, though Maia and Alcyone do seem to have some indication of periods at very low amplitudes. Notice the strong one cycle per day aliases which appear because cycle counts of one, two or a few more or less from one night to the next fit the data almost as well.

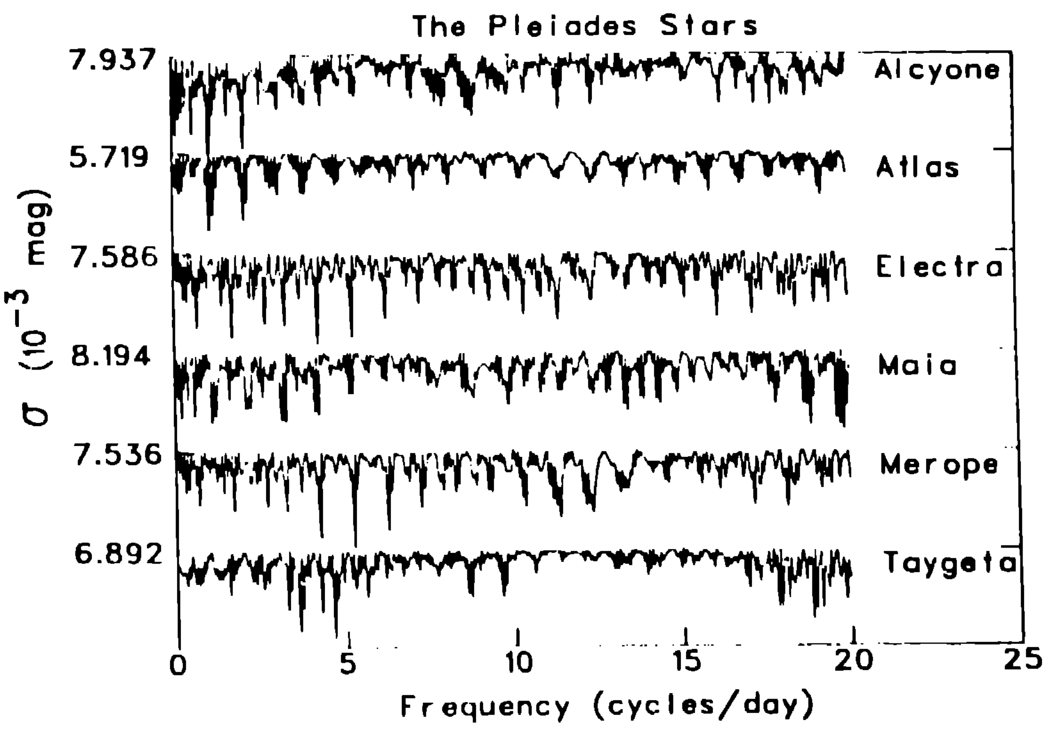

Figure 3. The Fouriergrams for the six bright Pleiades stars showing no significant deep minima at any suggested pulsation.

The amplitude of a sinusoidal stellar variation is related to the decrease in the variance, $\Delta\sigma^2$, at its corresponding frequency, by

$$A^2 = 2\Delta(\sigma^2) \quad . \tag{6}$$

It appears that these stars do not vary by more than 0.005 magnitude because that is indicated by the deepest increment in the variance.

Let us now turn to the ultrashort variables discovered by Jakate (1979). These variables are listed in Table 2, where we list

TABLE 2
ULTRA SHORT PERIOD VARIABLES

Star Name	Spectral Type	Period	vsini	Light Amplitude	$\log(L/L_\odot)$	$\log T_e$
HR 3467	B3IV	.028	35	.015	3.08	4.229
HR 3582	B2IV-V	.021	0	.015	3.34	4.279
HR 5285	B2V	.035	25	.015-.020	3.33	4.307
HR 8768	B2V	.025	20	.025 var	3.29	4.260

the same data as for Table 1 plus the rotation velocity and light amplitude observed in the B filter.

Figure 2 also includes these four ultrashort variables at their high luminosities. As they are plotted, they are a bit off the theoretical zero age main sequence even though the luminosity class indicates that they are on the main sequence. This discrepancy may be due to a small difference in the composition between the Z value of 0.02 used by Iben (1967) for the evolution calculations and the actual Z which could easily be 0.03. Apparently these 6-7 solar mass stars are in the core hydrogen burning stage just as the Maia stars, but these two classes of stars seem to be earlier in their evolution than the β Cephei variables. We speculate that the turbulently convective core gives occasional overshooting to give the same kind of jolts that we see in all the stars that we have discussed so far. At lower luminosity, the decay rates are more rapid, and detection of the pulsations may be predicted to be more difficult if the jolts needed to temporarily excite the pulsations are rare.

Sareyan, LeContel. Ducatel, and Valtier (1979) have discussed the variablility of the star 53 Psc. So far it has the shortest period of any star seriously proposed to be a β Cephei variable. This period is 0.08 day for this B2.5IV star, and the light and radial velocity variations are, respectively, 0.01 magnitude and 10 km/s. Like the other β Cephei variables, these amplitudes are variable. The cause of the short period, about half that of a typical β Cephei variable, is certainly not known. At the luminosity appropriate for this star it would seem that the pulsation mode would have to be the first radial overtone or a higher one, or one of the nonradial p modes.

Once again we at Los Alamos have decided to try our hand at photometric observations, this time for the stars in the double galactic cluster h and χ Persei. Six stars have been observed in great detail in November, 1982 and in January 1983. Star 1586 on the Oosterfoff maps, HD 14250, seems to have a period of 0.38 day with an amplitude of 0.014 ± 0.007 mag. This period is very uncertain, and maybe these stars do not pulsate at all as Percy (1972) concluded. Johnson and Morgan (1955) give a spectral class for this star of B1III.

In their study of NGC 3293, Balona and Engelbrecht (1981) found that there was a range of about one magnitude over which the β Cephei variables occurred in that cluster. If that is an indication for our cluster h Per, the star 1586, if variable, would be near the top of the range because of its spectral and luminosity class. At 9.0 magnitude for 1586, we then could expect variables to occur between roughly 8.5 and 10.0 magnitude. Stars 1057, HD14134 and 662, HD14052, at magnitudes 6.6 and 8.2 and spectral classes B3Ia and B1Ib are definitely constant, consistent with the fact that no B supergiants are known to be in the β Cephei variable class. Star 1899, HD14357, at 8.5 mag is constant to within 0.012 mag as are 1078, + 56 524 at 9.8 and 978, + 56 518 at 10.6 mag.

The stars discussed in this lecture are not too well defined in their characteristics, but they are lower in luminosity and have shorter periods. I expect that they involve the same pulsation mechanism, but due to their lower luminosity and mass, the excitation jolts are not able to so easily pulsate the entire star, and when they occasionally do, the pulsations die out so rapidly, like a few years, that is in about 10^4 fundamental mode cycles, or even fewer for overtones, that they are difficult to discover. Can these stars retain their pulsation phase between episodes of excitation and observable amplitude?

After a lesson in linear pulsation theory in the next lecture, we return to even lower luminosity variables, the δ Scuti variables, which are much better known and have well understood pulsation properties.

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