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MAIA VARIABLES AND UPPER-MAIN-SEQUENCE PHENOMENA

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ABSTRACT

A sample of four stars, including Maia itself, which are located within the Maia instability strip are investigated for photometric variability. The data consist of over 1600 differential Strömgren y-magnitudes collected during 11 nights of observation. No evidence is found for variability over the 0.1–0.3 day period range suggested for Maia stars. Two stars, Merope and Atlas, do seem to show variability, but the lengths of their periods imply a closer relation to the 53 Persei stars. It is suggested that the Maia stars do not exist as a separate class of variable stars but are an extension of the 53 Persei phenomenon to cooler temperatures.

Convective core overshooting is hypothesized to be the mechanism responsible for the variability of these stars. It is noted that this process has also been found to be necessary in cluster isochrone dating analyses, in the formation of the blue straggler stars, in the explanation of the apsidal motion of α Vir, and as the instability mechanism for the β Canis Majoris stars.

Subject headings: convection — stars: variables

I. INTRODUCTION

In 1955 Struve suggested that a sequence of variable stars extending from B7 III to A3 II–A3 III might exist. These stars were called Maia stars after the presumed prototype Pleiadid star, Maia. Struve himself later abandoned this notion when he concluded that Maia was neither a light nor radial velocity variable. He did, however, note that this star showed a *non-periodic* change in its helium line strength (Struve *et al.* 1957). Despite Struve's disclaimer, the search for short-period variability in this spectral region has continued over the years.

The principal evidence supporting the existence of the Maia stars is due to a group at Allegheny Observatory. They claim to have found seven such variables (Beardsley and Zizka 1980; Beardsley, Worek, and King 1980) with periods ranging from 0.10 to 0.27 days. However, a large part of their data consists of pre-1921 radial velocity results, the quality of which is difficult to assess.

Other stars which have been suggested as Maia variables include γ CrB (Fernie 1969), σ And, θ Peg, and 2 Lyn (Antonello *et al.* 1978). However, independent observations by Percy (1970), Tippets and Wilcken (1970), and Breger, Light, and Scholtes (1979) failed to confirm those claims. Brolley *et al.* (1981) (hereafter BCHH) have presented photoelectric evidence suggesting the variability of a number of Pleiadid stars located within the assumed Maia spectral range. The noise level in their Fouriergrams is, however, rather high, making precise statements difficult (see Fig. 1).

Evidence against the reality of Maia variables also exists. Percy (1978) observed 12 stars within the Maia spectral range and found that none exhibited periodic light changes greater

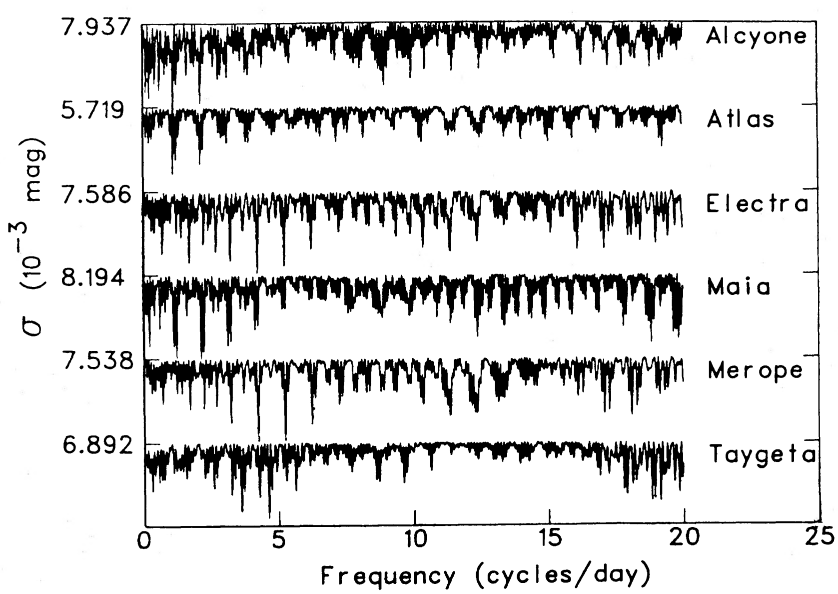

FIG. 1.—Fouriergrams for the six brightest Pleiades stars computed by Cox (1983) on the basis of photoelectrical data collected by Brolley

TABLE 1

OBSERVATIONAL LOG: NUMBER OF DIFFERENTIAL MAGNITUDES[a] AND OBSERVATION TIMES (hours)

Date (UT)	Maia	Merope	Atlas
1983 Sep 25	26 (4.4)	26 (4.4)	26 (4.4)
1983 Oct 8	35 (4.7)	74 (5.1)	34 (5.0)
1983 Oct 9	31 (4.8)	31 (4.8)	31 (4.8)
1983 Oct 22	44 (6.2)	45 (6.3)	45 (6.2)
1983 Oct 23	43 (6.0)	43 (5.9)	45 (6.0)
1983 Nov 8	58 (7.8)	106 (7.6)	58 (7.5)
1983 Nov 16	42 (5.5)	38 (5.4)	43 (5.4)
1983 Nov 29	97 (7.6)	92 (7.6)	99 (7.6)
1983 Nov 30	87 (7.3)	110 (8.2)	84 (7.1)
1984 Jan 21	27 (4.3)	25 (4.4)	28 (4.3)
1984 Jan 26	28 (2.0)	26 (2.1)	26 (2.1)
Total	518 (60.6)	616 (61.8)	519 (60.4)

[a] With Electra as the comparison star.

than 0.01 mag. Breger (1972) twice photoelectrically observed Maia over a time interval greater than its presumed period but found the star constant to within ~ 0.002 mag. At the present time there is little published evidence supporting the claimed existence of this class of star.

The recent discovery of the nonradially pulsating 53 Persei stars by Smith (1977) has, however, revived interest in stellar variability in this spectral region. The 53 Persei stars show line-profile variations, much as Struve noted for Maia, but are not always light variables. In the scenario presented by Breger (1979) the Maia spectral range would be populated by low–light-amplitude, nonradial pulsators.

The object of this study was to obtain a long, accurate set of observations of Maia candidate stars: first, to examine the reality of this class of variable stars; second, if the class was found to exist, to determine the stars' pulsation characteristics; and, last, to hypothesize how they might fit into the general scheme of upper–main-sequence peculiar phenomena reported in the literature.

II. DATA

The stars examined in this paper were among those found in the work of BCHH, specifically Atlas, Electra, Maia, and Merope. The choice of cluster stars was also desirable because their proximity allowed data to be acquired rapidly, thereby maximizing observational coverage over the suspected period range while minimizing extinction-related corrections.

Alcyone and Taygeta, although observed by BCHH, were not included in this study. Alcyone was omitted in order to avoid problems associated with coincidence loss corrections while Taygeta was omitted to maintain a short cycle time among the program stars.

The data were collected employing the New Mexico State University Tortugas 40 cm telescope and computerized data collection system. The Strömgren y filter was used. Observations consisted of two 30 s integration sets on each program star which were observed in a cyclical fashion. Nights with bright moonlight were avoided, as were nights of marginal photometric quality. Sky readings were taken about every 20 minutes, depending upon the sky's brightness.

Observations were obtained on 11 nights extending over 4 months from 1983 September 23 to 1984 January 26 UT and consisted of 1653 readings. A total of 61.8 hours of data were collected during this time. The observational log is given in Table 1.

III. DATA ANALYSIS

All observation times were converted into heliocentric values using the algorithm given by Henden and Kaitchuck (1982), and zeroed to JD 2445602.5. After various trial solutions, Electra was chosen as the principal comparison star in the formation of differential magnitudes. The Δm_y values for each program star were then Fourier analyzed. The first Fourier period search consisted of examining frequencies located between 0.01 and 50.0 cycles day^{-1}. It was apparent from this analysis that no frequencies greater than 20 cycles day^{-1} existed in the data. Thus a finer frequency search was made in the interval 0.01–20.0 cycles day^{-1}. This shorter frequency span corresponded to that searched by BCHH. The resultant power spectra are shown in Figure 2. The parameters indicated from this analysis are given in Table 2. According to the analysis by Scargle (1982) these frequencies are significant at the 99% confidence level.

The data collected by BCHH were analyzed in a different fashion from that presented above. They computed differential magnitudes by referencing the brightness of each star to the time-interpolated mean brightness of the other five stars in their sample. This procedure has the potential of yielding small errors in the differential magnitudes, but variability in a sample star influences the analysis of other stars. Our data were not examined in this fashion, specifically to avoid that potential problem. BCHH also employed the least squares method discussed by Faulkner (1977). In that analysis, periods are isolated by locating minima in the variance of least squares fits of sinusoidal functions. Since the results of the above Fourier analysis indicated that low-amplitude variations were present for Atlas and Merope, and since we wish to compare our results as directly as possible with those presented by BCHH, our data were reanalyzed, employing a similar phase dispersion technique. The algorithm used was that presented by Morris and DuPuy (1980). The results are shown in Figure 3. The values obtained using this alternative technique were the same as those found from the Fourier analysis.

Finally, the data for Atlas and Merope were phased by their

TABLE 2

PROGRAM STAR PERIOD SEARCH RESULTS

Star	Spectral Type	ν (cycles day^{-1})	Amplitude (y) (mag)	θ (radians)
Atlas	B7 III	0.5463 ± 0.0004	0.0027 ± 0.0002	4.0 ± 0.1
Electra	B6e III	...	$\lesssim 0.002$	...
Maia	B8 III	...	$\lesssim 0.002$	...
Merope	B6 IV	2.0417 ± 0.0002	0.0057 ± 0.0002	0.70 ± 0.07

[a] $\Delta m_y = A0 + A1[\cos(2\pi\nu t - \theta)$.

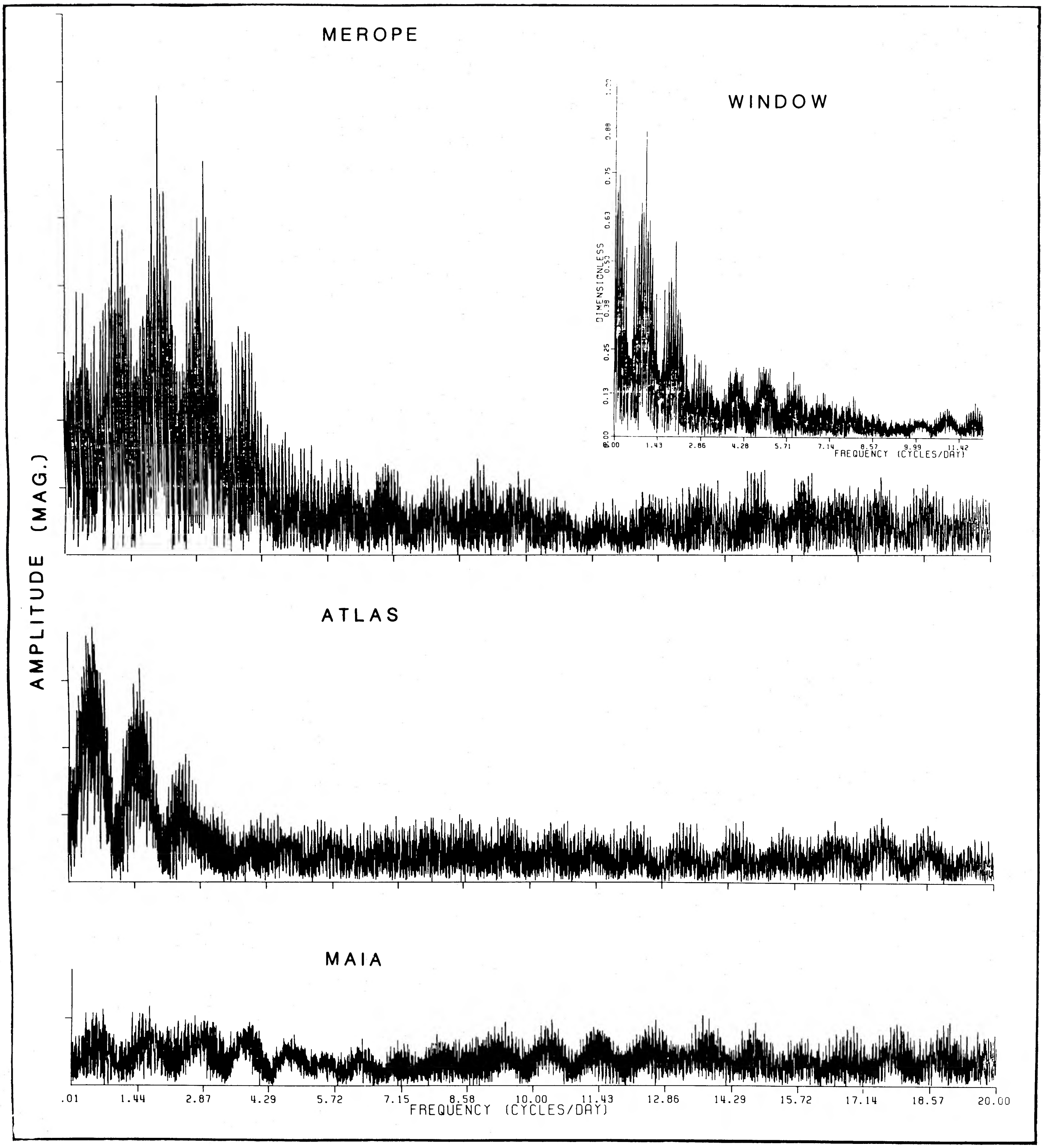

FIG. 2.—Power spectra for the stars studied in this paper. For comparative purposes the power is plotted to the same scale for each star.

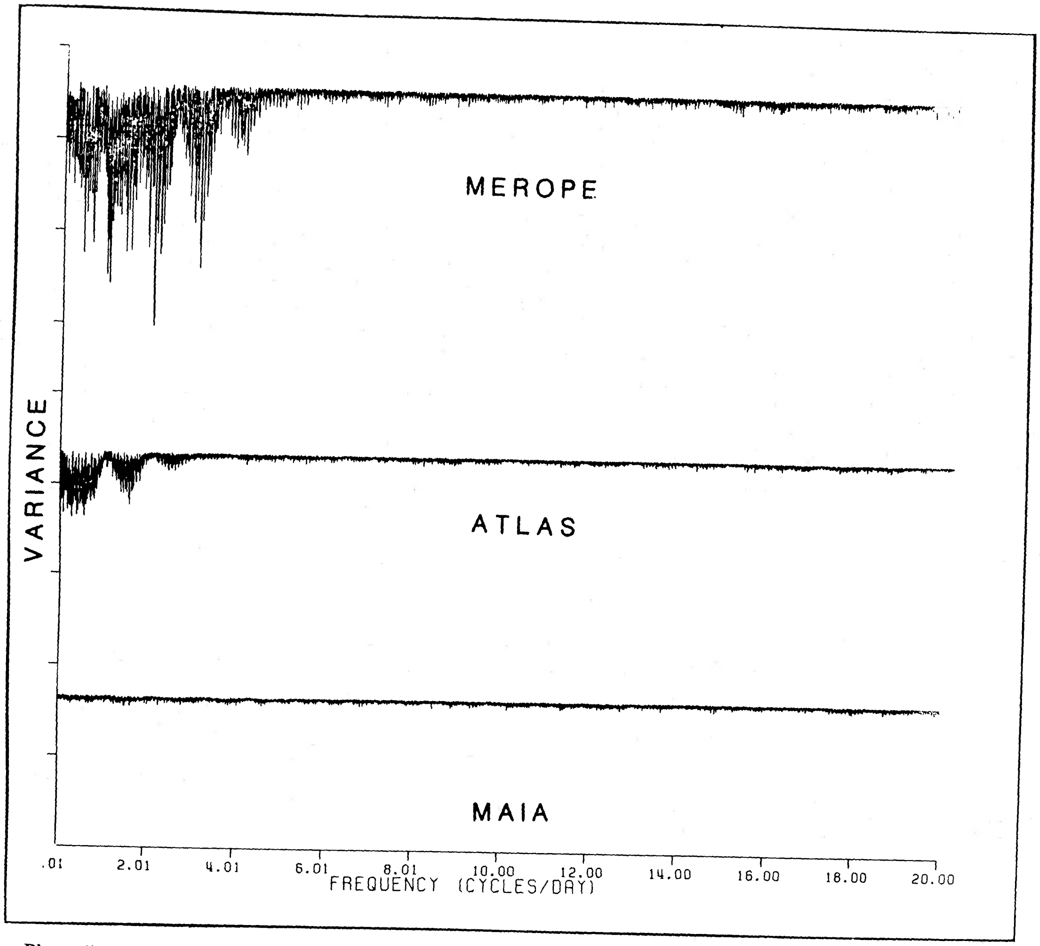

FIG. 3.—Phase dispersion plots for each of the stars analyzed in this paper. For comparative purposes all plots are at the same scale.

periods and plotted. These plots are shown in Figure 4. The result for Merope looks very convincing, but the incomplete phase coverage for Atlas makes any definitive statement impossible.

IV. DISCUSSION

The data collected for this study indicate that Merope and perhaps Atlas are variable but not within the period range suggested by the Allegheny Observatory group. The finding for Atlas is suspect and needs additional confirmation because of its low amplitude and long period. The periods found in this study do seem, however, to be related to those suggested by the BCHH analysis. For Merope, they find $\nu = 4.3$ cycles day^{-1}, close to twice the value found here ($\nu = 2 \times 2.04 = 4.1$ cycles day^{-1}) and for Atlas they find $\nu = 1.1$ cycles day^{-1}, which is again twice the value found in this study ($\nu = 2 \times 0.55 = 1.1$ cycles day^{-1}). A possible explanation for this relation will be given later.

Breger (1972) obtained photoelectric readings for each of the stars studied in this paper during the course of his search for δ Scuti stars within the Pleiades star cluster. In that study he found Atlas and Merope to be light constants. His data were collected in a similar fashion to that employed in this study, and thus his claim seems at odds with our finding. This conflict can be resolved by noting that the periods over which Atlas and Merope vary, i.e., 44 and 12 hours, respectively, are much longer than his monitoring windows. His results for our program stars are given in Table 3. Breger's determination of the light constancy of Maia is in agreement with our result. Because much of the controversy surrounding the existence/nonexistence of the Maia stars revolves around Maia itself, we will discuss this star in some detail.

Maia was first suggested as exhibiting a pulsational variable velocity by Henroteau (1921). These early data form much of the basis for the claim of this star's variability. Henroteau's velocity data have been phased to a 0.1 day period by the Allegheny group and are shown in Figure 5. The points in parentheses located between phases 0.4 and 0.5 are obviously in conflict with the assumed period. The Allegheny group attributes this to a dual shock wave phenomenon within the atmosphere of Maia. This interpretation, however, is unat-

TABLE 3

BREGER'S 1972) DIFFERENTIAL MAGNITUDES

Star	HD	Constancy	Time Observed (hours)
Atlas	23850	0.002	2.4
Electra	23302	0.003	3.6
		0.002	3.2
Maia	23408	0.002	3.3
		0.002	3.2
Merope	23480	0.002	4.4

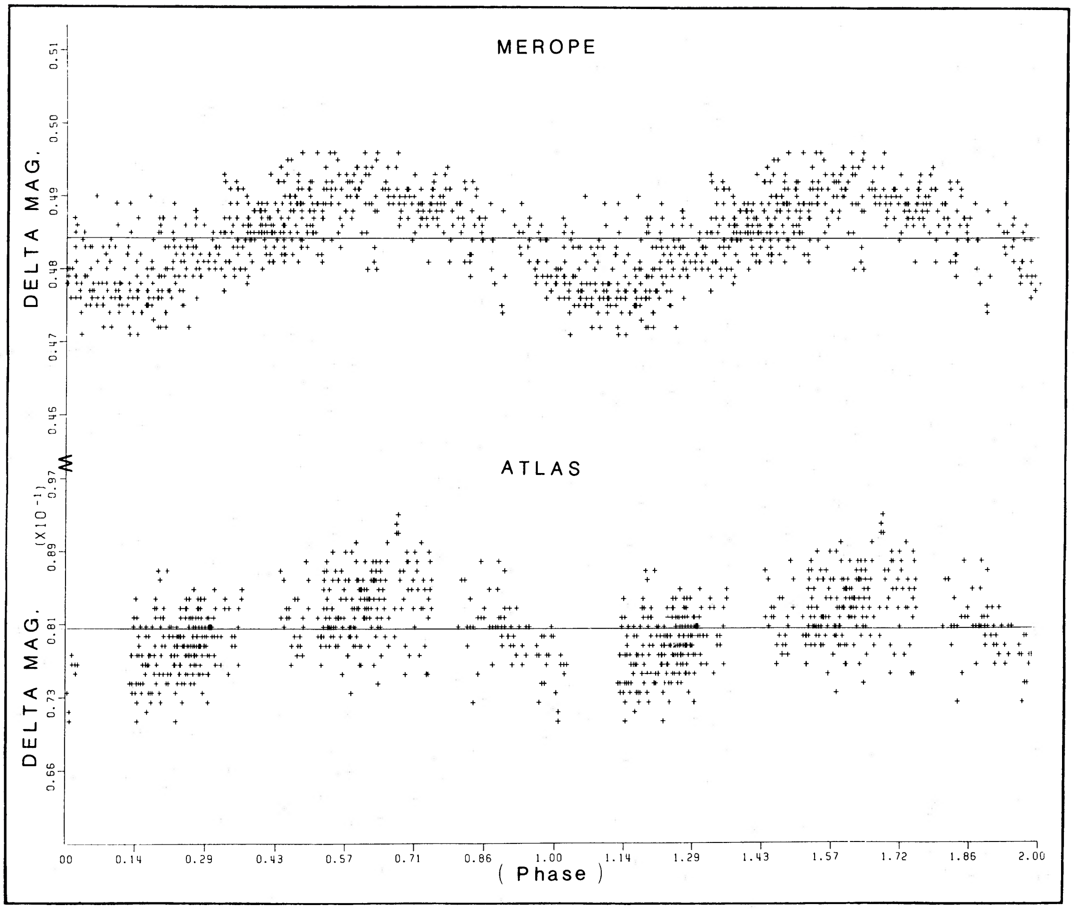

FIG. 4.—The phased data collected in this study for the stars Atlas and Merope. The data have been phased according to the periods given in Table 2. Two periods are shown.

tractive. First, the upper velocity curve does not show this phenomenon, although it has a point within the appropriate phase zone. Second, the reasoning is circular, since the explanation assumes the phenomenon it is presented to prove. Third, when one examines the complete set of velocity data collected by Henroteau and phased by the Allegheny period, the resulting plot yields only marginally convincing evidence for periodicity at that value (see Fig. 6).

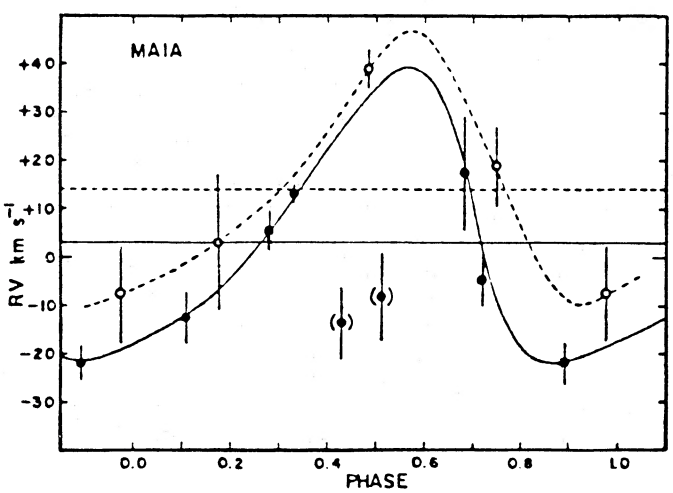

FIG. 5.—A phase plot of two nights of radial velocity data obtained by Henroteau (1921). The data have been phased by the period given by the Allegheny Observatory group. The meaning of the points in parentheses is given in the text. (Diagram taken from the work of Beardsley, Worek, and King 1980.)

Struve (1955), although commonly associated with the Maia stars, only speculated about their possible existence. In discussing the location of pulsating stars in the H-R diagram, he states, "The group labeled *hypothetical Maia Sequence* is at present quite uncertain." In a subsequent spectroscopic study of Maia (Struve *et al.* 1957), he reports finding no short-period velocity variations. He specifically notes: "It seems in order to point out that although Maia has long been considered as having a variable velocity (Adams 1904; Merrill 1914; Henroteau 1921) the star is recorded in the recent catalogues with constant velocity: 7.8 ± 0.5 km/sec in the Lick Catalogue and 7.5 km/sec in the catalogue by R. E. Wilson. The latter value is based upon the means from several observations: Michigan (40), 6.4; Ottawa (27), 6.1; Yerkes (13), 3.8; McDonald (6), 5.1; Lick (5), 10.9; Potsdam (4), 9.4; Mount Wilson (3), 9.4."

Struve himself obtained 100 inch (2.5 m) telescope coudé spectrograms of Maia at a dispersion of 10.2 Å mm^{-1} on 1955 November 23, 24, and 25 UT. The number of consecutive exposures taken on those nights were 27, 16, and 18, respectively, covering intervals of 8, 4.5, and 4.5 hours. No periodic velocity variations were found. He also reported (Struve *et al.* 1957) that Lynds was unable to detect any photometric variations larger than 0.01 mag during six nights of observations in 1955 September, October, and November. Struve's only finding suggesting unusual behavior for Maia was a variable

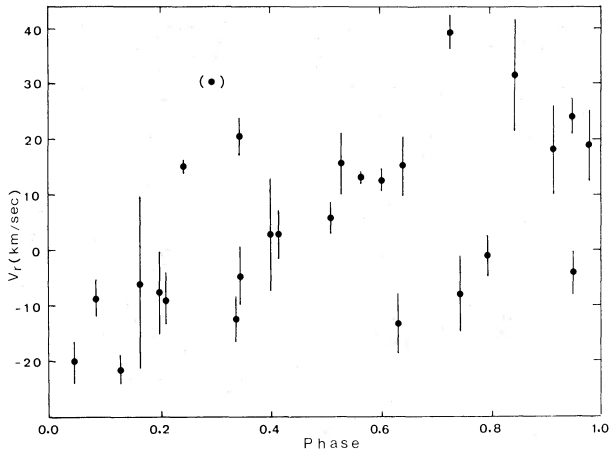

FIG. 6.—A phase plot of all six nights of radial velocity data obtained by Henroteau (1921). The data have been phased by the period suggested by the Allegheny group. The point in parentheses represents a velocity based upon a single line.

helium line strength, but even this was stated to be nonperiodic and difficult to detect on high-dispersion plates.

Five additional radial velocities of Maia were obtained by the Allegheny group in 1976 using the KPNO coudé spectrograph. The spectra were taken at a dispersion of 17 Å mm^{-1} and covered a time interval of about one and one-half times Maia's assumed period. The spectra yield a mean velocity of $\sim 6.5 \pm 2$ km s^{-1}, in agreement with the velocities given above. Although they fitted these observations using their 0.10 day period, the velocity amplitude indicated by their figure is a factor of 7 smaller than that reported by Henroteau (1921). It seems that the large velocity variation of Maia (-20 to $+40$ km s^{-1}) reported by Henroteau is a unique observation.

Photometric evidence supporting the variability of Maia does not exist. As mentioned earlier, Breger (1972) obtained observations of Maia on two separate occasions. He found this star to be constant to within 0.002 mag over its assumed 0.10 day period. It is possible, however, that if Maia pulsates in many modes, then by an unfortunate coincidence, his data could have been obtained during a time of severe destructive interference among its various waveforms. Our data, however, consist of 11 nights obtained from 1983 September to 1984 January and also show no evidence of variability as seen from its power spectrum or an examination of the nightly data. Over this time Maia was constant in brightness to within ± 0.002 mag (rms). This result is in qualitative agreement with the earlier finding of Lynds (see Struve *et al.* 1957).

It seems that one is forced to the conclusion that in the investigations of Maia conducted since 1957, this star has not shown any clear velocity or light variation. The bulk of the observations, with the possible exception of the BCHH Maia Fouriergram, support this star's constancy.

V. INTERPRETATION OF THE RESULTS

The relatively long periods found for Merope and Atlas suggest that these stars are nonradial rather than radial pulsators. Their spectral types along with their assumed mode of pulsation imply that the Maia phenomenon may, in fact, simply be an extension to cooler temperatures of the newly discovered 53 Persei stars. The 53 Persei stars are nonradial pulsators extending from λ Ori A (O8) to 53 Per (B6 III). The width of their spectral lines as well as the asymmetric nature of their line profiles can change over a period of a few hours. Some, like 53 Per itself, show light variations of $\lesssim 0.10$ mag, but for others like 10 Lac and 22 Ori no light variation has been detected. The above description seems to fit Maia rather well. The periods seen in a 53 Persei star range from 4 to 49 hours and can change in a matter of months or even days. This fact may explain why Electra looks like a small-amplitude variable in the Fouriergram computed by BCHH but was found to be constant in this study. Perhaps it is presently in a photometrically constant stage. It is also possible that its suggested variability is simply the result of including Merope and Atlas in the comparison star set. The structure of the Fouriergrams for the other stars could, however, be used to challenge this interpretation.

The 53 Persei stars have been known to change their periods by a factor of 2, and this may account for the difference between our periods and those of BCHH. Further observations are needed to confirm this hypothesis.

The nature of the instability for the 53 Persei stars is undetermined. Cox (1983) has suggested that these stars are excited by a joltlike phenomenon which occurs in the core of the star and is associated with convective core overshooting. The decay times for the nonradial *g*-modes excited in this manner can extend for more than a thousand years, whereas the decay time for an excited fundamental mode is about 10 years. At any particular time one would thus be more likely to observe one of these stars as a nonradial pulsator.

The suggestion that convective core overshooting is responsible for the 53 Persei stars is interesting in that a number of other puzzling observational phenomena can also be explained using that mechanism. Maeder and Mermilliod (1981) find that, in order to match theoretical isochrones to the observed young cluster color-magnitude diagrams, convective core overshooting is necessary. This process has a particularly strong effect in the color-magnitude diagram at the location of core hydrogen exhaustion. They also suggest that the size of the zone of extended mixing resulting from this process increases with the mass of the star. They cite as additional evidence for this mechanism a study by Odell (1974) of the apsidal motion of α Vir. That study finds the apsidal constant a factor of 2 smaller than is predicted from theory, indicating a larger central condensation than expected. Wheeler (1979) has also suggested that the blue stragglers are the result of internal mixing of hydrogen into the core region, thus prolonging the main-sequence life of these stars. Calculations by Saio and Wheeler (1980) support this claim, although the degree of mixing used in their models is more extensive than that suggested by Maeder and Mermilliod (1981). Cox (1983) has suggested that the β Canis Majoris stars owe their instability to internal mixing via convective overshooting. Finally, the peculiar light behavior of Vega reported by Fernie (1981) is suggestive of a joltlike mechanism.

It is unusual that such a host of unexplained phenomena find satisfaction through a single mechanism. This fact, coupled with Maeder's observation that the strength of convective overshooting increases with stellar mass and is particularly evident just in the phase of stellar evolution where the phenomena mentioned above exist, strongly suggests that it may play a key role in their explanation.

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