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PI AQUARII: A PULSATING Be STAR?

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ABSTRACT

Following the discovery by Ringuelet and Machado of large periodic radial-velocity variations in π Aqr, photometric observations of the star have been obtained. It is found that the star has undergone small but significant secular changes in brightness and color since observations made 11 years earlier, and that it also shows instabilities of the order of several hundredths of a magnitude on a time scale of hours or less.

Several possible explanations, such as rotation, presence of a binary companion, varying emission lines, and pulsation, are considered. Of these, only pulsation seems plausible.

Subject headings: Be stars — pulsation

I. INTRODUCTION

Ringuelet and Machado (1974) have drawn attention to the Be star π Aqr, variously classified as B0 Ve, B1 Vep, B1 nnek, etc. (Jaschek *et al.* 1964). They find that the star undergoes sinusoidal radial-velocity variations of amplitude about 150 km s^{-1} in a period of $0^{d}087$, a matter previously overlooked because of the extreme breadth of the spectral lines. The only photometric data available to these authors were isolated measures scattered in the literature, from which they concluded that π Aqr shows no very significant photometric variability. Clearly, however, it would be desirable to check this conclusion by more detailed observations and, in particular, to look for variability on the time scale of the 2-hour radial velocity period. This I have done during an observing run in Chile, where single observations of the star were obtained on seven successive nights, and a concentrated 2-hour run also obtained on one night.

II. OBSERVATIONS

The observations were obtained with the University of Toronto 61-cm telescope at the Las Campanas Observatory in Chile during 1974 September, using equipment described elsewhere (Fernie 1974). Unfortunately, a logistics problem resulted in a missing ultraviolet filter, so that no $(U - B)$ observations were possible, and only *BVRI* data are reported.

Eta Aqr, a B8 V star of similar magnitude and about 2° away from π Aqr, was used as a comparison star. The night-to-night observations of these stars are given in Table 1, and the results of the single 2-hour run on one night are given in Table 2. Results are given to three decimals of a magnitude because the internal consistency justifies it, but errors arising through the transformations are such that, when comparisons with other observers are made, the results should be rounded off to hundredths.

The results in Table 1 show no great degree of variability in π Aqr, although variations of up to 0.03 or 0.04 mag are not excluded. The averages of the nightly observations, listed on the last line of Table 1, become interesting, however, when compared with observations made in 1964 January (Johnson *et al.* 1966). On the basis of four consistent observations, these authors give

$$V = 4.64 \qquad B - V = -0.03$$
$$V - R = 0.15 \qquad V - I = 0.15\,.$$

TABLE 1
NIGHT-TO-NIGHT OBSERVATIONS

JD 2,442,300+	π AQUARII V	$B-V$	$V-R$	$V-I$	η AQUARII V	$B-V$	$V-R$	$V-I$
5.636.........	4.524	0.005	0.198	0.306	4.040	−0.096	−0.023	−0.075
6.592.........	4.526	0.009	0.197	...	4.024	−0.073	−0.008	−0.069
7.649.........	4.515	0.012	0.195	0.306	4.034	−0.087	−0.017	−0.086
8.644.........	4.532	...	0.198	0.306	...	...	...	...
9.606.........	4.512	0.022	0.211	0.308	4.037	−0.083	−0.011	−0.080
10.613.........	4.495	0.025	0.198	0.294	4.019	−0.086	−0.007	−0.073
11.609.........	4.495	0.022	0.206	0.302	4.013	−0.079	−0.007	−0.087
Means.......	4.514	0.016	0.200	0.304	4.028	−0.084	−0.012	−0.078

TABLE 2

OBSERVATIONS DURING 2-HOUR RUN

JD 2,442,309+	π AQUARII V	π AQUARII $B-V$	π AQUARII $V-R$	π AQUARII $V-I$	η AQUARII V	η AQUARII $B-V$	η AQUARII $V-R$	η AQUARII $V-I$
0.6056	4.512	0.022	0.211	0.308				
0.6076					4.037	−0.083	−0.011	−0.081
0.6104	4.503	0.029	0.200	0.301				
0.6125					4.031	−0.077	−0.012	−0.084
0.6153	4.504	0.024	0.200	0.301				
0.6181					4.038	−0.079	−0.010	−0.069
0.6222	4.504	0.036	0.201	0.306				
0.6243					4.033	−0.082	−0.011	−0.076
0.6264	4.505	0.025	0.201	0.302				
0.6285					4.033	−0.073	−0.004	−0.076
0.6312	4.505	0.028	0.201	0.302				
0.6333					4.033	−0.077	−0.004	−0.072
0.6354	4.515	0.013	0.212	0.314				
0.6382					4.040	−0.085	−0.003	−0.071
0.6396	4.515	0.021	0.204	0.306				
0.6424					4.040	−0.081	−0.003	−0.071
0.6444	4.514	0.021	0.212	0.310				
0.6465					4.033	−0.078	−0.004	−0.079
0.6493	4.514	0.021	0.203	0.306				
0.6521					4.046	−0.088	+0.005	−0.066
0.6535	4.514	0.029	0.203	0.301				
0.6556					4.040	−0.080	+0.004	−0.075
0.6583	4.522	0.025	0.197	0.309				
0.6597					4.039	−0.082	−0.003	−0.085
0.6618	4.522	0.024	0.205	0.309				
0.6639					4.039	−0.086	−0.003	−0.082
0.6660	4.531	0.020	0.208	0.316				
0.6681					4.038	−0.079	−0.004	−0.065
0.6701	4.530	0.025	0.199	0.311				
0.6715					4.038	−0.082	−0.004	−0.076
0.6743	4.537	0.057	0.201	0.319				
0.6764					4.043	−0.082	−0.010	−0.080
0.6792	4.546	0.040	0.220	0.338				
0.6812					4.043	−0.086	−0.004	−0.076
0.6840	4.527	0.022	0.206	0.313				
0.6861					4.035	−0.074	−0.026	−0.109

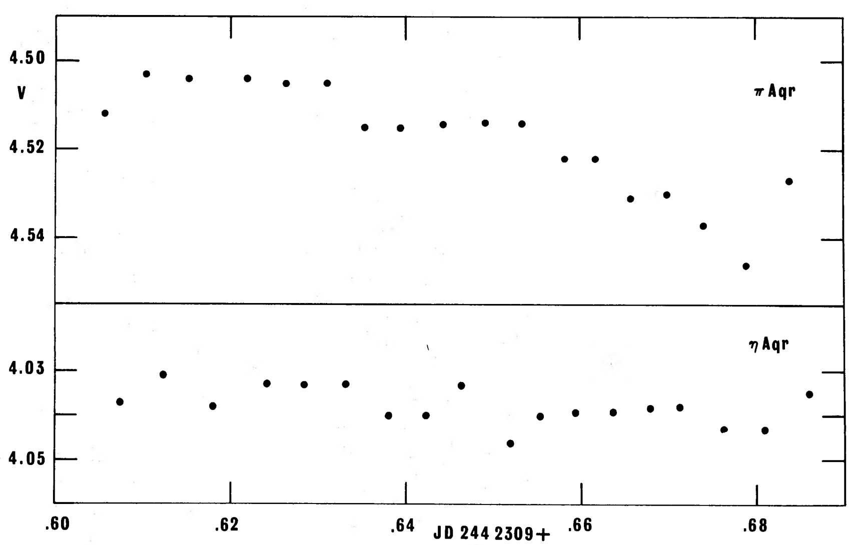

FIG. 1.—Observations of the V magnitude of π Aqr and η Aqr during the course of a 2-hour run. They are plotted separately to show that the variability occurred in π Aqr and not in η Aqr.

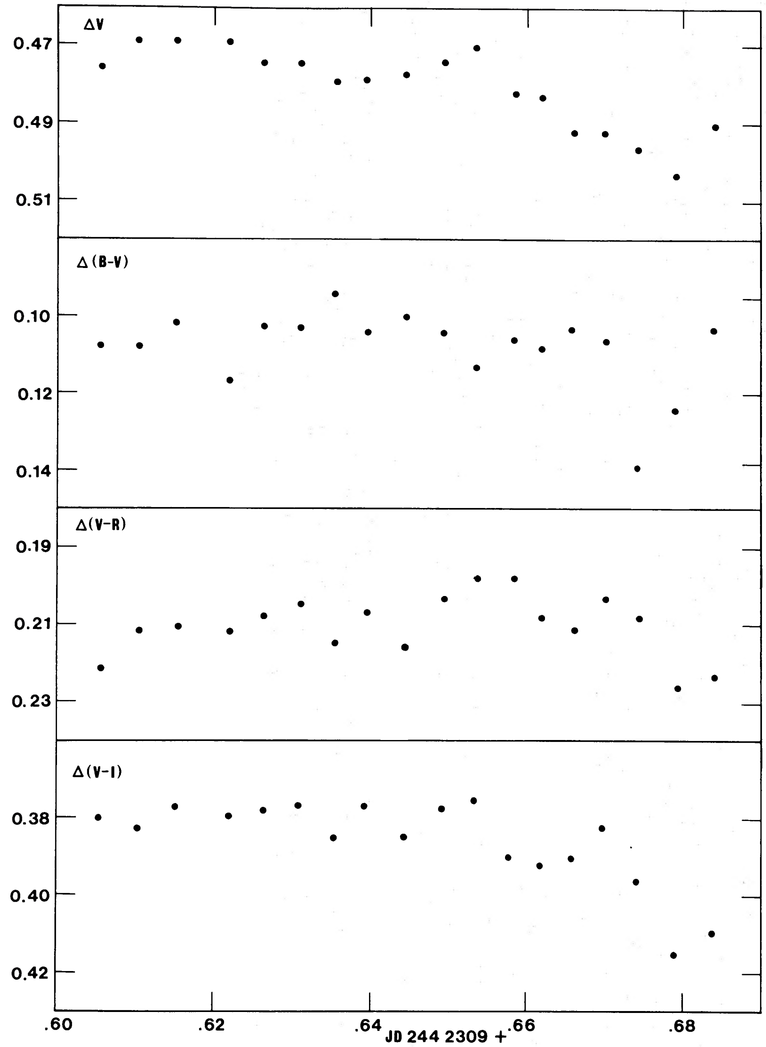

FIG. 2.—Differential magnitudes and colors (in the sense π Aqr − η Aqr) during the 2-hour run

For 32 other stars which the present observing program had in common with Johnson *et al.*, the agreement is very good. Average differences are

$$V\colon \pm 0.025 \qquad B - V\colon \pm 0.017$$

$$V - R\colon \pm 0.022 \qquad V - I\colon \pm 0.030 .$$

Thus the change in V of 0.13 mag is almost certainly significant. While the changes of 0.05 in each of $(B - V)$ and $(V - R)$ are marginally significant, the change of 0.15 in $(V - I)$ is quite striking. Almost certainly, π Aqr has become brighter and redder during the last decade.

Figure 1 shows separately the V magnitudes of the two stars measured during the 2-hour run. It is clear that the variability found during this interval occurred in π Aqr and not in η Aqr.

Figure 2 shows the results of the 2-hour run also, but now in differential form to gain maximum accuracy. The sinusoidal variation in V during the first hour or so (0.60 to 0.65 on the abscissa) may or may not be real, since its semiamplitude of about 0.005 mag is comparable to the random error in the digital readout of the electronics system. However, there is little doubt that the decline in brightness by almost 0.04 mag during the later part of the run is significant, appearing also as a reddening of the star. Thus, although we cannot confirm the period of $0^{\mathrm{d}}.087$ found by Ringuelet and Machado, it can be said that π Aqr undergoes photometric instabilities of the order of a few hundredths of a magnitude on that sort of time scale. In general, the appearance of the light curve is reminiscent of the modulated light curves seen in δ Scuti stars.

III. DISCUSSION

Allen (1974) gives for the characteristic B0 V star $R = 7.4\,R_{\odot}$, $\mathfrak{M} = 18\,\mathfrak{M}_{\odot}$; and for a B1 V star $R = 6.5\,R_{\odot}$, $\mathfrak{M} = 14\,\mathfrak{M}_{\odot}$. We may take $R \approx 7\,R_{\odot}$, $\mathfrak{M} \approx 16\,\mathfrak{M}_{\odot}$ for π Aqr. Given these figures, what likely explanation can be found for the $0^{\mathrm{d}}.087$ periodicity in π Aqr?

Since the star is a Be star, it is natural to begin with the possibility that rotation is the cause of the variability. It might be possible to invoke some patchiness in the distribution of surface brightness to account for both the radial velocity and the light variations, but the idea is effectively ruled out by the very short period. For a star of $7\,R_\odot$ to rotate in $0^{\mathrm{d}}.087$ would require an equatorial velocity well in excess of 4000 km s^{-1}, at which the ratio of centrifugal to gravitational forces would be about 40.

Binary motion is also ruled out by the short period. Kepler's Third Law shows that for any companion of mass up to $50\,\mathfrak{M}_\odot$, the semimajor axis of the relative orbit would be less than half the radius of π Aqr itself.

Hutchings (1970), Hutchings *et al.* (1971), and Bahng (1971) have shown that considerable changes in the structure of the Balmer lines, particularly Hα, can take place in Be stars on time scales of minutes. Can such effects account for the present photometric observations? Very likely not. First, we may note that for emission in only a few lines to influence the *BVRI* measures, the changes in the line must be very pronounced because of the wide bandpasses of these filters. There is no evidence in the above papers that these line changes are sufficient for this, particularly since π Aqr is not an extreme Be star. Second, we may note the distribution of the Balmer lines within the filters. The *V* filter is almost free of Balmer lines; Hα falls at the extreme longward tail of the bandpass, Hβ at the extreme shortward tail. Yet, as Figure 1 shows, the effect is as pronounced in *V* as in any filter. Furthermore, Hα occurs at the very peak of the *R* bandpass, yet as Figure 2 shows, the effects in *V* and *R* are quite similar ($V - R$ shows only a small variation). The *I* band, in fact, is completely free of Balmer lines, but then it is known (Hiltner 1947; Burbidge 1952) that in Be stars Balmer emission is also accompanied by Paschen emission, and the higher order lines of that series are included in the *I* band. Yet the variations in *I* are less than in *V*.

There remains pulsation. A period-radius-mass relation which gives good results for β Cephei stars and Cepheids (Fernie 1965) predicts a fundamental pulsation period of $0^{\mathrm{d}}.083$ for a star of $7\,R_\odot$ and $16\,\mathfrak{M}_\odot$; a change to $7.2\,R_\odot$ would give $0^{\mathrm{d}}.087$. This, then, seems plausible, but there remains a difficulty pointed out by Ringuelet and Machado: for so large a velocity amplitude as 150 km s^{-1}, would one not expect a much larger light variation? The ratio of velocity to visual light amplitudes ($\equiv f$), however, is a sensitive function of period. In β Cephei stars it is about 770 km s^{-1} mag^{-1}, in classical Cepheids about 54, while for Mira it is only about 2. Choosing representative periods for such stars, one finds that, very roughly,

$$f \approx 270\,P^{-0.82}\,,$$

so that for a period of $0^{\mathrm{d}}.087$ one might expect an amplitude ratio of about 2000. A velocity amplitude of 150 km s^{-1} would then imply a light amplitude of roughly 0.07 mag, which is not grossly different from that observed. In any case, the possibility of the variations being modulated by the presence of more than one period makes it difficult to compare the velocity amplitude at one epoch with the light amplitude at another.

Attention must be drawn to a negative result by Nordh and Olofsson (1974). From intermediate-band photometry for spectrophotometric purposes, they report that "no continuum changes larger than the dispersion in the measurements (0.01 mag) occurred in π Aqr during the time of observation." Nevertheless, intermittent behavior is not unknown among variable stars. Hutchings (1970) found it in the case of the line variations in the Be star γ Cas, it is known to occur in some δ Scuti stars, and it may even account for some of the scatter in the velocity curve of π Aqr found by Ringuelet and Machado.

Clearly, the case for pulsation in π Aqr remains unproven, but the present situation is interesting enough for future simultaneous spectroscopic and photometric observations of this star to be worthwhile.

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