THE APPLICATION OF VISUAL OBSERVATIONS TO THE STUDY OF A SMALL-AMPLITUDE VARIABLE STAR: RHO CASSIOPEIAE

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Abstract

We have used AAVSO and BAA visual observations to study the variability of the extremely luminous yellow supergiant rho Cassiopeiae. We first compared 30-day means of the AAVSO and BAA visual observations with each other and with photoelectric photometry, in order to identify any systematic errors. We then investigated the periodicity of the star by applying Fast Fourier Transform and autocorrelation methods to the visual means. There is a characteristic time scale of 275 to 400 days, which is consistent with the pulsational time scale for such a star, but the variability is far from regular. The star bears some resemblance to the Cepheids, and also to the R CrB stars (with which it is sometimes classified). Our results indicate that, in some cases, moderately small-amplitude variables can be studied visually, as long as the observations are made carefully, consistently, and sufficiently frequently.

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1. Introduction

Rho Cassiopeiae (HR 9045, HD 224014) is a bright ($V = 4^{m}.6$), extremely luminous yellow supergiant (F8p Ia). If it is a member of the association CAS OB5 as suspected (Humphreys 1978), it has an absolute visual magnitude of -9.5, a value which is generally consistent with the other properties of this star. It also undergoes two interesting kinds of variability: semi-regular variations with an amplitude of about $0^{m}.2$ and a time scale of about a year, and a unique episode in which the star faded by over a magnitude from August 1945 to June 1947 (Gaposchkin 1949). The star has therefore been classified as a possible R Coronae Borealis star, even though its fading is rather modest as R CrB stars go, and its spectrum lacks the carbon-rich, hydrogen-poor characteristics which are found in most R CrB stars. The semiregular variations found in some R CrB stars, however, provide another possible link with rho Cas.

The star has also undergone spectroscopic variations. During the fading in 1946-47, the spectrum showed quite well-developed TiO bands (indicative of a much cooler atmosphere) but in two years it was back to normal. Blue-displaced shell lines also developed after the minimum (Bidelman and McKellar 1957). A similar phenomenon occurred in the 1970's in rho Cas' spectroscopic "twin" HR 8752, though it is not clear that this was associated with a similar fading. These observations suggest that episodic mass ejection has occurred in these two stars.

In order to investigate the nature and cause of these variations, it would be desirable to obtain continuous photometry and spectroscopy over many decades. Unfortunately, photoelectric photometry has been sporadic, and spectroscopy even more so, due to the limited resources and attention span of professional astronomers. One solution is to enlist the aid of amateur astronomers (Williams 1983) with access to photoelectric photometers (Hall and Genet 1984). Rho Cas has already been placed in the photoelectric photometry program of the American Association of Variable Star Observers (AAVSO). Another solution is to attempt to use visual observations, which have been made regularly by the AAVSO and the Variable Star Section of the British Astronomical Association (BAA) for many years.

The BAA observations from 1964 to 1975 have already been published (Bailey 1978). They number 5636, with the number per year increasing progressively during the interval. They are grouped into 30-day means, whose formal standard errors range from about $0^m.05$ in 1964 to about $0^m.02$ in 1975. The BAA initially used a sequence of nine comparison stars, but two stars were eventually dropped. The magnitudes adopted for the comparison stars were about $0^m.1$ fainter than photoelectric **V** magnitudes. Bailey looked for systematic seasonal effects which might be due, for instance, to the changing orientation of the variable relative to the comparison stars, but found none.

The BAA observations exhibited semi-regular cycles with an amplitude of about $0^m.2$ and a time scale of 200 to 400 days, but no single period gave a good fit to the data. There were also variations of about $0^m.2$ in the mean magnitude. Bailey notes that these variations are near the limit of what can be detected by visual observers.

Bailey's paper contains references to most other visual studies of rho Cas, and also to some photoelectric studies. To these should be added Fernie *et al.* (1972), Percy and Welch (1981), and Arellano Ferro (1983). Numerous spectroscopic studies have been carried out, including those by Beardsley (1961), Sargent (1961), and Lambert and Luck (1978).

Our own interest in rho Cas stems from our studies of supergiant variability both within and outside the Cepheid instability strip (Percy *et al.* 1979; Percy and Welch 1981; Percy 1981). We had carried out sporadic photoelectric photometry of these stars, and were aware of the need for long-term observations and the role which amateurs could play. We have analyzed the AAVSO visual observations from 1962 to 1984 (those which are now in machine-readable form) and have used them to comment on the nature of the variations, and their possible relation to those of Cepheids and other variables.

2. The AAVSO Observations

The AAVSO observations are numerous, continuous and generally well-distributed, and give an average formal standard error of about $0^m.03$ in a 30-day mean. According to Bailey (1978), the comparison sequences used by the BAA and the AAVSO are "almost identical", but it is not clear that this is the case. Most of the comparison stars listed by Bailey are blue, whereas most of the comparison stars near rho Cas on the *AAVSO Variable Star Atlas* (Scovil 1980) are red. In particular, the BAA gradually dropped the convenient red comparison star tau Cas because they suspected that it was variable (see references in Bailey 1978). We find no evidence for such variability in our frequent photoelectric observations of this star (Percy *et al.* 1979; Percy and Welch 1981).

We have examined the AAVSO observations in detail, to see if there are any systematic differences between various classes of observers - novice and experienced, for instance. Unfortunately, it is difficult for us to classify observers in this or other ways. We note that there is a tendency for those who make large numbers of observations each month to measure bright, and for those who (dutifully following AAVSO instructions) make one observation each month to measure faint, but it is not clear that this difference is significant. We decided, after considerable thought, to include all observations in the 30-day means, except those which fell more than three standard deviations from the mean. A table of our AAVSO 30-day means (and also the BAA 30-day means) can be obtained by writing to one of us (JRP). The light curve of rho Cas is shown in Figure 1.

3. Comparison of AAVSO, BAA, and V Photoelectric Observations

We have compared the AAVSO and BAA visual observations over the interval of overlap from 1964 to 1975. At the beginning of this interval, the AAVSO measures were fainter by about $0^m.15$ than the BAA measures. By 1970, there was no significant difference. By the end of the interval, the AAVSO measures were brighter by about $0^m.1$ than the BAA measures. These changing differences are no doubt due to the choice of comparison stars and their adopted magnitudes.

Bailey (1978) has already compared the BAA measures with the photoelectric **V** observations of Landolt (1973) and has found a systematic difference BAA - **V** = $0^m.31 \pm 0^m.04$. We have compared the BAA measures with the photoelectric **V** observations of Fernie *et al.* (1972); we find BAA - **V** = $0^m.28 \pm 0^m.02$, which is consistent with Bailey's value. The errors quoted are the standard errors of the individual differences. Their smallness is an indication of the reliability of the visual measures. The systematic difference is due to the color difference between the variable and the mostly blue-white comparison stars (see Steffey 1978 for instance). In the language of the photoelectric photometrist, the "transformation coefficient" for visual observations ($\varepsilon = (V - m_v) / \Delta(\mathbf{B-V})$) is about $0^m.25$, and arises because the wavelength sensitivity curve of the eye does not match that of the standard **V** filter. Given the average color of rho Cas (**B-V** = +1.3) and the average color of the comparison stars (**B-V** = +0.1), the observed difference between m_v and **V** is to be expected.

4. Period Analysis

According to Bailey (1978) and other authors, the cycle lengths in rho Cas are 200 to 400 days. The average value in the BAA observations (as determined by counting) is 256 days. The average value in the AAVSO observations (1975 to 1984 only) is about 350 days. The average value in the entire set of AAVSO observations (1962 to 1984) is 325 days. Unfortunately, the irregularity of the star and the scatter in the observations make it difficult to count cycles dependably, and it is not clear what the physical significance of a "cycle count" period is in any case.

More elegant methods of period determination can be divided into those which assume that the star is strictly periodic and those which do not. We have experimented with various methods of the first kind, and we find the standard Fast Fourier Transform (FFT) to be quite adequate. The FFT power spectrum of the BAA observations is shown in Figure 2. There is a peak at a period of 275 ± 25 days, but it is only statistically significant at about the 90% level. The FFT power spectrum of the AAVSO observations contains no notable features. In neither case is there a peak at a period of 365 days, which might be due to spurious seasonal effects.

If the variability of rho Cas is cyclic but not strictly periodic, an autocorrelation method of period analysis might be more appropriate.

We have used the simple method outlined by Percy *et al.* (1981) to calculate a correlogram of two sets of visual means: all the AAVSO means, and the subset of (significantly more accurate) AAVSO means from 1970 to 1984. The correlogram (Figure 3) shows a weak correlation at a lag of about 400 days, with some suggestion that the lag is somewhat shorter over longer intervals. The significance of this effect, and of the difference between the periods obtained using the various methods, is not clear. It may possibly be related to the results obtained on model RV Tauri stars by Fadayev (1984), who found that the period of the envelope (which might be expected to behave most periodically) was shorter than that of the atmosphere.

5. The Cepheid Nature of Rho Cassiopeiae

This star lies on the upward extension of the Cepheid instability strip, but since its spectrum and color (and therefore presumably its temperature) vary substantially, it is not entirely accurate to say that it lies in the instability strip. In fact, the instability strip widens at high luminosities (indeed, it extends across the entire top of the H-R diagram), so the terms "instability strip" and therefore "Cepheid" lose some of their meaning.

The amplitude and time scale of rho Cas are not inconsistent with what would be expected in a very luminous Cepheid. There is a tendency for such stars to have lower amplitudes than less luminous Cepheids, both on observational and theoretical grounds (Carson and Stothers 1984).

Comparison of the time scale of rho Cas with the Cepheid period-luminosity relation is hampered by the fact that the luminosity of the star is not accurately known. It may be a member of the CAS OB5 (or IV CAS) association, but such membership is based mainly on positional coincidence. If it is a member, it has a true distance modulus of approximately 12.0 magnitudes (Humphreys 1978). Although some modifications to the distance scale have since been made, they are smaller than the uncertainty in this value.

In order to circumvent some of the problems of absorption, both interstellar and circumstellar, we will compare the period with that predicted by the infrared period-luminosity relations given by Welch *et al.* (1984). Infrared photometry of rho Cas is fragmentary. Gezari *et al.* (1984) give values of 2.59, 2.06, and 1.85 for the **J** (1.2 μ), **K** (2.2 μ) and **L** (3.5 μ) magnitudes, respectively. No **H** (1.6 μ) magnitude is listed. Applying absorption corrections consistent with a visual absorption of A_V = 2.13 (Humphreys 1978), we get true **J** and **K** magnitudes of 1.99 and 1.80, and true absolute **J** and **K** magnitudes of -10.0 and -10.2 approximately. For these absolute magnitudes, the infrared period-luminosity relations give periods of 302 and 240 days. These are in reasonable agreement with the time scales determined above. It should be stressed, however, that the variations of rho Cas are semiregular at best. The star seems to "remember" what it has done for two or three cycles, but not more.

We conclude that rho Cas resembles the Cepheid variables in some respects. It differs from them in its lack of regularity, probably because of its large radius/mass ratio. In this respect, it is more like the RV Tau and R CrB stars, and other variables with distended envelopes. The unique fading of rho Cas in the 1940's may be due to the marginal instability of its outer layers. Visual observation of this star should continue, both to monitor the semi-regular variations and to look for any repetition of the fading episode. We have shown that visual observations can be used to study variables such as rho Cas with amplitudes as small as $0^m.2$, as long as the observations are made frequently, carefully, and consistently.

6. Acknowledgements

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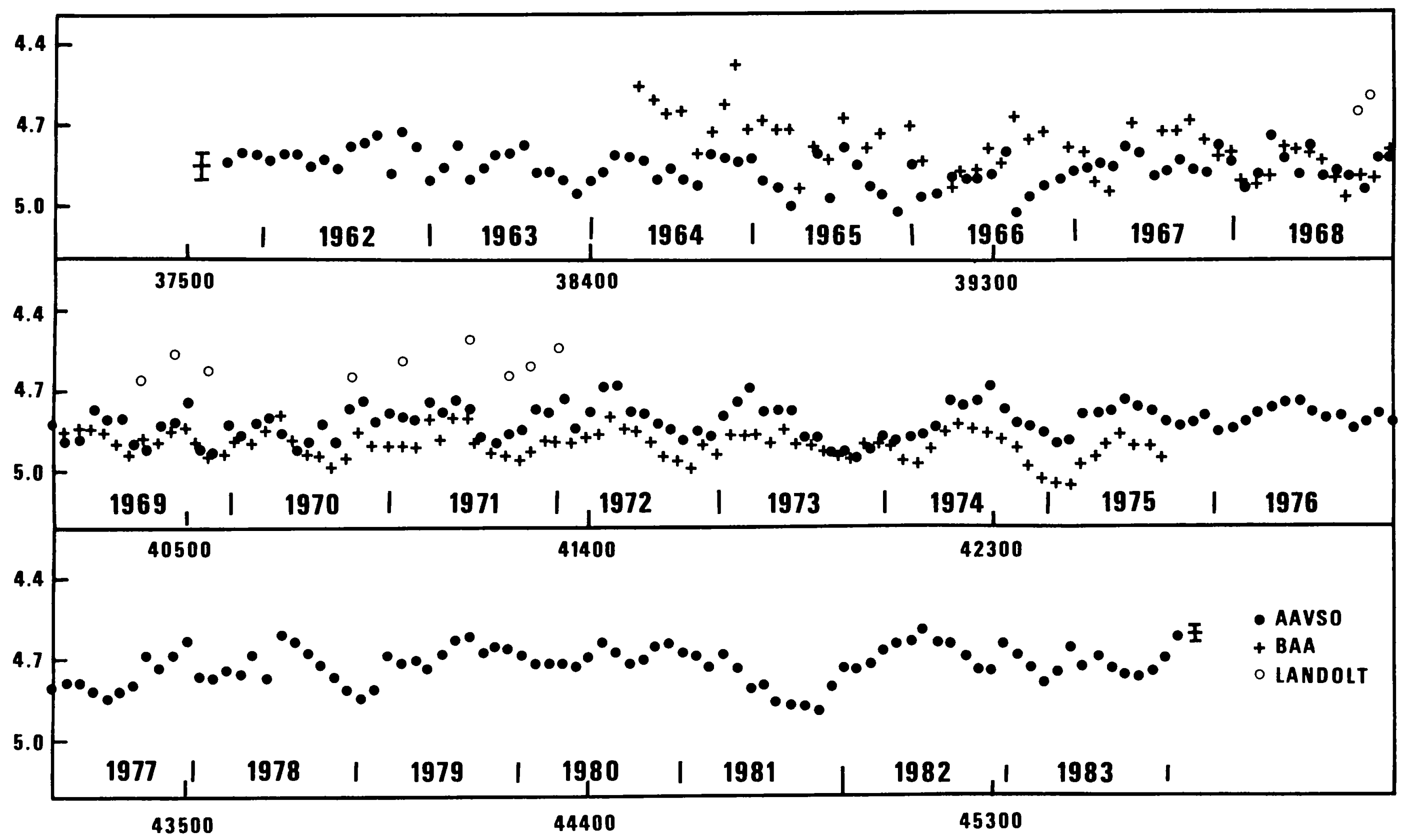

Figure 1. The Light Curve of Rho Cassiopeiae. The solid circles are 30-day means of AAVSO visual observations since 1962. The standard error of the mean is shown at the beginning and the end; the accuracy improved as more observers contributed. The crosses are 30-day means of BAA visual observations (Bailey 1978). The open circles are photoelectric observations by Landolt (1973). The reasons for the differences among the three sets of observations are discussed in the text. The cyclic variations on a time scale of about a year are certainly real.

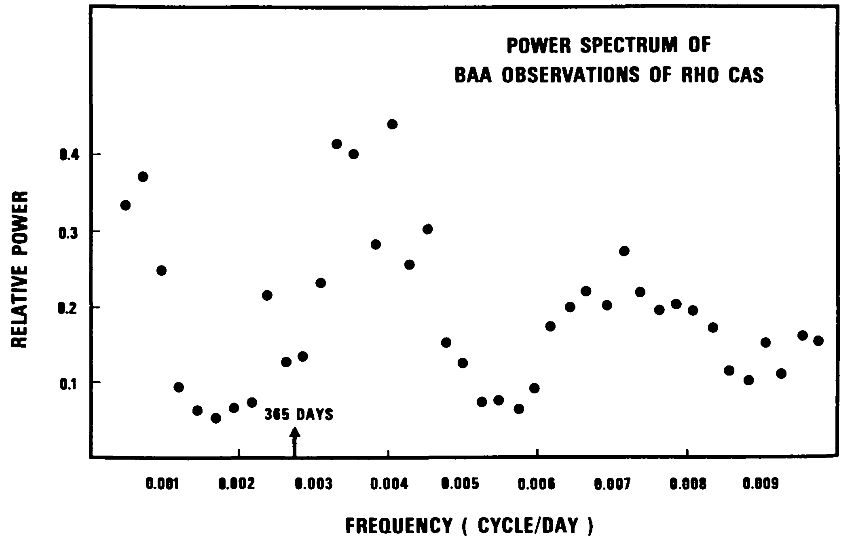

Figure 2. The Power Spectrum of BAA Observations of Rho Cassiopeiae. The spectrum was obtained by applying the standard Fast Fourier Transform to 30-day means of BAA visual observations (Bailey 1978). There is some evidence for a period of about 275 days, but this period is not found in the larger set of AAVSO observations. This suggests that the star is not strictly periodic.

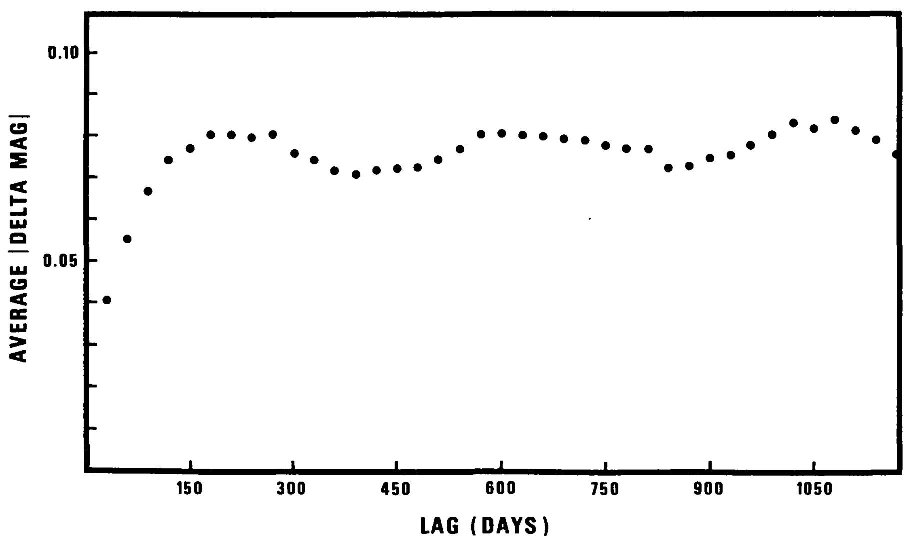

Figure 3. The Correlogram of the AAVSO Observations of Rho Cassiopeiae. A correlogram indicates whether observations are correlated with those obtained a given number of days (called the lag) earlier. In the present case, the observations show some tendency to repeat on a time scale of about 400 days.