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ANALYSIS OF SOME PHOTOMETRIC OBSERVATIONS OF GAMMA² VELORUM OBTAINED FROM THE SOUTH POLE

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ABSTRACT

We have obtained many hours of continuous photometry of γ^2 Vel with the South Pole Optical Telescope. In this paper we discuss the results and analysis of a 16-hour subset of these data. Indication of a 1.26-hour period of variability in the He II and C III emission lines at 4686 Å and 5696 Å, respectively, is presented. Although such a period has not been reported by other investigators, recent theoretical studies indicate that such a period may have certain theoretical implications.

Key words: Wolf-Rayet binary–emission lines–photometry

I. Introduction

Gamma² Velorum is a well-known spectroscopic binary with an orbital period of $78^{d}_{.}52 \pm 0^{d}_{.}01$ (Pike, Strickland, and Willis 1983). According to a spectroscopic study by Conti and Smith (1972) this system consists of a WC8 star and an O9 supergiant. The Wolf-Rayet component of this system exhibits very strong, broad emission features which are formed in an extended atmosphere resulting from stellar wind. Although such lines are in fact a signature of this class of objects, those formed in some Wolf-Rayet stars, including γ^2 Vel, have been detected to vary in line profile and line strength. Those authors who have detected fluctuations in line intensity for γ^2 Vel, in particular, generally associate these events with very short-period phenomena which can be as rapid as 150–200 seconds in length (e.g., Sanyal, Weller, and Jeffers 1974). A brief summary of the investigations of the rapid fluctuations of γ^2 Vel has been published by Jeffers, Stiff, and Weller (1985). It is apparent that these short-period variations are not present in all data sets obtained by observers, and one is led to believe that the events are probably ephemeral or intermittent. Results of recent theoretical modeling of Wolf-Rayet stars (e.g., Cox and Cahn 1988) have made it even more necessary to acquire a better understanding of these line-intensity variations. In this paper we present some interesting results of the analysis of 16 hours of continuous photometry of γ^2 Vel.

II. Observations

In January 1986 the University of Florida established an 8-cm automated refracting telescope at the Amundsen-Scott South Pole Station (Chen, Oliver, and Wood 1987). Our primary purpose is to exploit the unique conditions which exist at this site for nighttime astronomical research (Taylor 1988). The photometric system of the South Pole Optical Telescope (SPOT) consists of an EMI9781A photomultiplier maintained at approximately −5° C. The telescope is equipped with the Johnson standard *B* and *V* filters and several narrow-band filters which were chosen for our research on γ^2 Vel. The specifications of these filters are presented in Table I along with the corresponding optimum integration times for this star. The emission lines in which we are particularly interested are the He II feature at 4686 Å and the C III feature at 5696 Å.

In this paper we present the analysis of data obtained on 1986 July 10 covering the time period 5.1 UT–21.3 UT. A total of 2428 observations of γ^2 Vel were recorded where each observation is the average of 32 separate deflections taken within the specified integration time (Table I). In the course of this project, several different observing sequences have been implemented. The observing program used for the acquisition of these data consists of a set of sky readings, followed by 12 sets of stellar integrations, followed by another set of sky readings; each set of deflections consists of an observation in the helium, carbon, blue continuum, and oxygen filters.

TABLE I

Filter Specifications

Peak Wavelength (Å)	Half-Power band-width (Å)	Integration time (secs)	Purpose
4686	32	4	HeII
5696	32	8	CIII
4768	92	2	Continuum
5600	100	8	OI

The oxygen filter is centered on the strong O I auroral emission line at 5577 Å and allows us to monitor auroral sky variations which could contaminate the data. No such phenomena were detected by our telescope or recorded in South Pole meteorological reports during this time interval.

Since we are interested in emission-line variations relative to the continuum, it is not necessary to observe a comparison star as is typically the case in more conventional stellar photometry. Also, since the sky is extremely stable in the narrow-band filters used in this study, the 25–30 minutes which elapse between successive sky readings are not unreasonable. All of these considerations have resulted in a time resolution of about 1.6 minutes. This data spacing is not adequate to investigate thoroughly the periodic variations of 150–200 seconds reported by other authors; in those cases an observation was made every 5–10 seconds for an hour or less. According to the Nyquist criterion, the shortest period which can be resolved in a given data set is 2 Δt where Δt is the time between successive data points. In our case, then, the shortest period which could be detected is 3.2 minutes. A slightly more conservative range of periods, which is adopted here, assumes a minimum of three samples per cycle and covers the range from 5.4 hours to 4.8 minutes.

We have used Deeming's method of Fast Fourier Transforms (1975) for unequally spaced data to search for evidences of periodic phenomena in our data. The power function is computed with the relation,

$$P(v) = \frac{4}{N^2}\left\{\left[\sum_{i=0}^{N} D(t_i) \times \cos(2\pi v t_i)\right]^2 + \left[\sum_{i=0}^{N} D(t_i) \times \sin(2\pi v t_i)\right]^2\right\} , \tag{1}$$

where N is the number of data points, $D(t_i)$ is the ratio of the emission line to the continuum at time t_i, and v is the frequency in cycles day^{-1}. The corresponding power spectrum of the sampling function can be calculated with the formula

$$G(v) = \frac{1}{N^2}\left\{\left[\sum_{i=0}^{N} \cos(2\pi v t_i)\right]^2 + \left[\sum_{i=0}^{N} \sin(2\pi v t_i)\right]^2\right\} . \tag{2}$$

A plot of $D(t_i)$ as a function of time for the helium data is shown in Figure 1. The first step in the search for periodicities was to compute the power spectrum using the entire data set. The most prominent peak occurred at v = 19 corresponding to a period of 1.26 hours. In order to define this peak more accurately, and to determine whether or not the peak prevailed over the entire data set or was more of a transient phenomenon, the database was divided into subsets of approximately five hours each including a two-and-a-half-hour overlap with the preceding subset. For reasons stated previously, it is possible to detect periods in the range 1.7 hours–4.8 minutes. Figure 2(a)–(e) shows the resulting power spectra for each of these subsets. The arrow in the lower left of each plot represents the noise level assuming that all of the variation is white noise. The spectral power due to white noise is computed with the formula $\sigma_N = 4\,\sigma^2/N$ where σ is the standard deviation of the data set. As one can see, a rather strong peak is evident in plots (a)–(d) around v = 20. In plot (e) the peak occurs at a slightly lower frequency, v = 15.65. The generally accepted criterion for a peak to be statistically significant is a peak of at least four times the noise level. This particular peak has an amplitude ranging

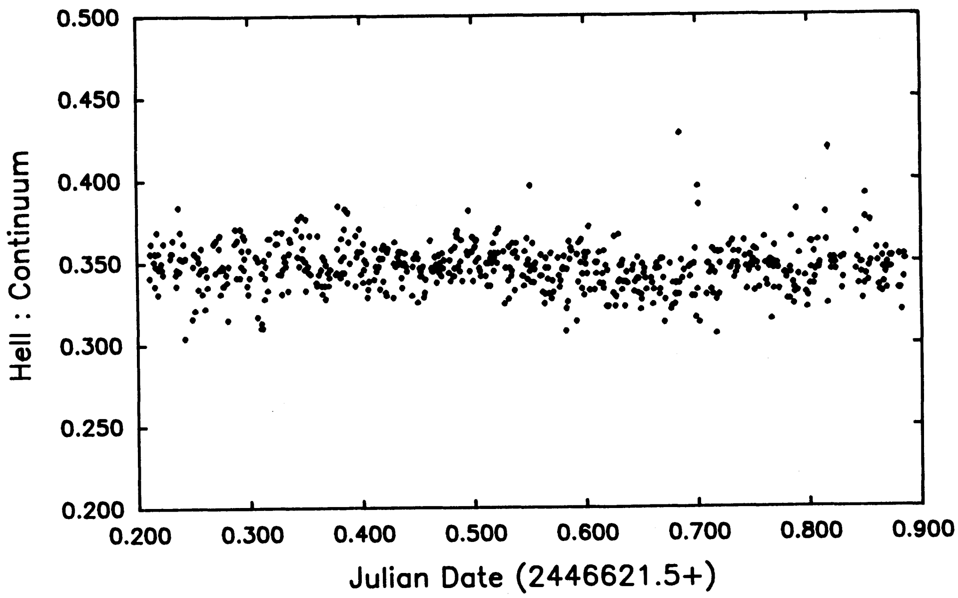

FIG. 1–The intensity of the He II emission relative to the blue continuum as a function of time.

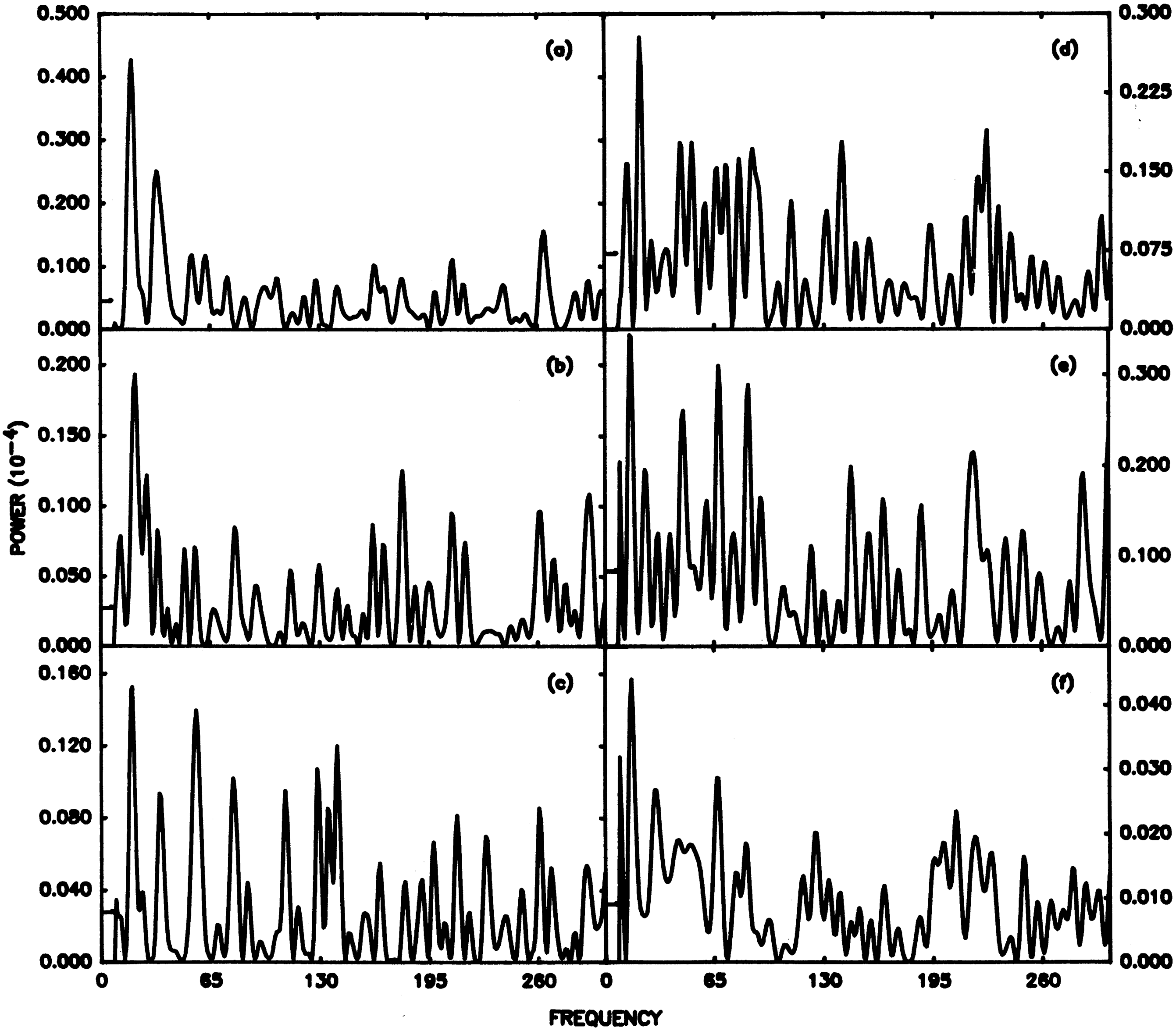

FIG. 2–Relative power spectra as a function of frequency (cycles day^{-1}) for γ^2 Vel. Plots (a)–(e) were computed from the helium data and (f) was computed from the carbon data.

from 3.9 σ_N on plot (d) to 9.8 σ_N on plot (a). Thus, even in the noisiest of data, this peak seems to indicate a real statistical variation. If we assume that the peak in each of these five power spectra is attributed to the same physical phenomenon, then we have evidence of periodic variations with

$$P = 1^{\rm h}\!.26 + 0^{\rm h}\!.16 \atop \qquad\quad - 0^{\rm h}\!.13 \; .$$

The only other statistically significant feature occurs in the first five-hour subset (Fig. 2(a)) at $v = 33.8$, $P = 42.6$ minutes. However, this peak is not discernible from the noise in any of the other spectral plots.

The corresponding measurements recorded with the carbon filter(Fig. 3) have also been analyzed in a manner similar to that described for the helium data. Here, $D(t_i)$ represents the ratio of the intensity of γ^2 Vel in the carbon filter to the intensity in the continuum filter. When the Fourier transform of the data in each subset was taken, the primary peaks corresponded quite well in frequency to those which resulted in the analysis of the helium data. With the exception of the last subset, however, the peaks did not climb substantially above the noise level; generally the amplitudes were only about 3 σ_N. The power spectrum of the last subset which is depicted in Figure 2(f) corresponds in time to Figure 2(e). In this case the amplitude of the peak is about 4.6 times the noise level and represents a statistically significant phenomenon. Again, as in the power spectrum of the helium observations, no peak is detected at $v = 20$ but instead occurs at the lower

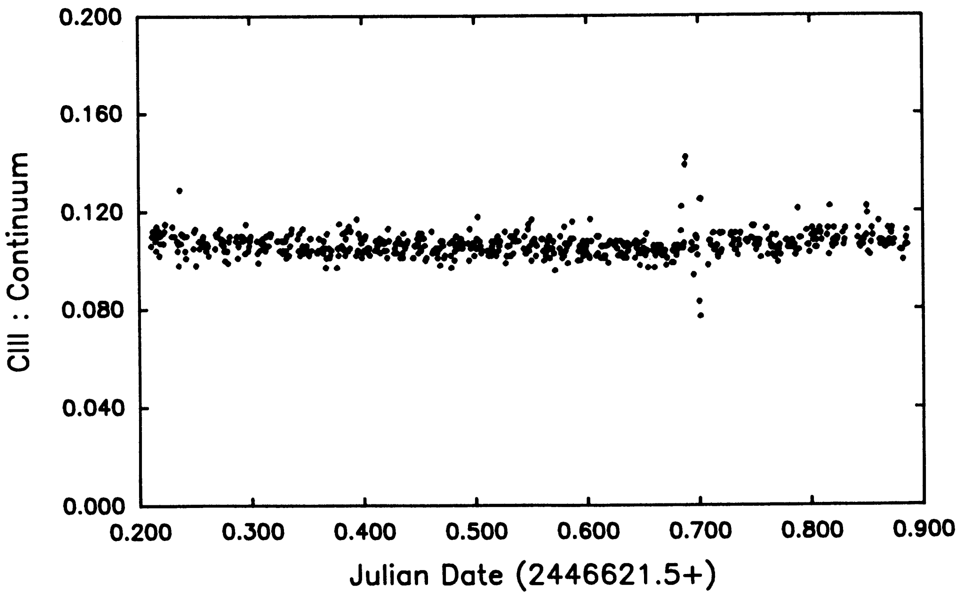

FIG. 3–The intensity of the C III emission relative to the blue continuum as a function of time.

frequency $v = 16.0$, very close to the frequency of the peak in Figure 2(e). The fact that the primary peaks in the power spectrum derived from the carbon data are not particularly strong is not surprising; the carbon emission line is considerably weaker than the helium line and, hence, more difficult to discern from the noise.

Because of the possible uncertainties intrinsic to the method of Fourier transform analysis, an independent method of period determination was also employed. This procedure utilizes the method of least squares to fit a sine wave of the following Taylor expansion to the data:

$$D(t_i) = B_0 + A_0 \times \sin[(t-t_0)/P] \ . \qquad (3)$$

Periods between 3.2 minutes and 8.1 hours were tested. Using an upper limit of 30 iterations, the strongest convergence occurred for a period of 1.26 hours. The strong agreement between the results obtained with these two independent methods provides additional support for the existence of a 1.26-hour period.

If such a period is assumed to be prevalent in these data, it should be possible to compute a light curve. This was accomplished by determining the average magnitude in every tenth of a phase interval. The resulting plot of phase vs. magnitude, presented in Figure 4, indicates an amplitude of variation of about $0\overset{m}{.}03$.

III. Discussion and Conclusions

We have presented evidence of variability in the emission lines of γ^2 Vel with a substantially larger period than cited previously. The frequencies at which the strongest spikes occur are well correlated in both the He II and the C III data. This leads us to believe that the physical phenonomenon resulting in such a periodicity affects those portions of the atmosphere where the emission lines are formed, although probably not to the same degree. Vreux (1987) has presented an overview of reported variations in WN and WC type Wolf-Rayet stars. Of the nine WN types and the seven WC types investigated, no periodic variations with periods between 2 minutes and 2 hours have been detected. However, fluctuations with periods on the order of minutes have been reported for some WC stars with the likelihood of periodic variations being greater for the later subtypes. Certainly, more observations of Wolf-Rayet stars are needed before we are able to provide the observational basis for a theoretical interpretation. In recent years the intensity variations of Wolf-Rayet stars have been considered to originate from stellar pulsations (e.g., Vreux 1987). Cox and Cahn (1988) have recently computed pulsational modes for five Wolf-Rayet star models with masses ranging from 20 to 120 $\mathfrak{M}_\odot$. In the context of the results presented in this paper, it is interesting to note that their 85 $\mathfrak{M}_\odot$ model yields the linear nonadiabatic radial modes of 1.95 hours and 1.23 hours for the fundamental and first harmonic periods, respectively. The periods computed for linear nonadiabatic nonradial modes are considerably longer, ranging from 2.95 hours to 20.8 hours. As stated by Vreux (1986): "Observational evidence for nonradial pulsations in Wolf-Rayet stars will require new observations which allow a search for periods less than one day and a search for multiple periodicities." This assertion certainly lends support for continued observation of these stars from the South Pole. We are presently analyzing the remaining data obtained with SPOT to search for the presence of other periodicities and to determine whether the 1.26-hour period reported in this paper is a transient phenomenon or a more persistent feature.

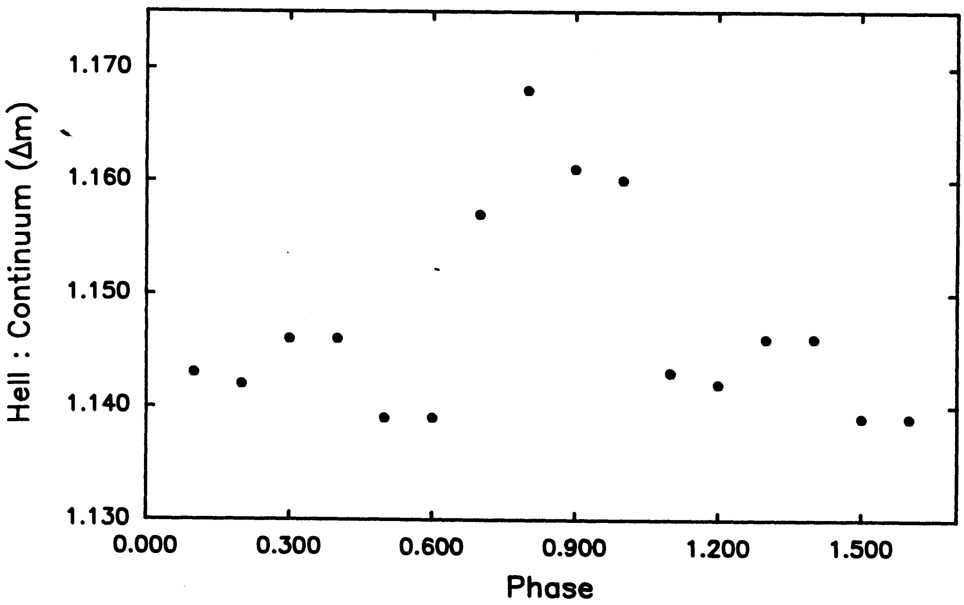

FIG. 4–A phase magnitude for γ^2 Vel assuming a 1.26-hour period.

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