ANALYSIS OF THE HELIUM STRONG STAR HD 37017

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ABSTRACT. High resolution and signal-to-noise spectra (0.22 A; S/N $\geq$ 50) of the H-alpha and He I 6678 A lines have been obtained over most of the cycle of the intermediate helium strong star HD 37017 with the Coude spectrograph and CCD camera at KPNO. These spectra are modeled with the non-LTE code of Mihalas to derive properties of the star. Both of the observed lines show small equivalent width variations on the previously known timescale of 0.901 days. The profiles can be simulated by a model with temperature 20,000K, log g=3.4, and helium number fraction 0.25, and which has a helium-rich spot of radius 40° and helium number fraction of 0.60 on the equator. Other possible models are discussed, as well as a model of the weak emission on the wings of H-alpha.

1. INTRODUCTION

The intermediate helium strong stars are early B stars, normally associated with very young groups of stars, which show abnormally strong lines of He I that seem to vary in strength with a timescale of about one day. They also exhibit variable hydrogen line profiles, both in absorption and emission, and variable magnetic fields. With these features in mind, I undertook a study at KPNO to obtain high quality spectra of the H-α line and a helium line to quantitatively interpret the behavior of several of these stars. At that time, only red-sensitive CCD detectors were available, and so the He I line at 6678 A was chosen. This line is formed in non-LTE conditions in the stellar atmosphere, and so models using this physics must be employed in any interpretation.

The star HD 37017 in the belt region of Orion is the star with the least extreme helium enrichment of those in Orion, and so is the first chosen here for analysis. The only detailed atmospheric study to date

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was made by Lester (1972), using photographic spectra, and with no accounting for possible variability on short timescale. He concludes that the temperature is 21,000K, log g is 4.4, number fraction of helium is 0.19, and the mass and radius are small for the effective temperature. Blaauw and van Albada (1963) solved for a binary orbit with a period of 18.65 days. Pedersen (1979) showed that the He I line at 4026 A varies in strength with period of 0.901175 days.

This paper summarizes an analysis of the H-α and the He I 6678 lines in HD 37017 in terms of non-LTE model atmospheres enriched above normal in helium atoms. Heasley and Wolff (1983) have analyzed the H-α profile of normal B stars, and found that the cores of such lines are in agreement with non-LTE atmospheres but the wings near the line core are too deep in the observed profiles (the discrepancy not exceeding 3%). Heasley, Wolff, and Timothy (1982) compared the profiles of the He I lines in several normal B stars to non-LTE models and concluded that the He I 6678 line is somewhat too strong in the observed profiles compared to models which mimic the star in the blue helium and hydrogen lines. This discrepancy is most serious for stars of higher temperature and lower surface gravity than the star under discussion.

2. THE SPECTRA

A total of 13 usable spectra of HD 37017 were obtained on three nights during January 1982 with the Coude spectrograph and feed telescope of KPNO using a Fairchild CCD camera. The configuration covered wavelengths 6540 A to 6690 A with a dispersion of 0.22 A/pixel. A signal-to-noise over 50 could be achieved in ten minutes for the helium stars in Orion.

Figure 1 shows the spectrum at five phases throughout the 0.901 day cycle, each scan being the average of two or three individual spectra. In the left panel is the H-α profile, and in the right panel is the Helium I 6678 A profile.

Typically the spectra show a rounded profile of the helium line, with equivalent width about 0.8 A and rotation of about 130 km/sec. They also show a sometimes-rounded, sometimes-pointed H-α line, with emission appearing on the red or the blue wing. The C II lines which appear on the red wing indicate a temperature of about 20,000K, even though other researchers have suggested a somewhat higher value.

3. THE ANALYSIS

Since only two lines were observed, the following strategy was adopted for the analysis. I assume a temperature of 20,000K based on the results of Lester (1972) and the visibility of the C II lines. The helium line strength implies a range of gravities and compositions which are almost independent of the assumed temperature. The hydrogen line strength implies a similar requirement, but one which is more sensitive to the assumed temperature and is not sensitive to the gravity. Thus for each spectrum, at the assumed temperature, there is only one gravity and composition for which the model has the observed line strengths.

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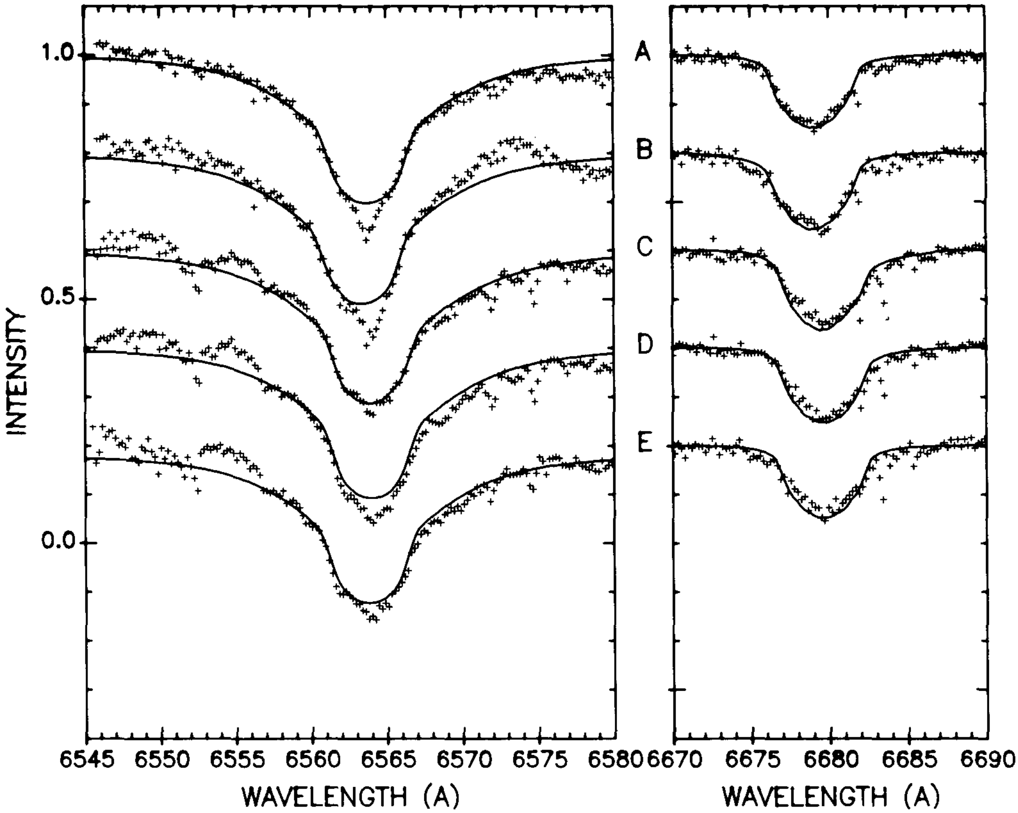

FIGURE 1--Spectra of HD 37017 taken at five phases during its cycle. In the left panel is the H-α profile, and in the right is He I 6678A.

Profile	Phase	W (H-α)	W (He I)	Comments
A	0.06	3.05	0.72	shows sharp H-α core
B	0.31	2.85	0.81	sharp H-α core, red emission
C	0.64	3.15	0.84	blue emission on H-α
D	0.72	3.35	0.76	blue emission on H-α
E	0.86	3.70	0.75	blue emission on H-α

The solid line through each profile is the prediction of a non-LTE model atmosphere which has a temperature 20,000K, log g≈3.4, NHE/NTOT (helium number fraction)≈0.25, rotational velocity 130 km/sec. The model, which is viewed equator-on, has a helium rich spot on the equator 40 degrees in radius and with NHE/NTOT 0.60.

The phase convention is the same as Pedersen (1979) where P = .901175 day and phase zero is at HJD 2442777.5. This means that the helium lines reach maximum strength at phase 0.5; this is when the spot is viewed on the center of the model's disk.

Models of helium rich stellar atmospheres were generated for several temperatures, surface gravities, and helium number fractions with the non-LTE code written by Mihalas. These atmospheres, described in Odell and Voels (1986), use simple geometry (plane-parallel) with no vertical or horizontal variation of composition. The variablility of line strength observed in the intermediate helium strong stars has been interpreted as due to regions of helium enhancement on the surface. Here it is assumed that the region inside the spot differs from its surroundings only in helium content, and that the intensity of light coming from any point on the star's surface is that from an atmosphere with the local composition, i.e., the temperature and surface gravity are assumed the same inside the spot as outside it.

It was found that intensities at a certain zenith angle and wavelength can be interpolated linearly in log g and NHE/NTOT to about 1% in the range of characteristics for which atmospheres were computed. Thus for any assumption of stellar characteristics, line profiles can be computed from the model atmospheres. From the line profile of He I 4026 A, the R-index defined by Pedersen (1977) can be predicted. This index is contaminated in the sense that the He I line at 4009 A affected the blue continuum band. Unfortunately, this other line was not included in the computation of the model atmospheres, and so the He I 4387 A line (from the same series) was used to correct for this effect. In all of the models reported here, this correction was small and amounted to less than three percent.

4. RESULTS OF THE MODEL

Figure 2 shows the equivalent width of the helium line as it varies with phase. Both the He I 4026 A line strength parameter R of Pedersen (1979) and the He I 6678 A equivalent width show a constant value for the first and last quarter of the cycle, which I interpret as the helium rich spot being on the far side of the stellar disk. From the line profile taken during this phase (spectrum A in Figure 1), the normal stellar surface can be understood as having surface gravity log g=3.4 and NHE/NTOT=0.25. The solid lines through the two profiles in spectrum A are the prediction of this model. Although the helium line agrees well with the model, there is a sharp absorption feature at the center of H-α which is discrepant from the model. On the far red wing of H-α (between 6575 and 6580 A), there is a slight depression of the observed intensities below the predicted profile; this is due to the C II lines, which are not included in the model atmosphere calculation.

I had thought that variations in the profile of the helium line would uniquely define the geometry on the stellar surface. Figure 2 shows an increase in both the R-index and the He I 6678 A line equivalent width as the spot of helium-rich material comes onto the visible face of the star. The spotted model reveals that almost the only effect of the spot appearing on the approaching limb of the star is to increase the line strengths. The changes in the profile which are expected even from this extreme case (spot on the equator) are too small to be noted in the 6678 A line profile.

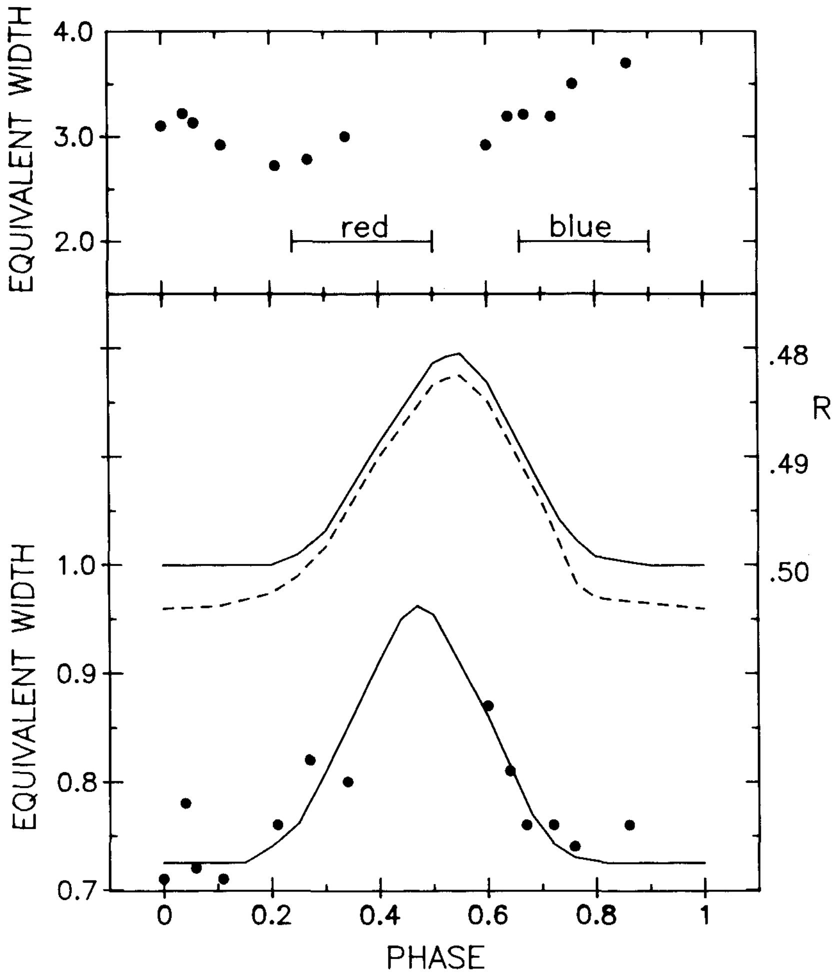

FIGURE 2--The top panel presents H-α equivalent width, as a function of phase (ephemeris same as figure 1). Also shown in the top panel is the range of phases where emission is seen on the red and blue wings of H-α.

The bottom panel shows the R-value (He I 4026 line strength observed by Pedersen (1979), shown dashed), and He I 6678A equivalent width. The predictions of the model stellar atmosphere, described in the figure 1 caption, are shown in solid lines.

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Spectrum B in Figure 1 (phase 0.31) shows the helium line somewhat stronger due to the appearance of the spot on the approaching limb. The hydrogen line still exhibits the sharp core, and also has an emission feature on the red wing, at about 6573 A, or a velocity of +500 km/sec from the absorption center and about 5 A (250 km/sec) wide. In the individual spectra it persists until phase 0.50 before disappearing.

During the last part of the rotation cycle, as the spot passes toward the receeding limb, the helium lines return to their initial strength, as shown in Figure 2. The hydrogen line loses most or all of the central absorption feature, but in spectrum C, D, and E there can be seen an emission feature on the blue wing, at 6553 A, or -500 km/sec from the absorption core, about 250 km/sec wide. The emission is seen between phase 0.64 and 0.92.

Groote and Hunger (1982) point out that for spotted models of Sigma Orionis E, the behavior of a helium line depends on its strength. In the weaker lines, increasing the helium abundance increases the depth of all points across the line, while in the stronger lines, the central core of the line actually gets shallower, even though the line becomes stronger as a whole. According to this definition, the He I 6678 A line is intermediate in strength and should show no large variation of profile as the spot becomes visible on the surface.

The lack of line profile variation in the observations means that other models would also yield acceptable fits. It is not necessary to place the spot on the equator, as was done here. If it were closer to one pole, the line profiles would vary even less. The data do not require a spot--the banded model proposed by Bolton (1984) could also be made to fit the changes of the helium lines.

A more interesting case would be that geometry suggested by the magnetic field variations observed by Borra and Landstreet (1979). If the stellar radius were 4 $R_{\odot}$ as they take it to be, then the rotation speed and period imply an inclination about 42°. The magnetic field behavior then requires an obliquity of magnetic pole to rotational pole of 39°. A model with a normal helium abundance everywhere but in a spot centered on the magnetic pole cannot reproduce all of the helium line characteristics. Even though this geometry would naturally explain why the other pole does not exhibit a spot (that pole is never on the visible disk), the spot would have to be too big and/or too helium rich to produce such small variations in the helium line strength.

The hydrogen line does not behave in a simple fashion compared to the models. For any temperature and gravity, the hydrogen lines increase strength with increasing helium content. This is due to a more rapid decline of continuum opacity than line opacity with increase in helium abundance. Figure 2, however, shows that the hydrogen line has maximum equivalent width at phase 0.00 rather than at helium line maximum. The hydrogen line strength being out of phase with the helium spot cannot be understood in terms of any changes of the model stellar atmosphere.

The photospheric hydrogen line is certainly modified by both an excess absorption near the line core and the emission which appears on each wing. It is possible that this interference causes the hydrogen strength anomolies, but a more likely explanation is the pervasive telluric water vapor absorption and its erratic effect on the H-α line.

5. THE CIRCUMSTELLAR MATERIAL

The behavior of the H-α emission and absorption puts very severe restrictions on the model invoked to explain them. The emission is coupled to the rotation period, presumably forced to rotate with the stellar surface through the magnetic field. In order to have the proper velocity compared to the photosphere (i.e., about three times the rotation velocity), the emitting gas must be at least two stellar radii above the surface, and further out if it is at high latitude.

However, the velocity of the gas is observed to be always the same, appearing first at high velocity, as can be seen in the blue wing of the H-α line in spectra C, D, and E of Figure 1. If the material were to appear from behind the stellar disk, the component of the velocity in the line of sight of the earth would be only 150 km/sec -- far from that which is observed. If the gas were close to the stellar surface, so that it would be moving directly toward the earth when it became visible, it would never achieve a velocity shift larger than 200 km/sec.

Another feature which is seen in the individual spectra is that the red emission is stronger (about 0.25 A in equivalent width) than the emission which appears later on the blue wing (which is never more than 0.13 A in equivalent width). This is only possible if the emitting region which is seen receding is not the same as the one seen later to approach, or if the gas is optically thick and not homogeneous.

Nakajima (1981) has suggested a magnetospheric model in which gas left over after star formation is trapped at the points where the magnetic and rotational equators intersect. Qualitatively, this model is appealing, but the observations require a more complicated geometry. The profile shown in that paper for an obliquity of 90° between magnetic and rotational poles bears remarkable similarity to the features seen in HD 37017. However, the gas density must be at least 100 times less than the critical density in Nakajima's model. Further, the time dependent behavior of his model will be different from the observations, and the second junction point of magnetic and rotation equator must be empty for this star.

A model which qualitatively fits the appearance and disappearance of the spectral features requires that the gaseous region strech about one-third of the way around the star. Thus the sharp absorption core appears on H-α when the cloud is superposed on the star's disk between phase 0.0 and 0.35. The gas only contributes a noticeable red emission feature when it is seen at elongation and receding, from phase 0.25 to 0.50. The gas is first seen approaching earth at elongation when the phase is 0.65 and remains visible until phase 0.90.

Whether this distribution of gas will quantitatively predict the line profiles which are observed, and whether this model is compatible with the magnetosphere of Nakajima remains to be demonstrated. The model also leaves unexplained the asymmetry of the gas distribution on the two sides of the star.

6. CONCLUSIONS

1. HD 37017 is only moderately enriched in helium over normal B stars with helium number fraction about 0.25. The star is rotating at about 130 km/sec, projected to the line of sight.

2. The surface gravity is low, about 3.4 for log g. This implies a mass much smaller than that of typical B stars and suggests that the star is helium-rich throughout.

3. The variation of the line profiles during what is presumably one rotation is minimal; the details of the variable line strengths over the cycle cannot be explained by a model having normal composition and a spot that is always visible.

4. The generally accepted explanation of the source of the emission is mass trapped by the magnetic field, which is carried by that field as the star rotates. In HD 37017, the behavior of H-α can be understood in terms of a thin stream of gas about two stellar radii from the surface which passes across the face of the star between phase 0.00 and 0.35. The gas is so tenuous that it can only be seen in emission when it is at the elongation points.

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