A FIVE-YEAR SPECTROSCOPIC AND PHOTOMETRIC CAMPAIGN ON THE PROTOTYPICAL $\alpha$ CYGNI VARIABLE AND A-TYPE SUPERGIANT STAR DENEB

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ABSTRACT

Deneb is often considered the prototypical A-type supergiant and is one of the visually most luminous stars in the Galaxy. A-type supergiants are potential extragalactic distance indicators, but the variability of these stars needs to be better characterized before this technique can be considered reliable. We analyzed 339 high-resolution echelle spectra of Deneb obtained over the five-year span of 1997 through 2001 as well as 370 Strömgren photometric measurements obtained during the same time frame. Our spectroscopic analysis included dynamical spectra of the $\alpha$ profile, $\alpha$ equivalent widths, and radial velocities measured from Si ii $\lambda\lambda$ 6347, 6371. Time-series analysis reveals no obvious cyclic behavior that proceeds through multiple observing seasons, although we found a suspected 40 day period in two, non-consecutive observing seasons. Some correlations are found between photometric and radial velocity data sets and suggest radial pulsations at two epochs. No correlation is found between the variability of the $\alpha$ profiles and that of the radial velocities or the photometry. Lucy found evidence that Deneb was a long-period single-lined spectroscopic binary star, but our data set shows no evidence for radial velocity variations caused by a binary companion.

Key words: stars: early-type – stars: individual (Deneb) – stars: mass-loss – stars: variables: general – supergiants

Online-only material: color figures, machine-readable and VO tables, supplemental data (FITS) file (tar.gz)

1. INTRODUCTION

$\alpha$ Cygni variables are highly luminous OBA stars that exhibit low amplitude variations both in photometry ($\Delta V \lesssim 0.15$ mag; van Genderen et al. 1989) and velocity (e.g., Abt 1957). These variations are common for massive stars and are observed in most hot supergiants as well as the overluminous supergiants such as luminous blue variables. The variations have been observed in some main-sequence massive stars, and the mechanism responsible for the variations has eluded theory and observers. Photometric and spectroscopic campaigns on multiple stars that span the upper H–R diagram and exhibit these variations will be crucial to understanding these variations and their source.

Deneb ($\alpha$ Cygni, HR 7924, HD 197345) is an early-type A supergiant (spectral type A2 Iae) and is the prototype for the $\alpha$ Cygni type variable stars. With a great apparent brightness and because it can be observed for most of the year at northern latitudes, Deneb can be easily studied spectroscopically with small or moderate aperture telescopes. Deneb has been one of the most studied A-type supergiants. Fath (1935) and Paddock (1935) made the first variability studies of this star, using photometry and radial velocities, respectively. Abt (1957) observed nine supergiants, including Deneb, and showed that early- and intermediate-type supergiants exhibited oscillations of their atmospheres. Lucy (1976) presented a harmonic analysis of Deneb which demonstrated that multiple oscillations were present in the atmosphere of the star. He also discovered what appeared to be a binary period in the radial velocities of Deneb. Parthasarathy & Lambert (1987) made 123 spectroscopic observations of Deneb in the near-infrared between 1977 and 1982 at McDonald Observatory. They found radial velocity variations similar to those observed by Paddock and analyzed by Lucy, and claimed that the binary motion was recovered but presented no time-series analysis.

The underlying cause of the brightness and velocity variations of the $\alpha$ Cygni variables has been recently analyzed by a few authors. Saio et al. (2006) found that long-period oscillations in HD 163899 could be understood as $g$-mode pulsations that are trapped in a convection zone positioned above the H-burning shell of the star. An investigation of Deneb’s variability by Gautschy (2009) gave evidence that Deneb also has a subphotospheric convection zone driving the variability. Cantiello et al. (2009) showed how iron convection zones above the H-burning shell could be the cause of the microturbulence and clumping in the base of the wind of hot stars. The variability for the $\alpha$ Cygni variables decreases in amplitude and timescale toward higher effective temperatures, and therefore these processes are easier to observe in the cooler A-type supergiants such as Deneb (e.g., Lefever et al. 2007).

Kauf er et al. (1996, 1997) examined the radial velocity variations and the $\alpha$ profile variations of Deneb and five other supergiants. They found that the radial velocities were multi-periodic and showed different periods in different observing seasons. They also found that the equivalent width of $\alpha$ exhibited multiperiodic variations and evanescent periodicities. In contrast, Morrison & Mulliss (1998) reported finding a much more active, and possibly cyclic, variability in the $\alpha$ profile. Often there are “absorption events” in which a secondary absorption component appears on the blue wing of the absorption component of the $\alpha$ profile.

The literature on the photometry of Deneb is remarkably sparse, mostly due to its great apparent brightness ($m_V = 1.25$), combined with the fact that there are no comparison stars of similar brightness in the vicinity of Deneb. Adelman & Albayrak (1997) used HIPPARCOS observations of Deneb, as well as...
other early A-type supergiants, to show that these objects are small or moderate amplitude variables (a few hundredths or a tenth of a magnitude in amplitude). The light curve was not complete enough to state more than there was a period of the order of about 2 weeks, but there were most likely other effects to take into account.

It has long been known (e.g., Abt & Golson 1966) that the strength of the Hα emission in hot supergiants is correlated with the stellar luminosity. The potential of this fact for the use of techniques for echelle spectroscopy via an IRAF5 script.

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4. RESULTS AND TIME-SERIES ANALYSIS

4.1. Dynamical Spectra of Hα

Dynamical spectra were created for each observing season in order to explore the temporal behavior of the Hα profile. Figure 1 shows the variations of Deneb during calendar year 1997. Several strong absorption events occur on the blue wing of the P Cygni profile at intervals of approximately 40 days. We define an absorption event for Deneb by the presence of a second absorption component in the blue wing of the principal absorption component. Usually this second absorption had a velocity blueshifted less than 100 km s\(^{-1}\). The emission component remained fairly static, with the exception of two periods of strengthening. The absorption events we observed do not show a progression to the terminal velocity, as seen in discrete absorption components of other hot, massive stars or in the high-velocity absorption events described by Kaufer et al. (1996) in hotter supergiants such as Rigel (B8 Ia). Aufdenberg et al. (2002) found that the terminal wind speed for Deneb is 225 km s\(^{-1}\). Neither this observing season nor subsequent observing seasons show evidence that the Hα absorption reaches the terminal wind speed. The line probably has a low optical depth at large distances from the star due to insufficient population in the \(n = 2\) level.

The cyclic-type behavior during the 1997 observing season was not repeated in the other observing seasons. The 1998 season (Figure 2) exhibits two absorption events, which are farther apart than the 40 day interval of the 1997 season. The emission feature is nearly static for that year of observations. The 1999 season (Figure 3) shows an exceptionally static Hα profile for this star, with a possible beginning of an absorption event at the end of the observing season. One absorption event is observed in 2000 (Figure 4), but showed a more rapid onset and disappearance than the other observed events in our data set. The 2001 season (Figure 5) began with a very strong absorption event, and included one smaller event around HJD 2452075–2452100. The time span of September and October of 2001 (HJD 2452160–2452240) provided an interesting event that is discussed in Section 4.2.

4.2. The High-velocity Absorption Event of 2001

The remarkable event of late 2001 began with a quick onset of a strong emission component. The absorption component reached a larger negative velocity than had previously been
Table 1
Spectroscopic Measurements of the Hα Profile and Si ii Doublet

| HJD      | Wλ Hα, Net (Å) | Wλ Hα, Emission (Å) | Wλ Si ii 6347 (Å) | Vλ Si ii 6347 (km s⁻¹) | Vλ Si ii 6371 (km s⁻¹) | σ(Vλ) (km s⁻¹) |
|----------|----------------|---------------------|-------------------|------------------------|------------------------|----------------|
| 2450546.91051251 | 1.46           | -0.29              | 1.75              | -5.18                  | -4.88                  | 0.81          |
| 2450588.86303180 | 1.24           | -0.21              | 1.45              | -1.50                  | -1.91                  | 0.85          |
| 2450590.84395394 | 1.26           | -0.21              | 1.48              | -1.75                  | -1.57                  | 0.77          |
| 2450591.85544913 | 1.28           | -0.18              | 1.46              | -1.73                  | -1.59                  | 0.76          |
| 2450604.79591576 | 1.21           | -0.20              | 1.42              | -5.35                  | -4.69                  | 1.00          |

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)

4.3. Hα Equivalent Widths

We measured the net equivalent widths of all our Hα profiles (Table 1, available online). The errors in these net equivalent width measurements are typically 1% of the measured value as determined using the methods of Chalabaev & Maillard (1983). The Hα profile shows a P Cygni type profile, so the net equivalent width does not provide a simple measure of all the variability. Using the IRAF task splot, we measured the equivalent width of the emission component by trying to interpolate linearly across the base of the component. Unfortunately, this method is prone to personal error. From multiple measures from the same spectrum, we derived a typical error for the equivalent width of the Hα emission component to be 5% of the measured value. We then subtracted the emission component from the net equivalent width in order to obtain an absorption equivalent width.

We found that the net equivalent width had an average value of 1.318 Å with a standard deviation of 0.197 Å. The overall estimated strength of the absorption component(s) varied by slightly more than a factor of two (Wλ Hα, abs = 2.172 Å on HJD 2450999; Wλ Hα, abs = 1.067 Å on HJD 2450669). The absorption component was 1.616 Å with a standard deviation of the mean of 0.209 Å.
Figure 6. Line profiles of Hα observed during the major 2001 absorption and emission event. Features to note are the development of deep secondary and tertiary absorption components, the increase in the Hα emission, and the near disappearance of the emission component beginning at HJD 2452214.5. All spectra are normalized to unity in the continuum and are plotted in the rest frame of Hα. The HJD − 2450000 is shown to the nearest integral day in each plot.

Table 2

| HJD     | u        | v    | b    | y    | u - b | b - y | c1   | m1   |
|---------|----------|------|------|------|-------|-------|------|------|
| 2450750.6404 | 2.292 | 1.347 | 1.172 | 1.171 | 1.057 | 0.001 | 0.707 | 0.174 |
| 2450751.6399 | 2.222 | 1.336 | 1.164 | 1.158 | 1.058 | 0.006 | 0.714 | 0.166 |
| 2450752.6566 | 2.215 | 1.332 | 1.158 | 1.153 | 1.057 | 0.005 | 0.709 | 0.169 |
| 2450753.6364 | 2.210 | 1.322 | 1.155 | 1.141 | 1.055 | 0.014 | 0.721 | 0.153 |
| 2450754.6564 | 2.197 | 1.314 | 1.142 | 1.142 | 1.055 | 0.000 | 0.711 | 0.172 |

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)

4.4. Radial Velocities and Photometry

In order to derive the systemic velocity of Deneb, we computed an unweighted average over all the observations of the Si ii λλ 6347, 6371 doublet, assuming no wind contamination of these lines. The result was $-2.77 \text{ km s}^{-1}$, which is consistent with values derived from other studies (e.g., Lucy 1976; Parthasarathy & Lambert, 1987). The radial velocity had a range of values from $-10.8$ to $9.1 \text{ km s}^{-1}$, consistent with the sum of the multiple pulsation mode amplitudes ($10.44 \text{ km s}^{-1}$) derived by Lucy (1976).

The differential $uvby$ Strömgren measurements (Table 2, available online) were averaged over all data to adopt the photometric parameters for Deneb given in Table 3. $u$, $v$, $b$, and $y$ had a range of 0.09, 0.14, 0.41, and 0.19 mag, respectively. The colors $u-b$ and $b-y$ had a range of 0.075 and 0.081 mag, respectively. The Strömgren indices $c1$ and $m1$ were found to vary by 0.233 and 0.141 mag, respectively.

4.5. Time-series Analysis and the Binarity of Deneb

In order to verify the reliability of various time-series analysis algorithms, their output was compared to that obtained by Lucy...
Figure 7. Dynamical spectrum of the Hα profile during the 2001 high-velocity absorption event. The average profile for this time period, plotted in the lower panel, has been subtracted. There is an onset of high-velocity absorption, followed by a second absorption event ∼40 days later. The second portion of this event is followed by an onset of absorption on the red wing, causing the emission to appear the weakest that we observed during the five years of data presented in this study.

Figure 8. Plots of the frequencies derived in the CLEAN time-series analysis. The symbol size is proportional to the relative strength of the derived frequency. The photometry produced similar results for all bandpasses, but only the y filter is plotted.

(1976) for the data collected by Paddock (1935). A Scargle periodogram analysis (Scargle 1982) of the data from Paddock (1935) only reproduced one aspect of the analysis of Lucy (1976), the long-term variability that was suspected to be binary motion of Deneb.

The confirmation of the binary nature of this prototypical supergiant would be useful for understanding the star, as well as its early evolution (including mass transfer) and estimating the current mass. We used the Scargle periodogram and the CLEAN algorithm (Roberts et al. 1987) to search our data set for the binary period and found that the power spectrum reached a relative minimum in the period range that was suspected. As Lucy (1976) could not add other data to the data of Paddock to better constrain the orbit (Section III of his paper), and our data do not suggest any binary motion, the binary hypothesis for Deneb is not supported.

A method that is more robust for data sets containing multiple periodicities, the CLEAN algorithm, was used to search for periodicities in the data sets. An analysis of the radial velocity data from Paddock (1935) produced similar results to that of Lucy (1976). The frequencies found with CLEAN in our data set are shown in Figure 8, where we plot the frequencies and their relative strengths found for each observing season for net Hα equivalent width, Si II radial velocities, and Strömgren y.

The time-series analysis was performed on the entire data set, but because of the changing characteristics of the star, no global properties were found with a high probability of being real. If the same period were found for all three data sets, there would be some evidence for a photospheric-wind connection, but our analysis showed no evidence of this behavior. Similarly,
if there were evidence for similar periods in just the photometry and radial velocities, that would provide information about pulsational behavior of the photosphere of Deneb.

4.6. Radial Pulsations

Our analysis did find some periods that were the same for the radial velocities and for the photometry during 1998 and 1999. The phased (to HJD 2450000.0) data were fitted (minimum $\chi^2$) with a sine curve of the form

$$N = A \times \sin(2\pi(p - x_c)) + c \quad (1)$$

where $N$ is the parameter we are fitting (radial velocity or magnitude), $p$ is the arbitrary phase we are solving for, $A$ is the amplitude, $x_c$ is a phasing offset, and $c$ is an offset for the systemic velocity or magnitude. The period was not allowed to vary during these fits. The parameters for our photometric and radial velocity fits are given in Table 4 for the two epochs of radial pulsations and the variations are shown graphically in Figure 9. The offsets in phase between the photometry maximum and radial velocity maximum for the two periods with the highest probability of radial pulsations (epochs with strong signals that match with both the photometry and radial velocity data; the fall of 1998 ($P = 17.8$ days) and the fall of 1999 ($P = 13.4$ days)) are roughly $0.25P$, which strongly supports the hypothesis that Deneb was experiencing radial pulsations at these epochs.

5. DISCUSSION

We have searched for high-velocity absorptions in a sample of B8 Ia–A2 Ia supergiants that have been monitored at Ritter Observatory since 1992. Our initial results, which are shown in Table 5, begin to constrain the range of effective temperatures in which supergiant stars exhibit high-velocity absorption events. With the five years of data we have analyzed combined with the data presented in Kaufer et al. (1996), only one high-velocity absorption event has been observed in Deneb. These events are thus very rare for this star. Other stars of similar properties ($\nu$ Cep$^b$ and 6 Cas) have not shown any signs of high-velocity absorption in a long time series of observations. We can therefore conclude that Deneb is at the lower end of the range of effective temperature and luminosity ($T_{\text{eff}} \sim 8500 \pm 200$ K, $\log(L/L_\odot) \sim 5.2$; Aufdenberg et al. 2002) for which supergiants can exhibit high-velocity absorption events.

As discussed in Section 4.6, we found evidence for radial pulsations in the atmosphere of Deneb at two epochs during our five-year investigation on this star. These pulsations were present for a few cycles and then vanished. Kaufer et al. (1997) did not find radial pulsations for Deneb, although their data may have suggested such variability. Simultaneous photometry of the star is necessary for finding the radial pulsations because the atmosphere is also unstable to many non-radial modes simultaneously. The light curves at the epochs

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6 For $\nu$ Cep, there are numerous cases of enhanced absorption in the blue wing with maximum absorption around $-100$ km s$^{-1}$ and edge velocity around $-200$ km s$^{-1}$ as in the Kaufer et al. (1996) definition, but the equivalent width involved is small. These velocities are sometimes hard to estimate because of water line contamination and/or indistinct edges. From the Mg ii profiles in the Verdugo et al. (1999) atlas, the terminal wind speed of $\nu$ Cep is lower than Deneb’s by about 35 km s$^{-1}$, so events will be harder to distinguish for that reason.
Gautschy (2009) has demonstrated that the variability of Deneb will potentially lead to a better understanding of its interior. A complete look at all the available data collected for this star for such a bright target, it is necessary to find such behavior. (see, e.g., Unno et al. 1979 for a description of non-radial where we found radial pulsations have an amplitude such that they cannot be easily explained with non-radial modes (see, e.g., Unno et al. 1979 for a description of non-radial oscillations).

6. CONCLUSIONS AND FUTURE WORK

Evidence was found for radial pulsations at two epochs during this campaign. Radial pulsations are somewhat rare in the atmosphere of Deneb, where the atmosphere does not usually display these variations. With only two short epochs having radial pulsations, we find that Deneb displays radial pulsations \( \lesssim 20\% \) of the time. While photometry was difficult to obtain for such a bright target, it is necessary to find such behavior. A complete look at all the available data collected for this star will potentially lead to a better understanding of its interior. Gautschy (2009) has demonstrated that the variability of Deneb may be indicative of an underlying convective region for this star. Detailed analyses of the variability of a larger population of supergiants could demonstrate if these intermittent radial pulsations are normal for the population.

A 40 day period was found with absorption events in 1997 as well as in the high-velocity absorption event of 2001. A similar period is reported by Kaufer et al. (1996) for the 1991 observations (\( \text{H}\alpha \)) of Deneb. Aufdenberg et al. (2002) derived a stellar radius of 180 \( R_\odot \) and \( v \sin i = \approx 25 \text{ km s}^{-1} \) for Deneb, which corresponds to a rotational period of 58 days. The \( v \sin i \) was used in the spectral line fitting of the star, and no error bars were given, but a small increase of \( \approx 10 \text{ km s}^{-1} \) to this parameter will yield a rotational period of \( \approx 40 \) days. Similarly, the radius of the star could be reduced by \( \approx 30\% \) to yield this period. With a poorly determined parallax (\( \pi = 2.31 \pm 0.32 \text{ mas}; \) van Leeuwen 2007), the interferometric radius determined by Aufdenberg et al. (2002) cannot be used to constrain this parameter. Therefore, we conclude that the 40 day period is consistent with the rotation period of the star and these observations may indicate occasional coupling between the photosphere and the wind.

During each observing season, the behavior of the \( \text{H}\alpha \) profile was different. Therefore, long-term monitoring (over multiple seasons) is crucial to understanding the variability mechanisms of stars such as Deneb. With the extreme variability seen at the time of the high-velocity absorption event in 2001, caution should be used in assigning mass-loss rates and other parameters to a single-epoch observation for Deneb and similar stars. Further work will be needed for the wind–momentum luminosity relationship (Kudritzki 1999; Kudritzki et al. 1999) with the variability of these stars taken into account.

There is a need for observing campaigns at high spectral resolution for stars in the temperature and luminosity regime of Deneb. The high-velocity absorption event we observed in 2001 is the only observed event for Deneb. High-resolution spectroscopic monitoring of Deneb at Ritter Observatory spans nearly two decades (1993 through present), and analysis of the entire data set is planned and will provide additional insights into the frequency of occurrence of high-velocity absorption.
events, of episodes of radial pulsation, and perhaps of other phenomena. Similar stars (in temperature and luminosity) need monitoring to see if Deneb is unique and where the temperature and luminosity boundary for high-velocity absorption events is located.

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