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ABSTRACT
The shape of the Ti I 6303.8 Å spectral line of Aldebaran as measured by the line bisector was investigated using high signal-to-noise, high resolution data. The goal of this study was to understand the nature of the 643-day period in the radial velocity for this star reported by Hatzes and Cochran. Variations in the line bisector with the radial velocity period would provide strong evidence in support of rotational modulation or stellar pulsations as the cause of the 643-day period. A lack of any bisector variability at this period would support the planet hypothesis.

Variations in the line asymmetries are found with a period of 49.93 days. These variations are uncorrelated with 643-day period found previously in the radial velocity measurements. It is demonstrated that this 50-day period is consistent with an \( m = 4 \) nonradial sectoral g-mode oscillation. The lack of spectral variability with the radial velocity period of 643 days may provide strong evidence in support of the hypothesis that this variability stems from the reflex motion of the central star due to a planetary companion having a mass of 11 Jupiter masses. However, this long-period variability may still be due to a low order \( (m = 2) \) pulsation mode since these would cause bisector variations less than the error measurement.

Key words: Stars: individual: Aldebaran - Stars: oscillations - Stars: variable - Stars: late-type

1 INTRODUCTION
Recent work has demonstrated that several K giant stars exhibit low-amplitude, long-term radial velocity (RV) variations with periods of several hundreds of days (McClure et al. 1985; Irwin et al. 1989; Walker et al. 1992; Hatzes & Cochran 1993). The nature of these variations is presently unknown. Radial pulsations can be excluded as a cause since the period of the fundamental radial mode is expected to be about a week. (These stars also show short-term variability on timescales of a few days which are due to radial or non-radial pulsations.) This leaves nonradial pulsations (NRP), rotational modulation by surface features, or low-mass companions as possible explanations for the long-period RV variations. K giant stars have large radii and low projected rotational velocities so the period of rotation for these stars is expected to be several hundreds of days. Rotational modulation thus seems to be a front-running hypothesis for explaining the long-term variability. If the surface features are related to stellar activity (spots, plage, etc.) then we should expect to find variations in the equivalent widths of lines, particularly ones formed in the chromospheric. Indeed, Lambert (1987) found variations in the He I 10830 Å line in Arcturus with the same period (233 days) that was later found in the RV variations. Larson et al. (1993) found evidence for the 545 day RV period in the equivalent width variations of Ca II 8662 Å in \( \beta \) Geminorum. It thus seems that the long-period variability is consistent with rotational modulation, at least for Arcturus and \( \beta \) Geminorum.

The confirmation of rotational modulation as the source of the RV variability has yet to be established for Aldebaran (= \( \alpha \) Tauri), a K giant with an RV period of 643 days and a 2-K (peak-to-peak) amplitude of 400 m s\(^{-1}\) (Hatzes & Cochran 1993; hereafter HC93). The interesting aspect of this variability is that it seems to have been present and coherent (same amplitude and phase) in RV measurements spanning over 12 years. If surface structure is responsible for the RV variability of this star then it must be very long-lived, which at first seems unlikely, but since nothing is known about surface structure on K giants this hypothesis cannot be summarily rejected. The lifetime and coherency of the long-period RV variations in Aldebaran would normally argue in favour of a low-mass companion. After all, one would expect changes in the amplitude and phase of the variations if they were due to a surface structure that was evolving (changing shape, size, or location on the stellar surface). However, the fact that so many K giants show long-period variability at about the same timescales makes us reluctant to embrace the low-mass companion hypothesis.

In a recent study of Aldebaran, Larson (1996) found...
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no evidence of the 643-day period in the equivalent width measurements of the Ca II 8662 Å, which is an indicator of chromospheric activity. This casts some doubt on rotational modulation as a possible explanation for the RV variability. However, the surface features on Aldebaran may be different from those which normally constitute stellar active regions (spots, plage, faculae) and as such these may show no modulation in chromospheric lines. One thing is certain though, for a surface feature, regardless of its nature, to produce RV shifts in the stellar lines it would have to alter the line shapes. Consequently the RV variations should be accompanied by spectral variability and the detection of these would provide strong confirmation of the rotational modulation hypothesis. Of the current explanations for the RV variability of Aldebaran, a low-mass companion seems to be the only one which should not produce changes in the spectral line shapes. Both surface features (e.g., Toner & Gray 1988; Dempsey et al. 1992) and nonradial pulsations (Hatzes 1996) should produce spectral line variations. A lack of such variability would provide more support for the planetary companion hypothesis.

Aldebaran is a slowly rotating star so the best method for discerning changes in the spectral line shapes is via line bisectors. Bisectors (the locus of the midpoints of horizontal line segments spanning the line width) have proved to be a powerful tool for studying subtle changes in the line shape due to the convection pattern on the star (Gray 1982; Dravins 1987) or cool surface features (Toner & Gray 1988; Dempsey et al. 1992). Recently, a study of the spectral line bisectors of 51 Peg was recently used to cast serious doubt on the validity of the planet hypothesis for this star (Gray 1997).

The objectives of this paper are simply to search for line bisector variability in Aldebaran. Such variability with the RV period would immediately eliminate the planet hypothesis as a cause of this period. A lack of bisector variability would exclude rotational modulation and possibly pulsations as viable hypotheses. The organisation of this paper is as follows. The data are described in Section §2 and the analysis of the spectral line bisectors is presented in Section §3 and it is demonstrated that bisector variability is indeed present, but at a period unrelated to the RV period. In Section §4 the nature of the bisector variability is examined. Finally, in Section §5 the implications of the bisector variability on the interpretation of the 643-day period is in examined.

2 DATA ACQUISITION

For the past several years at McDonald Observatory we have been using precise stellar radial velocity measurements (σ = 10–20 m s⁻¹) to study a variety of phenomena in stars, including K giant variability. In the early years of this programme the telluric O₂ lines were used as a wavelength reference for measuring stellar radial velocity shifts. This technique was first proposed by the Griffin & Griffin (1973) and we have confirmed their claim that it is capable of measuring stellar radial velocities to a precision of 15 m s⁻¹. These data are an ideal set for searching for spectral variability as they were taken at high spectral resolution, with high signal-to-noise ratio, and only a few of the spectral lines are blended with telluric O₂. There is the added advantage that the stellar radial velocity and line shape measurements were made from the same data set.

The observations were acquired at McDonald Observatory using the coudé focus of the 2.7-m telescope. An echelle grating was used in single pass along with a Texas Instruments 800×800 3-phase CCD. The wavelength coverage was 11.6 Å centred on 6300 Å at a spectral resolution of 0.036 Å (130 µm slit which subtends 2 pixels on the CCD). An interference filter was used to isolate the appropriate order from the echelle grating. Figure 1 shows a typical spectrum of Aldebaran taken with this setup. The horizontal lines mark the location of the telluric O₂ lines. (The wavelength scale of this spectrum has been corrected for both the Earth’s orbital motion and the overall radial velocity motion of the star. Although this places the stellar lines at the true rest wavelength, the telluric O₂ lines appear shifted from their proper wavelength position.) Typical signal-to-noise ratio per resolution element for a given exposure is about 450.

3 RESULTS

3.1 Line bisector measurements

For line bisector work one would like to use a relatively deep, unblended line. Unfortunately, Aldebaran is a cool star with a plethora of stellar lines so blending is a problem. From Figure 1 it appears that Fe I 6301.5 Å, Fe I 6302.5 Å, and Ti I 6303.8 Å satisfy this requirement. Regrettably, the two iron lines are often blended with a telluric O₂ line and this severely limited the size of the data set used for searching for variability. Consequently the Ti I 6303.8 Å line was best suited for computing spectral line bisectors. It is never blended with a telluric line and the stellar lines to either side are far enough from the Ti I feature so as not to affect the overall shape of its bisector, except near the continuum. Since we are primarily concerned with changes in the bisector shape, the small effect these blends may have on the absolute shape of the 6304 Å bisector is not a concern.

Figure 2 shows the spectral line bisectors of the 6304 Å line. On a given night typically 2–4 individual observations

![Figure 1. The spectral region of Aldebaran around 6300 Å.](image-url)
were made of Aldebaran and each bisector shown in Figure 2 represents a nightly mean. The horizontal lines to the left of the bisector represents a typical error in the bisector for a given flux level. These were computed assuming an average of two bisectors. Frequently, more than two bisectors were used in computing the nightly mean, so these bars represent a “worst case” error. Although many of the bisectors seem to fall on a mean curve bounded by the typical error, there appear to be instances of significant variability. Two bisectors showing extreme variability are marked by circles and squares.

To investigate in greater detail the bisector variability, the velocity span of the individual (nightly averages) bisector was measured. The velocity span, $S$, is merely the difference in velocity between two points lying on the bisector. In measuring this span it is important to avoid regions of the bisector with the largest errors, namely the core of the lines and the wings. The wings should also be avoided due to line blending. The flux levels of 0.45 and 0.85 were chosen for the end points of the velocity span. Table 1 lists the velocity span measurements for the nightly bisector. The typical error for a mean velocity span is about $\pm 25$ m s$^{-1}$.

<table>
<thead>
<tr>
<th>Julian Day (-2440000)</th>
<th>Span (m s$^{-1}$)</th>
<th>Julian Day (-2440000)</th>
<th>Span (m s$^{-1}$)</th>
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<tbody>
<tr>
<td>7429.9782</td>
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<td>7785.9796</td>
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</tr>
<tr>
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<td>7787.8543</td>
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<td>7611.6076</td>
<td>349</td>
<td>9260.9224</td>
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</table>

3.2 Period analysis

A period analysis was performed on the velocity spans in Table 1 using a Scargle-type periodogram (Scargle 1982). The results are shown in the top of Figure 3. The lower panel in the figure shows the window function. There is significant power at a period of 49.93 days and the probability that this peak arises from pure noise is 0.7% using the equation in Scargle (1982). This false alarm probability was also confirmed through numerical simulations. First, a series of 10,000 data sets consisting of random noise with $\sigma = 25$ m s$^{-1}$ and sampled in the same manner as the data yielded peaks in the periodograms that were larger than the data periodograms only 0.25% of the time. Finally, the bisector span measurements were randomly shuffled keeping the time values fixed. The fraction of a large number (10,000) of these “shuffled-data” periodograms also gave a measure of the false alarm probability. This value was 0.2%.

Figure 4 shows the velocity span of the bisectors phased to the period of 49.93 days. The vertical line represents a typical error for a span measurement. There are clear and convincing periodic variations with an amplitude at least twice that of the typical error.

3.3 Bisector variations of a constant star

It is important to establish that the bisector variations found in Aldebaran are indeed real and not due to some systematic error. A prime candidate for such systematic error is changes in the instrumental profile (IP) from run-to-run. These may cause slight changes in the shape of the line profile which would manifest itself as bisector variability. Although the coude spectrograph is very stable and great care is taken to ensure a constant IP (as a testament to this stability is the fact that the precision of our RV measurements is about 15 m s$^{-1}$; large variations in the IP would result in a poorer
RV precision) one should check that there is no significant variability in the bisector of a constant star.

Fortunately, as part of the programme, routine observations were made of the Moon which we use as an RV standard. These lunar observations have the advantages that 1) they are of comparable S/N as the Aldebaran data, 2) the Sun is known to be constant (at least to the level that we are interested in), and 3) the observations were taken on the same nights as the Aldebaran measurements. Because of the last point, any variations in the spectral line shapes that are due to changes in the IP from night-to-night would be apparent in bisector measurements for the Moon. Unfortunately, the Ti 6304 Å line in the solar spectrum is rather weak. However, two strong, apparently blend-free lines seemed to be suitable for bisector measurements: the Fe I 6302 Å line and the Fe I 6298 Å line. (The RV variations of the Moon were such that the Fe I 6302 Å line was always clear of the nearby telluric line; this was not the case for Aldebaran.)

Figure 5 shows the periodogram for the bisector span measurements of the Fe I 6302 Å line (top panel) and the Fe I 6298 Å line (bottom panel). The dashed line represents a false alarm probability of 1%. There are no significant peaks at a period of 50 days, nor is any peak significant below a false alarm probability of about 10%.

3.4 Stability of the instrumental profile

As a final test of the stability of the instrumental profile, the full-width at half maximum (FWHM) of a thorium emission line that was nearest in wavelength to the Ti 6304 Å feature was measured using spectra of calibration lamps taken on the same nights as the data. The rms variations of the FWHM was about 5%. Figure 6 shows the periodogram of the measured FWHM for the thorium feature. Once again there is no significant power near the period of 50 days ($\nu = 0.02 \text{ d}^{-1}$).

4 ON THE NATURE OF THE 50-DAY BISECTOR VARIABILITY

The residual RV data after removal of the 643-day period shows no obvious evidence for the presence of a 50-day period (see Section §4). Therefore, any mechanism for producing the line bisector variations must do so without introducing significant RV variability. Hatzes (1996) examined the spectral and RV variations expected for nonradial sectoral ($l = \pm m$, where $l$ and $m$ are quantum numbers of spherical harmonics) pulsations in stars whose spectral lines are not appreciably broadened by stellar rotation. These calculations showed that the largest RV amplitude was produced by the low order $m = 2, 3$ modes, but the largest change in the line bisectors occurred for the intermediate $m = 4$ or 5 modes. Particularly for g-modes the magnitude of the
metric changes in the line bisector span at \( m = 4-5 \) and declined toward lower and higher \( m \)-number.

To investigate whether nonradial pulsations can account for the spectral variations of Aldebaran, theoretical spectral line profiles from a nonradially pulsating star were calculated using a disk integration on a synthetic star that was divided into 120 × 120 cells. Local line profiles for each cell consisted of the Ti I 6304 Å generated using 20 limb angles and a model atmosphere for a K1 III star tabulated in Bell et al. (1976). A stellar inclination of 80° and a projected rotational velocity of 3 km s\(^{-1}\) were adopted in the modeling. The latter is comparable to the projected rotational velocity measured for this star (HC93). A macroturbulent velocity of 3 km s\(^{-1}\) was also included in the calculation.

The analysis of the bisector data revealed, to our surprise, no evidence for variability with the 643-day period. What are the implications for the various hypotheses that have been invoked to explain the RV variability? Before this can be answered we must be certain that 1) the 50-day period is not merely an alias of the 643-day period and 2) that a 643-day period is not hidden somewhere in the bisector variations.

**Figure 7.** The predicted radial velocity amplitude from nonradial pulsations which also produce a change in the line bisector velocity span of 100 m s\(^{-1}\).
5.1 Where is the 643-day Period?

The periodogram in Figure 3 shows no evidence for the 643-day period found in the radial velocity measurements of HC93. It is impossible for the long period to have been absent at the time of the bisector measurements since both these and the RV values were determined from the same data set. The closest peak is one at 550 days, a feature that is most likely associated with a feature in the window function. Monte Carlo simulations were performed to investigate whether aliasing or noise can cause a 643-day period to appear as a peak at 50 days in the periodogram. Synthetic data using a sine waves with a period of 643 days and an amplitude of 50 m s\(^{-1}\) (the amplitude of the span variations) were generated. These sine waves were sampled in the same manner as the data and random noise at a level of \(\sigma = 25\) m s\(^{-1}\) was also added. A series of 1000 synthetic data sets were generated and the periodograms calculated. In all but 18 cases the highest peak of the periodogram coincided with the input period. Of those 18 discrepant periods only one (at 60 days) was marginally close to the 50-day period of the bisector periodogram. (The other false periods occurred at 28 days, 20 days, 14 days, and 11 days.) We thus estimate that the chance of the 50-day period in the bisector measurements being caused by noise and alias effects of a true 643-day period is no more than 0.001. We are convinced that the 643-day period is not present in the bisector velocity span measurements.

Further evidence that the 50-day bisector period is uncorrelated to the RV variations is shown in Figure 8 which shows the velocity span of the bisectors plotted as a function of radial velocity. Although there seems to be a slight trend of decreasing velocity span with increasing RV velocity, the correlation coefficient, \(R = -0.29\), indicates that the two measurements are uncorrelated. More convincing evidence that the bisector span variations are unrelated to the RV variability is provided by a closer examination of some individual bisectors. The top panel of Figure 9 shows two line bisectors with the same radial velocity but whose velocity span differ by almost 80 m s\(^{-1}\). The lower two panels each show two bisectors whose velocity span differ only by 11 and 4 m s\(^{-1}\), respectively, but whose radial velocity difference is 285 and 185 m s\(^{-1}\), respectively. This figure demonstrates that large bisector variations are not always accompanied by large changes in the radial velocity. There are other instances when changes in the RV measures produce no measurable change in the bisector span.

Finally, the top panel of Figure 10 shows the velocity span measurements phased to the RV period of 643 days. The lower panel shows the radial velocity residuals (from HC93) after subtraction of the 643-day component, phased to the bisector period of 49.93 days. There is no strong evidence (as confirmed by periodogram analyses) of the 643-day period in the bisector span measurements or of a 49.93-day variation in the residual radial velocity measurements.

The absence of the 643-day RV period in the line bisector variations places better constraints on the nature of the long-term RV variability. The fact that the RV and line bisector variations are uncorrelated firmly excludes rotational modulation as a cause of the 643-day period. This leaves two hypotheses for the source of the RV variability: low-order \((m = 1-3)\) nonradial pulsations or a planetary companion.

5.2 Planetary companion

Table 2 lists the implied orbital parameters for the possible companion to Aldebaran. (Note that the orbital solution
found a slightly different period. The RV period will still
be referred to as the 643-day period which is the one found
via periodogram analysis). The fit of this orbit to the RV
measurements can be found in HC93. The implied m sin i
for the companion is 11 Jupiter masses.

There are a number of arguments in support of the
planet hypothesis for the RV period, besides the lack of
bisector variability at this period. First, as established in
HC93, the long-term RV period in Aldebaran has been
present at the same amplitude and phase for at least 12
years. It is difficult to understand why a single, long-period
mode could be so long-lived. Indeed, one K giant, Arcturus,
shows a number of presumably nonradial modes, not all of
which seem to be present at any given time (Smith et al.
1987; Belmonte et al. 1990; Hatzes & Cochran 1994). Also,
the two periods may result from two dis-
sipation modes have periods that can differ by more than a
order of magnitude which also seems un-
likely. However, long-term stable pulsations certainly exist
in Cepheid variables and it may well be that different pul-
sation modes have periods that can differ by more than a
factor of ten. Also, the two periods may result from two dis-
tinct pulsation modes. For instance the 50-day period may
result from nonradial g-modes, whereas the 643-day period
may result from Rossby (r-modes). Theoretical studies are
needed to resolve these issues in particular whether r-modes
can produce significant RV variability.

### 5.3 Nonradial pulsations

It is possible for a low order (m = 2) nonradial pulsation
mode to cause the RV variations since the amplitude of the
bisector velocity span variations should be significantly less
than those produced by an m = 4 mode. But are these
small enough to have been missed in the bisector analysis? The
RV amplitude of 150 m s\(^{-1}\) is reproduced by an m
= 2 mode with an amplitude of only 0.2 m s\(^{-1}\) (using k
= 1000 determined from Eq. 4). This results in variations
in the bisector velocity span with an amplitude of 15-20
m s\(^{-1}\) which is less than the error of the measurement (σ
= 25 m s\(^{-1}\)). One could be argue that if this additional
bisector variability was present then it should contribute
to the error of the bisector measurement. It is true that
rms scatter of the bisector measurements in the phase curve
(Fig. 4) is near that expected from photon statistics which
tentatively supports the lack of other sources for bisector
variability. However, the number of data measurements are
too few and the exact error of the bisector measurements
too ill-determined to say anything conclusive. (For example
bisector error of 20 m s\(^{-1}\) added in quadrature to a variation
with a 15 m s\(^{-1}\) can reproduce the scatter about the mean
curve in Fig. 4).

The shape of the RV curve may provide further con-
straints on the nature of the long period variations and this
shape is best quantified by the eccentricity of the “orbital”
solution. The eccentricity of the orbit is ε = 0.147 ±0.008.
The predicted RV curve from an m = 2 pulsation mode (true
for all sectoral modes) is very nearly sinusoidal (see Gray &
Hatzes 1997) with an eccentricity of only 0.002. This would
argue against pulsations as a mechanism for producing the
RV variations, but again this is not conclusive for a number
of reasons. The pulsational period is quite large compared
to that of the fundamental radial mode and there can be
temperature variations or non-linear affects. The long pe-
period also implies a high radial order (n ≈ 100) for the pul-
sations which translates into a rather short vertical wave-
length. Consequently, the vertical velocity structure may be
changing rapidly through the line forming region which may
affect the source function. All of these mechanisms may af-
flect the shape of the integrated RV curve resulting in a
slightly eccentric “orbit.” The predicted RV curve from the
pure kinematic model which does not take into account any
temperature variations or any vertical velocity structure to
the pulsations may thus be too simplified a treatment for a
complicated physical process. Finally, there is no reason to
expect only sectoral modes. Other modes, or combination of
modes may be present and these may produce an RV curves
that departs from a pure sine wave.

### 6 DISCUSSION

The 50 day period found in the line bisector variations of
Aldebaran is most likely associated with a nonradial pul-
sation mode. The long period of the variations implies a
\(g\)-mode oscillation. Although this variation can be modeled
with an \(m = 4\) nonradial mode, we cannot exclude the pos-
sibility that this arises from a higher order mode, possibly
even one that is non-sectoral (l ≠ m). The bisector period
found in Aldebaran may be related to one in Arcturus. That
star showed a 46 day period with an amplitude $\approx 50$ m s$^{-1}$ in the RV measurements after subtracting the dominant 233 day component (HC93). Possibly these $\approx 50$ day periods represent an intermediate $g$-mode between the very short ($\approx$ days) $p$-mode oscillations and the very long ($\approx$ years) pulsation modes.

The lack of line bisector variability in Aldebaran with the 643-day RV period seems to support the hypothesis that these variations are due to a planetary companion. However, the presence of a low order $m = 2$ nonradial mode can also account for RV variations and apparent lack of bisector variability. Also, the fact that two periods have now been identified in Aldebaran would argue in favour of the pulsation hypothesis for both periods. Clearly, other types of measurements are needed before we can distinguish between the two hypotheses.

As previously mentioned, if the 643-day period is indeed due to a nonradial $g$-mode, then the vertical wavelength should be quite short. If the vertical velocity structure of the atmosphere is indeed changing rapidly, then this might manifest itself in the RV behaviour of different spectral lines. For instance, strong lines are formed, on average, higher up in the stellar atmosphere than weak lines. An investigation of the radial velocity as a function of line strength may reveal differences in the amplitude and phase between strong and weak lines which would provide confirmation of the pulsation hypothesis. Unfortunately, there are too few telluric O$_2$ lines (used as the wavelength reference) to do a line-by-line analysis of the radial velocity of Aldebaran with the data used in this study.

Photometric measurements may also help us choose between a planet or pulsations, although these may be difficult to make. The analysis of Buta & Smith (1979) can be used to estimate the expected photometric variations for Aldebaran. Geometric effects will only be considered because, as pointed out by Buta & Smith, temperature variations for long period pulsations are difficult to predict as these can be in-phase or out-of-phase with the geometric variations. Furthermore, the predicted photometric amplitudes for the temperature variations can be orders of magnitude too large due to nonadiabatic effects. The predicted photometric amplitude from geometric effects is only about $\Delta V \approx 0.1$ mmag for the 643-day period (assuming an $m = 2$ mode). Considering the brightness of Aldebaran (and the difficulty of finding a suitable comparison star) this may be an impossible measurement.

Photometry may be better able to confirm the 50-day bisector period. If this is indeed due to an $m = 4$, then the predicted pulsational amplitude is about 40 m s$^{-1}$ which would produce a photometric amplitude (from geometrical effects) of about $\Delta V \approx 0.6$ mmag which is comparable to the precision of the best ground-based photometric measurements (Henry et al. 1996).

In summary we have found evidence for changes in the spectral line shape of the Ti I 6303.8Å feature in Aldebaran with a period of 49.93 days. These variations are uncorrelated with the 643-day period found previously in the radial velocity measurements for this star. The 50-day period most likely arises from an $m = 4$ mode, although higher order modes cannot be excluded. The lack of spectral variations with a 643-day period excludes rotational modulation as a source of the RV variations. At the present time the planet hypothesis seems to be the simplest one which can explain the 643-day RV period as well as the lack of bisector variability with that period. However, due to the fact that so many K giants exhibit multi-periodic RV variations makes us somewhat reluctant to declare with certainty that Aldebaran is another star with a confirmed planetary companion. Ancillary measurements are needed to decide between these competing hypotheses.

7 ACKNOWLEDGMENTS

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REFERENCES


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$R = -0.29$
Relative Flux

Velocity (m/s)

$\Delta S = 77 \text{ m/s}$

$\Delta V_r = 0 \text{ m/s}$

$\Delta S = 11 \text{ m/s}$

$\Delta V_r = 285 \text{ m/s}$

$\Delta S = 4 \text{ m/s}$

$\Delta V_r = 185 \text{ m/s}$