Time-Series Photometry of M67: W UMa Systems, Blue Stragglers, and Related Systems

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ABSTRACT

We present an analysis of over 2200 V images taken on 14 nights at the Mt. Laguna 1 m telescope of the open cluster M67. Our observations overlap but extend beyond the field analyzed by Gilliland et al. (1991), and complement data recently published by van den Berg et al. (2002) and Stassun et al. (2002). We show variability in the light curves of all 4 of the known W UMa variables on timescales ranging from a day to decades (for AH Cnc). We have modeled the light curve of AH Cnc, and the total eclipses allow us to determine $q = 0.16^{+0.03}_{-0.02}$ and $i = 86^{\circ}{}^{+4}_{-8}$. The position of this system near the turnoff of M67 makes it useful for constraining the turnoff mass for the cluster. We have also detected two unusual features in the light curve of AH Cnc that may be caused by prominences. We have also monitored cluster blue stragglers for variability, and we present evidence hinting at low level variations in the stragglers S752, S968, and S1263, and we place limits on the variability of a number of other cluster blue stragglers. Finally, we provide photometry of the sub-subgiant branch star S1063 showing variability on timescales similar to the orbital period, while the "red straggler" S1040 shows evidence of an unexplained drop in brightness at phases corresponding to the passage of the white dwarf in front of the giant.

Subject headings: stars: — stars: blue stragglers — open clusters: individual (NGC2682)

1. Introduction

Thanks to high stellar densities and small velocity dispersions, stellar clusters stand out as environments with high frequencies of strong gravitational interactions between stars. In the cores of the densest globular clusters, collisions of single stars may occur relatively frequently (Hills & Day 1976). However, even for less active environments like open clusters, strong interactions between binary stars probably play an important role in modifying the orbital parameters of the binaries and facilitating stellar collisions (Hurley et al. 2001; Portegies Zwart et al. 2001). Current thinking identifies blue stragglers as one of the likely products of stellar interactions, so that an in-depth understanding of these stars could lead to a better understanding of the overall importance of environmental effects within stellar clusters (see Bailyn 1995 for a review).

As a byproduct of our project to monitor the partially-eclipsing blue straggler S1082 (designation from Sanders 1977), we made extensive observations of the fields around the core of the open cluster M67. In order to get complete coverage of the light curve of S1082 (period 1.0677978 d) observations over several nights needed to be made. After it was discovered that the light curve was variable on timescales of a month or less, our observational dataset was expanded further. The observations of that system are presented and analyzed in a separate paper (Sandquist et al. 2003). However, in combination with the large archive of radial velocity measurements for M67 stars (e.g. Milone & Latham 1994), photometric studies of blue stragglers can provide us with important clues to their current states, and may also lead to an understanding of the evolutionary route they followed before becoming identifiable as blue stragglers. W UMa variables are one class of binary star that can produce blue stragglers after angular momentum losses cause the two stars to coalesce.

M67 is a somewhat difficult target for comprehensive variability studies because of its large angular size, but several groups have presented results on the cluster. For example, Gilliland et al. (1991) combined relatively deep observations from several different observatories in a study of the core of the cluster. They serendipitously discovered two W UMa variables (S1036 and III-79), two blue stragglers with low amplitude δ Scuti pulsations (S1280 and S1284), and evidence of longer period variations in other stars. Their field was relatively small, however, so that it was nearly certain that other variables would be found. Recently van den Berg et al. (2002, hereafter vSVM) and Stassun et al. (2002, hereafter SvMV) presented photometric studies of variables in a larger field in M67. Their studies were initiated to look for variability among the X-ray sources within the cluster. Several of the known X-ray sources were shown to be low-amplitude variables, and photometry was presented for an additional W UMa variable (S757).

The present study complements these photometric studies in several ways. In a number of instances we are able to present better delineated light curves than vSVM and SvMV because we took shorter exposures and focused on observations in a single filter band. In addition, by combining our results with those of the other studies we are able to build a better picture of the variability of the light curves themselves on timescales ranging from days to decades for some of the better known variables. In §2 we briefly describe the observations, in §3 we discuss the reduction of the photometry, and in §4 we discuss the variables.

2. Observations

All of the photometry for this study was taken at the 1 m telescope at the Mt. Laguna Observatory using a 2048 × 2048 CCD on 19 nights between December 2000 and March 2002. The nights of observations are given in Table 1. The photometry was primarily in V band with typical exposure times of 20 s (ranging between 15 and 60 s depending partly on atmospheric transparency) to optimize the counts for the variable S1082. Exposures were usually separated by about 2.5 minutes due to a relatively long readout time for the CCD.

Guiding jitter and poor air flow at the site of the telescope typically restricts image quality to greater than 4 pixels (1.6 arcsec) in the best conditions. Observing conditions for the nights varied greatly, reaching FWHM of 13 pixels for some of the worst frames. The relative sparseness of the cluster worked in our favor though because decent photometry could still be done for many of the stars in the field.

Several hundred columns of the chip developed charge transfer problems during the December 2000 run. Because of this, measurements of stars that fell near these columns were eliminated. The remainder of the chip was not noticeably affected by this problem. In the January and February 2001 runs this problem was almost entirely corrected. The CCD was replaced for the March 2001 run and a two-amplifier readout was employed, which doubled the duty cycle for our observations. For the remainder of the observations the replacement CCD was used with a one-amplifier readout.

3. Analysis

3.1. Photometric Reduction

The object frames were reduced in usual fashion, using overscan subtraction, bias frames, and flat fields (usually twilight flats, with the exception of Dec. 11/12, 2000, Feb. 17/18 and 18/19, 2001, for which dome flats had to be used). We chose to rely on aperture photometry for this study. In the analysis we used the IRAF[1] tasks DAOFIND and PHOT from the APPHOT package. Curve-of-growth analysis was conducted using the IRAF tool DIGIPHOT.PHOTCAL.MKAPFILE in order to bring all photometric measurements to the same total aperture size. The general procedure is discussed in Stetson (1990). Individual nights were run separately through the curve-of-growth analysis.

In order to improve the accuracy of the relative photometry for the light curves, we used an ensemble photometry method similar to that described by Honeycutt (1992) in order to get a simultaneous solution for median magnitudes of all stars and relative zero-points for all image frames. Our implementation is described in more detail in Sandquist et al. (2003). The solution was improved iteratively until none of the frame zero-points or median star magnitudes changed by more than 0.0005 mag between iteration steps. We allowed for the possibility that magnitude residuals could be a function of star position on the CCD for each frame by fitting second-order polynomials to the residuals in the x and y directions, and subtracting these fits during the solution iteration. Occasionally these corrections amounted to a few centimag.

In reducing the data, we paid close attention to possible correlations of residuals with external variables like seeing, airmass, sky intensity, exposure time, and the photometric zeropoint of the frame (see Gilliland et al. 1991 for a detailed discussion of the reasons). During the photometric reductions, we discovered that the photometry of a handful of the bluest stars in the sample showed significant variations of approximately 0.02 mag from night to night. On further investigation, we found that for several of these stars the photometric variations around the median values were definitely correlated. Although we have been unable to determine the exact cause of this problem, we were able to verify that the correlations in the variation were only detectable in stars with $B-V \leq 0.3$. In our sample this affected the blue stragglers S752, 968, 977, 1066, 1263, and 1267. None of these stars had strong variations, but in order to try to look for low amplitude changes we computed a running weighted average of the residuals derived from all of the stars observed on a frame and on up to 6 other frames closest in time. The correction was subtracted from the brightness measurement for each star. The results of this analysis will be discussed in more detail in §4.2.2.

[1]IRAF (Image Reduction and Analysis Facility) is distributed by National Optical Astronomy Observatories, which are operated by Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

3.2. Variability Analysis

To judge the significance of observed photometric variations, we used two different measures: the rms variations about the median magnitude σ_V and the Welch-Stetson index I_{WS} (Welch & Stetson 1993). I_{WS} measures the degree of correlation of pairs of brightness measurements, and is generally the more sensitive method of the two for detecting variability. This index gives high scores for previously known variables, with the δ Scuti star S1280 (a variable of low-amplitude) having the lowest score ($I_{WS} = 2.55$). In Fig. 1, we plot both measures as a function of magnitude for the stars in our samples to provide the reader with a means of judging the significance of the variations discussed below. This is complicated by the fact that seeing variations could result in correlated residuals for a star if a nearby star of comparable brightness contributed light to the aperture used to photometer the star. The variability indices plotted in Fig. 1 were calculated for measurements with the best seeing (FWHM $\lesssim 2\farcs5$) in order to reduce this confusion, although some of the stars with high scores are still affected by this effect. However, for the objects discussed in this paper, we verified that there is no correlation between the photometric residuals (defined as observed minus median magnitude) and seeing.

We used two different techniques to determine periods for the variables we observed: the Lafler-Kinman statistic (Lafler & Kinman 1965, hereafter L-K), and the Lomb-Scargle (Scargle 1982, hereafter L-S) periodogram. These two statistical methods measure slightly different characteristics of trial light curves. The L-K statistic measures the quality of a light curve for a given trial period using the sum of the differences in magnitude between observations made at adjacent phases. Variations in the overall brightness of the system on different orbits can cause problems with this test, however. The L-S periodogram is basically a harmonic decomposition of the observations.

3.3. Light Curve Analysis

For the systems with the most stable light curves, we modeled the light curve using the program NIGHTFALL[2], which includes model atmospheres (Hauschildt et al. 1999) and physical effects such as detailed reflection (which is important for close binaries). Detailed fitting of the eclipsing binaries requires some care in choosing the prescription for limb-darkening. Significant systematic differences in parameters such as mass ratio and inclination

[2]See http://www.lsw.uni-heidelberg.de/∼rwichman/Nightfall.html for the program and a user manual (Wichmann 1998)

can result from this choice. We have chosen to use a two-parameter square-root law primarily because the use of linear or quadratic limb darkening laws resulted in significantly higher χ^2 values due to poor fits to the eclipses for our variables. Our choice is supported by comparisons between predictions from model atmospheres and best-fit limb-darkening laws (Van Hamme 1993; Díaz-Cordovés et al. 1995) that indicate that square-root or logarithmic laws are to be preferred for stars with surface temperatures near those of our W UMa variables.

4. Light Curves

In this section, we discuss the important features of the light curves of the variable stars we detected. Unless otherwise listed, the ID numbers are from Sanders (1977). A color-magnitude diagram for the systems discussed below is shown in Fig. 2.

4.1. W UMa Contact Binaries

Four W UMa binaries are currently known to be members of M67. We present observations of all of these systems below, and we list their properties in Table 2.

S757: This star was slightly outside the field analyzed by Gilliland et al. (1991), but was identified as a probable variable star by both Nissen et al. (1986) and Rajamohan et al. (1988). SvMS discuss their identification of this system as a W UMa variable based on a likely period of 0.3600 d and color $(B-V) = 0.61$. They presented a partial light curve generated from two runs in 1998 and 2000 that indicate maxima and minima of roughly equal brightness. We independently identified the system, and are able to refine the period to $P = 0.35967 \pm 0.00002$ d from two seasons of data. In this case we found that the best period from the L-K method was in a smaller peak in the L-S periodogram. The amplitude of the light curve in V is approximately 0.09 mag, although this does vary from month to month. Regardless, the small amplitude indicates that the system has a fairly low inclination ($\sim 30°$). Our data phased to this best period are shown in Fig. 3.

Figure 4 shows our most complete single-day light curves. The observations from January 2001 in particular show significant changes in the light curve from night to night. The relative heights of the maxima clearly changed between Dec. 7, 2000 and Jan. 30, 2001 with phase 0.25 slightly brighter than phase 0.75 in December, but about 0.05 mag fainter in January. The magnitude level of the secondary eclipse is the portion of the light curve that seems to remain the most constant. The month timescale of these variations leads us to believe that the cause is starspots. Spots have been hypothesized on many of W UMa systems in connection with unequal brightness of the two maxima (generally called the O'Connell effect; O'Connell 1951). The case of S757 adds an additional wrinkle because the maximum following the primary eclipse did change from being brighter than the other maximum to being fainter (generally called a variable O'Connell effect). This could indicate that either there are significant spots present on *both* components or that hot *and* cool spots appeared on one component of the binary. We tend to believe the former explanation because the levels of the two maxima do not appear to remain at constant brightness. Because we focused on V-band observations, we do not have enough information to conduct a more detailed analysis of the temperatures of hypothesized spots. In any case, the fact that we are unable to establish the true brightness of the maximum of the light curve makes a derivation of reliable system parameters nearly impossible.

In spite of the apparent spot activity, S757 was not detected as an X-ray source in the cluster by Belloni, Verbunt, & Mathieu (1998). Both of the other W UMa systems of comparable brightness (S1036 and S1282) were detected. L_x/L_{bol} increases with increasing color for field stars, which implies that S 757 should be brighter than S1282 in X-rays. The periods of the two systems are very nearly the same, which means that differences in the rate of rotation are not likely to account for differences in X-ray activity. In addition, S757 falls in the region where the two X-ray fields of Belloni et al. overlap, meaning that there was a longer total integration on S757. There does not appear to be any unidentified X-ray sources in the vicinity of S757, so we are unable to explain the non-detection.

S1036 (EV Cnc): S1036 is classified as a blue straggler because accurate photometry shows it to be about 0.1 mag (in $B - V$) to the blue of the cluster turnoff. Gilliland et al. (1991) determined the period to be 10.59 h. vSVM redetermined the period to be 0.44144 ± 0.00001 d, and they note that this does not appear to be consistent with the Gilliland et al. value, although they could not judge how significant this was because Gilliland et al. did not quote an error. Using the vSVM data in combination with our own, we are able to improve the determination of the period very slightly. Both the L-K and L-S methods agree on slightly lower but different periods. The L-S result appears to phase the data slightly better, and the measured light curve parameters are presented in Table 2.

The asymmetry in the light curve of S1036 makes it somewhat unusual: for a contact binary with uniform surface temperature, the light-curve maxima should have equal brightness. For S1036, the two maxima differ in brightness by approximately 0.02 mag. The two light-curve minima also differ in brightness by approximately 0.09 mag, as can seen in Fig. 5. For eclipsing binaries a difference in brightness of the light curve minima normally implies a difference in temperature for the two stars, something which is hard to understand if the stars are in contact. In Table 2, we include measurements of eclipse depths $\Delta V_p = V_{p,min} - V_{max}$ and $\Delta V_s = V_{s,min} - V_{max}$, where p and s refer to primary and secondary minima, and max refers to the global maximum of the light curve.

We conducted limited modeling of S1036 using the program NIGHTFALL (see §3.3 for details of the code). Two factors conspire to prevent definitive determination of system parameters from the light curve: low inclination and the possibility of spots. For warnings about deriving system parameters from low-inclination systems, see Rucinski (2001) and the discussion related to the system S1282 below. The asymmetries in the light curves of W UMa variables have led many researchers to model these systems with spots, usually with no more than two spots. However, there are potentially many combinations of spot parameters (spot latitude, longitude, size, and dimming factor) that can model a single light curve. This is true of S1036 as well. However, to check on the possibility that the determination of a subset of the system parameters might be robustly determined from these models, we first determined a set of system and spot parameters that fits the system well ($\chi^2 = 0.98$), and then proceeded to compute grids of models varying two parameters at a time. This baseline solution had $q = 0.50$, $i = 0.32$, $f = 0.47$, and two spots (spot 1: facing us at phase 0.52, radius 30°, dimming factor 0.72; spot 2: facing us at phase 0.23, radius 38°, dimming factor 0.80). The filling factor $f = (C_1 - C)/(C_1 - C_2)$, where C is the Jacobi potential of the common envelope, and C_1 and C_2 are the corresponding potentials of the $L1$ and $L2$ points We provide χ^2 contour maps for two of these experiments in Fig. 6.

As can be seen in the figure, there is very little correlation between i and mass ratio q (which is very poorly constrained). We checked for correlations between inclination and spot parameters, and found that they were minor. The primary degeneracy is between i and the filling factor f. The light curve clearly allows for solutions covering the range of filling factors observed for most contact binaries ($0 < f < 0.5$; Rucinski 1997). The reader should keep in mind that the right panel of the figure was computed for a constant set of spot parameters, and some adjustment of these could reduce the χ^2 value for a given combination of i and f. Thus, solutions with the component stars detached should very much be considered to be viable. If the system is in contact, however, the inclination can be constrained to be $30° < i < 38°$.

At least one spot appears to be necessary in models of the light curve because the shallower minimum is displaced away from the expected position at phase 0.5 and the two maxima still have different brightness. vSVM saw no evidence for variation in color during the orbit, although their quoted upper limit on the color variation was 0.05 in $B - V$. The limits on color variations placed by the vSVM data do not distinguish between the possibilities that i) the surface temperatures of the stars are equal and the differences in maximum and minimum brightness are entirely due to cold spots, or ii) there is one strong cold spot that explains the differences in maximum brightness and a large temperature difference between the two stars that explains the differences in minimum brightness. However, neither hypothesis predicts color variations of more than about 0.01 mag, so much more accurate color information is needed to constrain the models strongly. As a result, we did not attempt to do a more systematic study of the binary parameters using our photometry. During our observations, we did detect slight variations in the shape of the light curve from month to month, although they are not as noticeable as those seen for S 757. Given that the timescales for variations in the light curves of the other W UMa variables discussed in this paper are in the range of months or years, studies of the light curve of S1036 over a longer time baseline could help determine whether starspots are the primary factor in determining the light curve shape.

S1282 (AH Cnc): With data from the studies of Whelan et al. (1979) and Gilliland et al. (1991), there are currently good datasets covering the entire light curve of this W UMa system for three epochs separated by over a decade. Gilliland et al. noted that both minima in the light curve appeared to have changed from curved and continuously varying (possibly indicating partial eclipses) in the Whelan et al. dataset to flatter (indicating total eclipses) in their dataset. Our light curves closely resemble those of Gilliland et al.: one flat-bottom eclipse covering approximately 0.1 in orbital phase, and a slightly deeper and more curved primary eclipse.

Figure 7 shows our observations along with those of vSVM and Whelan et al. (1979). We have phased our observations using the ephemeris of Kurochkin (1979), which includes a second-order time term, although we have added a phase shift of 0.5 to bring the deeper minimum to phase 0. The deeper minimum in the Whelan et al. data is *not* the deeper minimum in later data according to this ephemeris. As can be seen in the observations of Whelan et al., the minima were at approximately the same brightness level in 1973. The Kurochkin ephemeris does a good job of phasing the observations of vSVM with ours, clearly illustrating the necessity of using the second-order term. We had to include an additional phase shift of 0.04 to our data and those of vSVM in order to bring the primary minimum to phase 0, which indicates that the ephemeris needs to be revised. [We should note that the zero-point of the vSVM data appears to be different from that of our data. Shifting their data according to the difference between our median V magnitude (13.44) and their average V magnitude (13.54; SvMV) we find that the light curves differ by 0.05 mag. The difference is partly due to the difference between the median and average for this light curve. For Figure 7, we simply added a magnitude correction to their data to make comparison of the light curves easier.]

Based on the appearance of the eclipses in our data, the system is clearly an A-type W UMa binary (the deeper eclipse being a transit of the larger star by the smaller star, as seen from the curvature of the light curve near phase 0) rather than W-type as identified by Whelan et al. Given the position of S1282 near the turnoff of M67 in the color-magnitude diagram, it might have been predicted that it should be an A-type system since they are generally believed to have evolved components (Mochnacki 1981). The relationship between type and evolutionary state may be misleading, however, since S1282 appears to have effectively changed type in less than a decade (between the observations of Whelan et al. and those of Gilliland et al.). One should also look at the data for the systems S757 (discussed above) and III-79 (discussed below), which show that one eclipse minimum can go from being the fainter of the two to the brighter in a matter of months or years. Because this is much too short to correspond to any reasonable evolutionary timescale (nuclear, thermal, or even dynamical) for the stars themselves, we believe that this shows that the evolutionary status of a W UMa variable cannot be determined without an extended study of the light curve and its potential for variation. For S1282, we do have additional information that is not always available for a W UMa system: the binary is found at the turnoff of the cluster, and so the primary star is likely to have depleted much of its core hydrogen supply.

Because S1282 was close to our primary target (S1082) in the cluster, we have photometry from most nights of observations, and on some nights we were able to cover almost an entire orbital period. Previous modeling based on the Whelan et al. data (Maceroni et al 1984) indicated that the system significantly overfills the Roche lobes of the two stars. However, the presence and duration of the total eclipse invalidates the low inclination ($i = 62\overset{\circ}{.}9$) that Maceroni et al. derived. Given that the Whelan et al. observations of light curve minima occurred over a relatively short period of 2.5 months, it is possible that there was a short-term change in the light curve shape. We have observed shorter timescale changes to the light curve shape (for example, the deeper primary eclipse observed on January 25, 2001), and the variability seen by vSVM in their secondary eclipse observations during two runs seems to support this. However, the amplitude of the light curve from Whelan et al. seems to be somewhat smaller than the amplitude in our data, which would tend to rule out cool spots as the cause.

While Whelan et al. did present radial velocity measurements in order to measure the spectroscopic mass ratio, they were not able to constrain the velocity semi-amplitude of the secondary star precisely. The large differences between their light curve and later ones might also indicate that their radial velocities may have been systematically affected by spots (to give just one possibility). As a result, we will not take their spectroscopic mass ratio to be a primary constraint on light curve models. The radial velocity measurements were good enough to show, however, that the less massive star is totally eclipsed as it passes behind the more massive star, as would be expected if the more massive star is also larger in size.

In most cases, W UMa light curves by themselves provide very little information about the system parameters, and attempts to derive parameters using χ^2 fits are extremely dangerous (see Rucinski 2001 for a discussion). However, when a contact system shows total eclipses, the duration of totality strongly constrains the combination of mass ratio and inclination, and is insensitive to the degree of contact (Mochnacki & Doughty 1972). Because S1282 clearly has total eclipses, a fairly stable light curve during the period of our observations, and has not been modelled previously, light-curve models can provide valuable constraints.

We modeled the light curve of S 1282 using NIGHTFALL (see § 3.3 for details). We focus on data from December 2000 and January 2001 because nearly the entire light curve was observed in relatively short periods of time. We decided not to attempt to model data taken in 2002 because the maximum following primary eclipse was found to be significantly fainter ($0.02-0.04$ mag) than the maximum following secondary eclipse, probably indicating that spots were a significant influence.

The large width of both eclipses requires an inclination near 90° and a small mass ratio. Our best-fit values for the December 2000 and January 2001 data separately are presented in Table 3. In order to estimate the possible errors, we ran grids of models varying q and i to determine changes in χ^2. The resulting contour maps are shown in Fig. 8. The contours correspond to levels 1.0 and 4.0 above the minimum χ^2 fit for that dataset, which should roughly delineate the 1 and 2σ confidence regions q and i taken individiually. As seen in the contour maps, there is little correlation between q and i. The best fits contours for the two datasets agree well, although there is a small shift in q between the results for the two datasets. Using the information from the χ^2 maps and the systematic shifts between the best fit models for the two datasets, we quote best fit values of $q = 0.16^{+0.03}_{-0.02}$ and $i = 86^{\circ}{}^{+4}_{-8}$. The variations in the best-fit parameters due to month-to-month changes in the light curve appear to be comparable in importance to the random errors in the fitted value of q.

In Fig. 9, we show a selection of theoretical models against the observational data. The best fit model is almost lost among the observational points, with the poorest fit near $\phi = 0.25$. The upper panel of the figure shows two models with the best-fit inclination but with mass ratios 1σ away from the best model. The mass ratio is primarily constrained by the eclipse depths. The lower panel shows light curves with the best-fit mass ratio, but with different inclinations. The $i = 90°$ curve is almost indistinguishable from the best fit model, but the $i = 78°$ curve has eclipses of noticeably shorter duration.

Although the derived mass ratio for the system falls near the low end of the distribution for W UMa systems, W UMa systems tend to be found preferentially at low q values (Rucinski 2001), so this fact is not unusual. The filling factor for the system is constrained by the shape of the light curve before and after primary eclipse, and although it is correlated with the inclination (in the sense that lower inclinations require larger filling factors), there is negligible degeneracy between mass ratio and filling factor. For both of our best-fit models we find it necessary to use a filling factor ($f \approx 0.7$) that is probably larger than the majority of observed systems (Rucinski 1997). A lower limit on the filling factor is $f > 0.4$ based on χ^2 values measured for models with $i = 90°$.

The results of the light curve analysis contradict the earlier spectroscopic analysis of Whelan et al. (1979). Although their derived radial velocities were very uncertain ($K_1 \approx 100 \pm 15$ km s^{-1}, 138 km s$^{-1} < K_2 < 240$ km s^{-1}), the implied mass ratios are inconsistent with our photometric value. In addition, if it is assumed that the maximum K_2 value is approximately correct (giving a spectroscopic q value closest to our photometric value), the derived total system mass is substantially less that that predicted for a turnoff star in M67 from stellar evolution models ($\sim 1.25 M_\odot$) in spite of the system's position near the turnoff in the color-magnitude diagram. We are forced to conclude that the radial velocity data for this system are not currently of high enough quality to derive trustworthy masses. The importance of a good radial velocity curve for this system should be emphasized, since it would provide a valuable constraint on the cluster turnoff mass, and would thereby help more accurately age-date M67.

Our extensive observations allowed us to discover some unusual transient features in the light curves (Fig. 10). On January 23/24 and 25/26, 2001, we observed short ($\sim$ 30 min) brightness increases ($\sim$ 0.08 mag for both, compared to eclipse depths of 0.33 and 0.39 mag). Unusual features of these two brightenings were: they were observed at almost identical phase positions shortly before maximum, the following maximum did not show the feature, and on the two days the brightness increase was seen on *different* maxima. In addition, the primary minimum preceding the brightness increase on Jan. 25/26 was significantly deeper (by $0.04 - 0.05$ mag) than any other minimum observed. These features disappeared within two days.

These transient features bear some resemblance to variations seen in the light curve of the nearby W UMa variable 44i Boo (e.g. Duerbeck 1978), which appears to have active periods of a few years duration interspersed with quieter periods with undisturbed light curves. A similar cycle (probably related to the magnetic field) might help to explain the difference between the light curves of Whelan et al. (1979) and other observers.

The timing of the features shortly before maximum seems to argue against stellar flares. The short duration of the features argues against hot spots, which should persist for longer times. One hypothesis is based on magnetically-confined gas (prominences) on one of the stars on the portion of the surface facing away from the other star. If the gas has sufficient optical depth, it could potentially increase the effective surface area of the binary when a large slab is aligned edge-on, but could cause either modest or negligible dimming of the system when viewed face-on through the thin dimension of the slab. The increased depth of the first half of the primary eclipse on January 25 indicates that the feature was probably on the side of the secondary star facing almost directly away from the primary. Because our light curve was taken entirely in V, we have no direct information on temperature. (We wish to thank M. Blake for the suggestion that initiated this line of thought.)

III-79 (ET Cnc): This system was discovered by Gilliland et al. (1991) at $7'$ from the cluster center, and was also observed by SvMV. This binary is considerably fainter than the other three contact systems known. This system was in the field of our March 2001 observations, with the best data coming from night 13. We averaged observations to increase the S/N ratio in the data. Our data are presented in Fig. 11 along with those of SvMV from January 1998, phased to the same linear ephemeris using a period ($P = 0.270505$ d) that is consistent with the value quoted by SvMV to within the errors. Our measured median magnitude ($V = 15.90$) agrees very well with the average magnitude of SvMv (15.89), so no shifting in magnitude was done.

Although individual data points have considerably larger errors than those for the other W UMa systems discussed, a comparison of the light curves indicates a noticeable change in the light curve shape. While the brighter of the two light curve maxima follows the brighter minimum in the SvMV and Gilliland et al. datasets, the brighter maximum appears to follow the fainter minimum in our data. Although we do not have data completely covering the minimum plotted at phase $\phi = 0.5$, several points with good errors indicate that it has dimmed noticeably. Independent of this, the $\phi = 0.5$ minimum does not reach the same depth as the $\phi = 0$ minimum in the light curves of Gilliland et al. and SvMV. So the indication is that this system shows fairly extreme variations in the shape of the light curve. Without more information about the nature of this variation, it would be reckless to try to model this system.

4.2. Blue Stragglers

During the course of the observations we observed most of the cluster's blue stragglers during the majority of at least one night in order to look for variability on various timescales. The results of this search are given in Table 4. Our list of stragglers comes primarily from the list of Ahumada & Lapasset (1995), although stars have been excluded if the accurate photometry of Fan et al. (1996) indicated that the star was close to the cluster turnoff. Stars S2223 and S2226 were added to the list based on the photometry of Fan et al. (1996) and proper motion membership (Sanders 1977; Girard et al. 1989).

We have monitored a number of stragglers for the first time in this study, but we do not find any of these to be noticeably variable. We provide the values for our variability indicators σ_V and I_{WS} (discussed in §3.2) in columns 4 and 5 respectively. Typically nonvariable stars in the magnitude range of the stragglers had $\sigma_V < 0.015$ and $I_{WS} < 1.5$. We discuss most of the variability candidates in §4.2.2 below. We note that both indicators can give erroneously high scores if observations were taken during poor seeing conditions and a contaminating star was present nearby, as was the case for the straggler S975. We have provided information on the nights the stars were observed in order to lay the groundwork for constraining variations on longer timescales. We do, however, rule out the possibility that any of the other blue stragglers observed are W UMa variables of amplitude more than about $0.01 - 0.02$ mag.

4.2.1. δ Scuti Stars

The blue stragglers in the CMD cover the region where the instability strip occurs. We have roughly translated the instability strip of Pamyatnykh (2000) into our observational CMD, as shown in Fig 2. We will discuss our oscillation mode analyses of the two known blue straggler δ Scuti stars S1280 and S1284 in a separate paper in preparation. However, we find several other stragglers with photometry that places them inside the instability strip: S1263, S1267, S968, S1066 and S1434 to the blue of the known pulsators, and S752, S2226, S1082 and S975 to the red. We did not observe S1434 or S2226. S752, S975, and S1267 are known to be long period variables ($P = 1003$ d, 1221 d, and 846 d, respectively; Latham & Milone 1996), while S 1082 contains a close binary that may be part of a triple (van den Berg et al. 2001; Sandquist et al. 2003). Therefore, these systems are less likely to show photometric variations due to pulsation (although it is possible that components of the long period variables will still fall in the instability strip: in particular, the brightest component of S 1082 shows some evidence of being a δ Scuti star; Sandquist et al. 2003). As a result, S 968, S 1066, and S 1263 are the best candidates to search for pulsation. Gilliland & Brown (1992) observed S 1263 extensively, and also found no sign of variation. We do not find convincing evidence of pulsation in any of the three stars, although this may be due to low pulsation amplitudes or higher frequency (overtone) oscillations. We discuss all three stars in §4.2.2 with regards to longer period variations.

4.2.2. Possible Variables

As discussed earlier, to tightly constrain the photometric variations present in some of the bluest blue stragglers, we were forced to subtract off a systematic error (probably related to color response of the filter/CCD combination) that appeared as correlated slow low-amplitude variations among several stars. Once this correction was made several of the stars no longer showed any signs of significant variation (S 977, S 1066, S 1267). The remaining three (S 752, S 968, S 1263) still showed trends, and will be discussed below. None of these stars tripped the variability condition $I_{WS} \gtrsim 1.5$, although in the case of S 752 at least there is fairly clear evidence of variability in one interval of time. Before presenting the results, we note that we looked for correlations of the magnitude residuals with seeing and airmass for each star below, and found no evidence that such effects were responsible.

S 752: As noted earlier, S 752 is known to be a binary system ($P = 1003$ d; $e = 0.32 \pm 0.12$; Latham & Milone 1996) containing an Am star. This star was outside the field observed by Gilliland et al. (1991), and although it was observed by SvVM, it was not reported as variable. Simoda (1991) observed the star and found it to be non-variable. We present our observations in Fig. 12. While the vast majority of our measurements show no indication of variability, our December 2000 observations give the indication of a decrease in brightness of 0.03 mag over the course of a week, punctuated with something resembling a flare (0.05 mag increase in brightness lasting over 3 hours). However, see Gilliland et al. 1991 for a discussion of false flaring.

S 968: This blue straggler was not in the field observed by Gilliland et al. (1991), but was observed by SvMV although they did not report it as being variable. Our observations are shown in Fig. 13. For most of the nights this star was observed, it was fairly consistent with constant brightness. On other nights there appeared to be noticeable trends during a night (most notably February 18/19, 2001). This behavior could explain the non-detection by SvMV.

S 1263: SvMV indicate that their observations of this star have significant scatter of up to 0.03 mag, and Kim et al. (1996) find large dispersion in their measurements. There does appear to be a long term drift in the brightness of the star (of approximately 0.02 mag) as seen in Fig. 14, even after removing the effects of correlated residuals. Some of our nights of observations were compromised by very poor seeing and contamination by MMJ 5951 (Montgomery et al. 1993), which is about 9″ away. Based on trends seen in the photometric residuals in measurements during the poorest seeing, we eliminated measurements with seeing greater than 4.″8 FWHM. We attempted to look for periodic signals in the data, although we did not find convincing evidence of any (the best indications were for a period of 17.5 d). This system is not known to be part of a binary, so it should be monitored further to determine the manner of its variation.

4.3. Long Period Variables

S 1040: This system was determined by Mathieu, Latham, & Griffin (1990) to be a single-lined spectroscopic binary having a circular orbit and a period $P = 42.8271 \pm 0.0022$ d. The position of S 1040 to the blue side of the red giant branch in the color-magnitude diagram makes it a “red straggler”. Using ultraviolet imaging and spectra, Landsman et al. (1997) showed that the secondary companion to the red giant primary is likely to be a helium white dwarf. Landsman et al. (1997) also laid out a hypothetical history for the system in which a main sequence binary began mass transfer at a period of approximately 2 d when the more massive star had a helium core mass of $0.16 M_{\odot}$. Mass transfer continued until the envelope of the initially more massive star was depleted, creating a system composed of a helium white dwarf and a blue straggler. Once the blue straggler evolved to the red giant branch, a system like S 1040 would be created.

In previous variability studies, (Gilliland et al. 1991) found evidence for low amplitude (0.012 mag) variation with a period of 7.97 d, while vSVM found no evidence of variation. We plot our data (averaged in 0.1 d bins to improve the errors) in Fig. 15, and tabulate it in Table 5. We have observed several nights for which the system brightness decreased by as much as 0.06 mag compared to the peak level. When the data is phased to the ephemeris of Mathieu et al. (1990), there is an indication of a systematic decrease in brightness at a phase corresponding to the passage of the white dwarf in front of the giant. Because our phase coverage is incomplete, we are unable to determine the exact depth of the feature. However, a feature of this depth and shape cannot be explained as an eclipse of the red giant by the white dwarf. Observations on two nights do not match up well with the light curve formed from the rest of the observations. We probed a variety of periods from 1 to 70 d, but did not find satisfactory light curves from any of the best trial periods from the L-K or L-S methods. Additional observations should be made to better determine the shape of the light curve, and the nature of the variation.

S 1063: This system is a binary with orbital period of 18.396 ± 0.005 d and eccentricity 0.206 ± 0.014 (Latham et al. 1992; Mathieu et al. 2002), although an orbit has not yet been published for the system. S 1063 is known to be unusual in its X-ray emission (Belloni et al. 1998) and position in the color-magnitude diagram (fainter than the subgiant branch). There is good evidence of proper motion membership though (Sanders 1977; Girard et al. 1989, $> 90\%$ probability).

This system fell just outside the Gilliland et al. field, but was observed by vSVM in their examination of X-ray sources. vSVM identified the system as as a non-periodic variable based on an examination of periods up to the length of their longest interval of continuous observations (18 d). Their Figure 5 makes it clear that at the very least there is a great deal of variability in the light curve, and that the variation is not obviously related to the orbital characteristics of the system.

We averaged observations from a given night in 0.1 d windows to improve the error in our measurements, and they are presented in Table 6. In our data, the system shows slight photometric trends during the course of a night, but systematic offsets in the star's photometry are clearly detected from night to night. Using an L-S periodogram, we do not find any evidence of variation on the orbital timescale, but there is slight evidence of variation with a period of approximately 23 days. This period seems to bring the maxima and minima of our data into approximate alignment. As shown in Fig. 16, a comparison of data from different observing runs indicates that the brightness level of the minimum of the light curve probably varies a few centimag from cycle to cycle. During the course of our observations the light curve appeared to maintain a roughly similar shape, but one that appears to differ from the portions observed by vSVM. Although the system does not show periodicity on the orbital period, the similarity of the timescale may indicate that the variability is related via tides and/or magnetic activity. Further progress on this system will require observations over much longer periods and a more detailed examination of the relationship with the orbit.

[We have three nights of observations of another sub-subgiant branch system (S 1113), but our phase coverage for this system is fairly poor, so we do not discuss it.]

5. Conclusions

We have presented V observations for the open cluster M67, and have discussed the light curves for the known W UMa contact binaries and the monitoring of the majority of the blue stragglers for variability. We find that all of the known W UMa binaries show light curve variations that occur on timescales of days to months. Two systems (S757 and III-79) show large changes in the shapes of their light curves. The relative brightnesses of both the two maxima and the two minima in the light curve of S757 have been observed to change on timescales of less than a month. The faint system III-79 shows a substantial change in the shape of the light curve between the January 1998 of SvMV and our observations in March 2001. The other two systems (S1036 and S1282) show smaller variations. S1282 changed between a W-type and an A-type configuration between the 1973 observations of Whelan et al. (1979) and the 1988 observations of Gilliland et al. (1991). The existence of two systems which appear to change between these subtypes indicates that the classification is perhaps not a robust indicator of the evolutionary state of the stellar components. The blue straggler system S 1036 shows smaller light curve variations, but a stronger and more stable O'Connell effect.

We have verified that S 1282 is a highly-inclined totally-eclipsing system with $q = 0.16^{+0.03}_{-0.02}$ and $i = 86^{\circ}{}^{+4}_{-8}$. Because this system falls right at the cluster turnoff, we strongly encourage further spectroscopic work to provide a constraint on the cluster turnoff mass, and thus on the cluster age. This system has also shown unusual short disturbances in its light curve that may relate to magnetic activity, and which should be followed up.

Among the blue stragglers, in addition to the two known δ Scuti pulsating variables, we find possible evidence of longer period variations in the stars S752, S968, and S1263. While these stars did not satisfy our criteria for a definite claim of variability, we see trends in the photometry and apparent changes in the mean brightness level that should be investigated.

Finally, we present a series of observations of two long-period binary systems. For the poorly understood sub-subgiant branch system S 1063, there are indications of quasi-periodicity on timescales similar to the orbital period, as well as variations in the mean brightness level of the light curve. For the giant-white dwarf system S 1040, we find evidence of a drop in brightness at phases corresponding to the passage of the white dwarf in front of the giant using the ephemeris derived by Mathieu et al. (1990). Although this drop in brightness cannot be due to an eclipse of the giant by the white dwarf itself, there may be associated material within the system that could account for the variability. This information can probably be used to contrain the inclination of the system.

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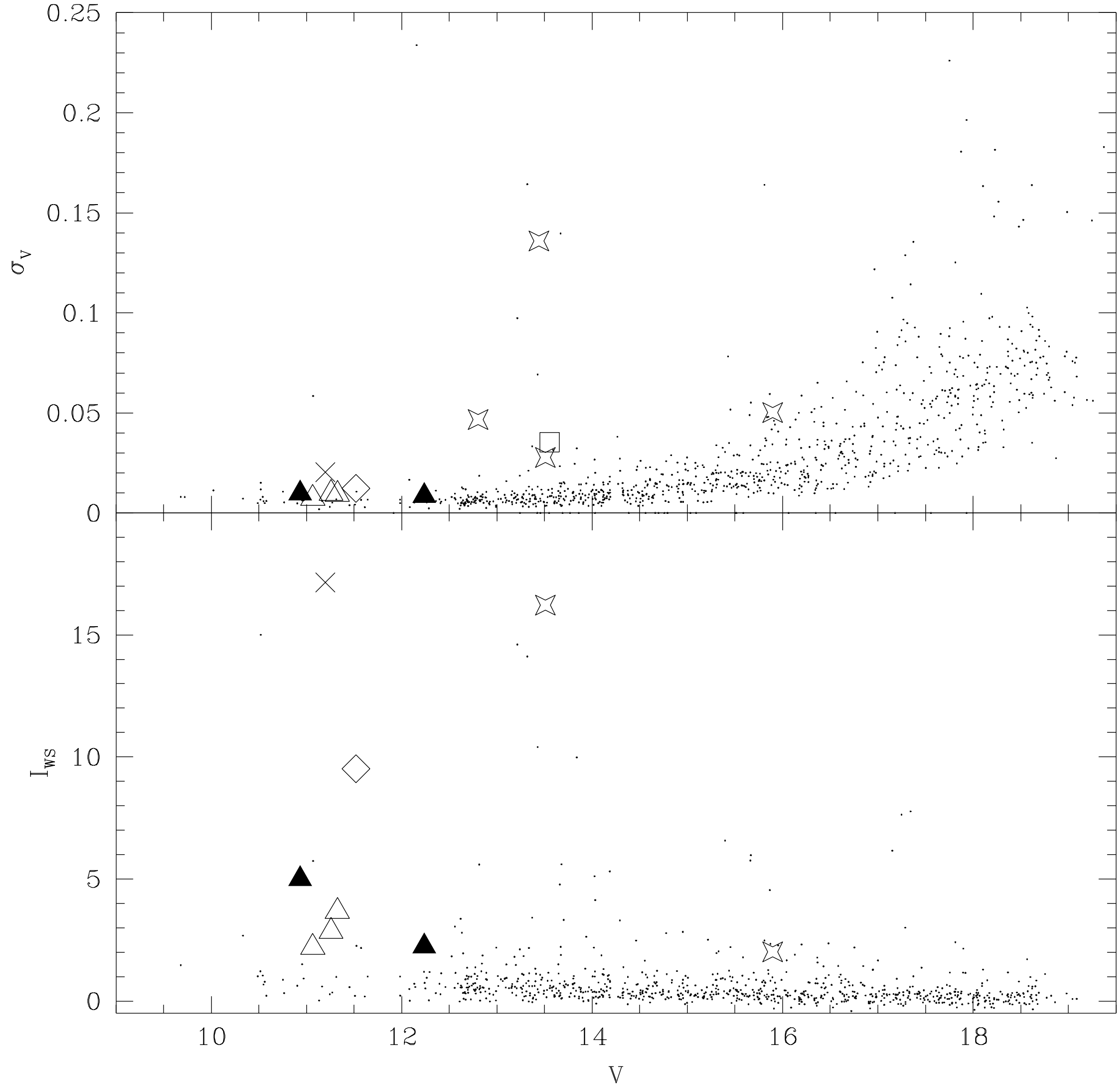

Fig. 1.— Variability indicators σ_V (rms scatter in V measurements) and Welch-Stetson index I_{WS} versus magnitude. Measurements taken under poorest seeing conditions (FWHM $\gtrsim 2''.5$) have been eliminated from the calculations of the plotted indices. The meaning of the symbols is given in Fig. 2. Note that the W UMa variables S1036 and S1282, and the sub-subgiant branch star S1063 are off the top of the plot in the lower panel.

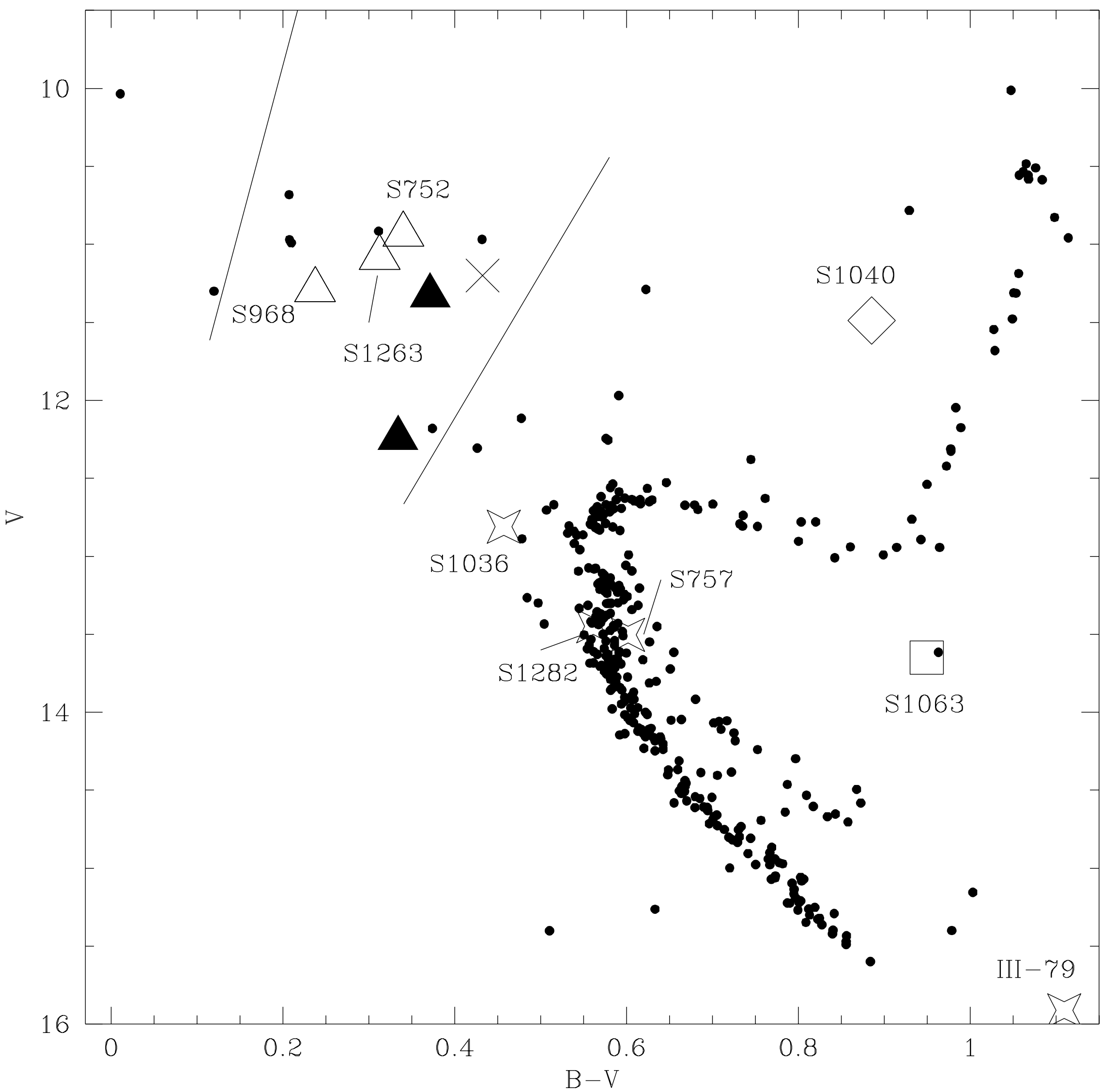

Fig. 2.— The turnoff region (including blue stragglers) of the color-magnitude diagram of M67 from the data of Fan et al. (1996) and cleaned of probable non-members using the proper motions of Sanders (1977). The approximate boundaries of the δ Scuti instability strip are shown with solid lines. The labelled open symbols represent systems discussed in the text. The observed W UMa contact binaries are marked as open stars, previously known δ Scuti pulsators are marked as filled triangles, possible low amplitude variables are open triangles. The sub-subgiant branch star S1063 is an open square (with the related system S1113 a dot in the corner of the square), the "red straggler" S1040 is an open diamond, and the RS CVn system S1082 is marked with a $\times$.

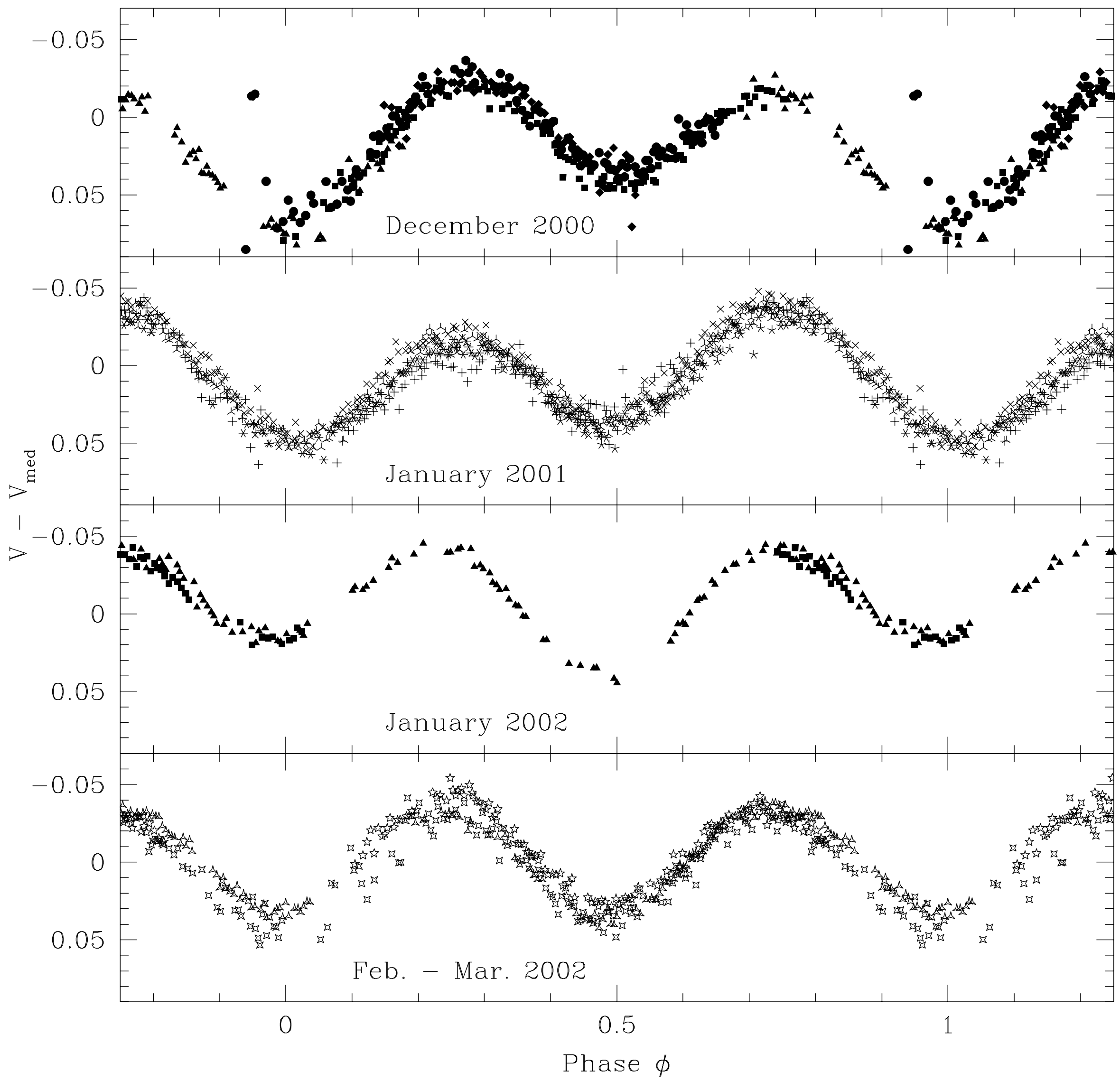

Fig. 3.— Phased V light curves for the contact binary S757, separated by month of observation. The median V magnitude used was for the complete dataset. Zero phase was chosen to be the photometric minimum. Different symbols correspond to different nights of observation (see Fig. 4 for identifications).

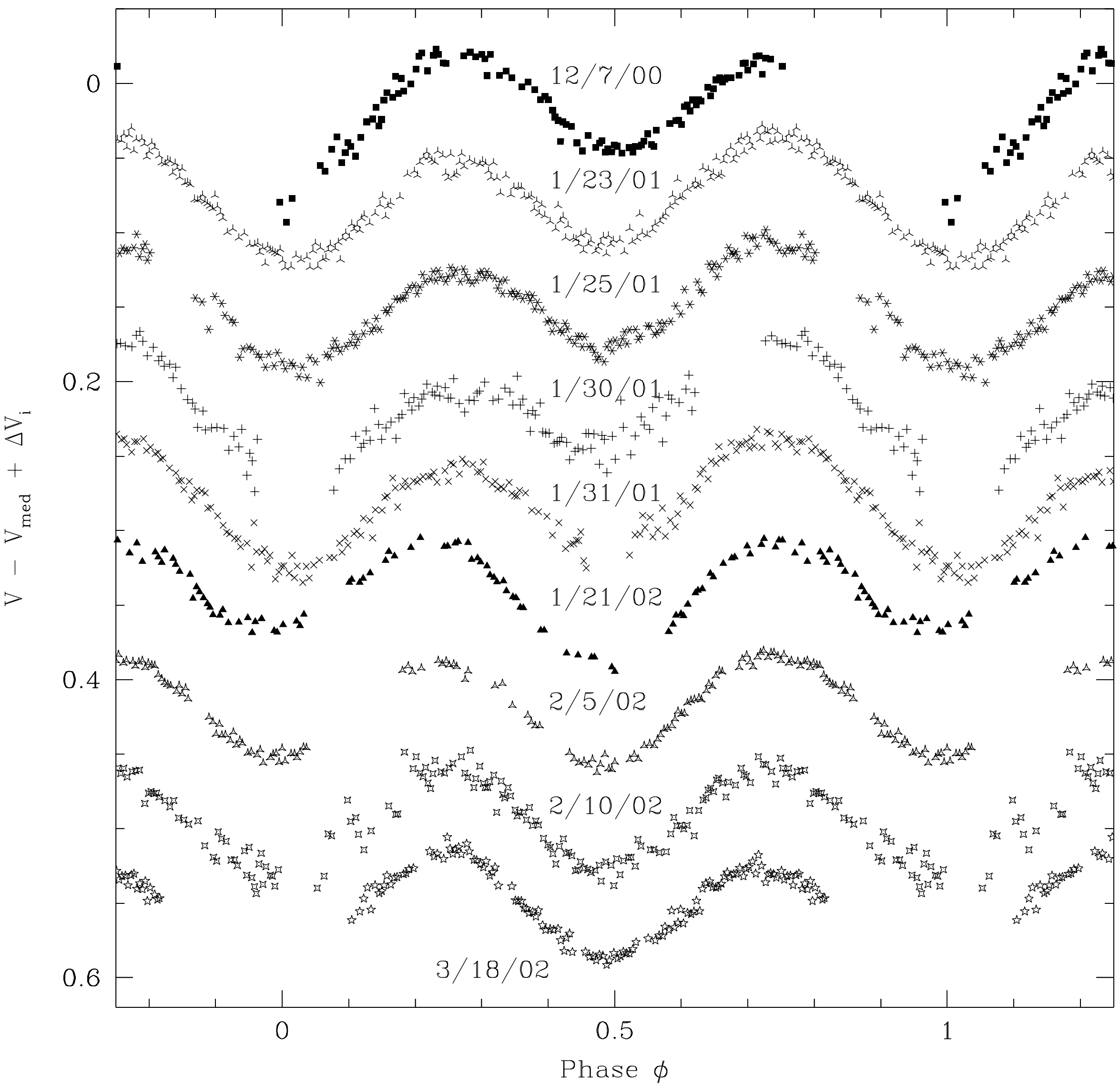

Fig. 4.— The most complete single day V light curves for the contact binary S757. Successive light curves have been offset by 0.07 mag.

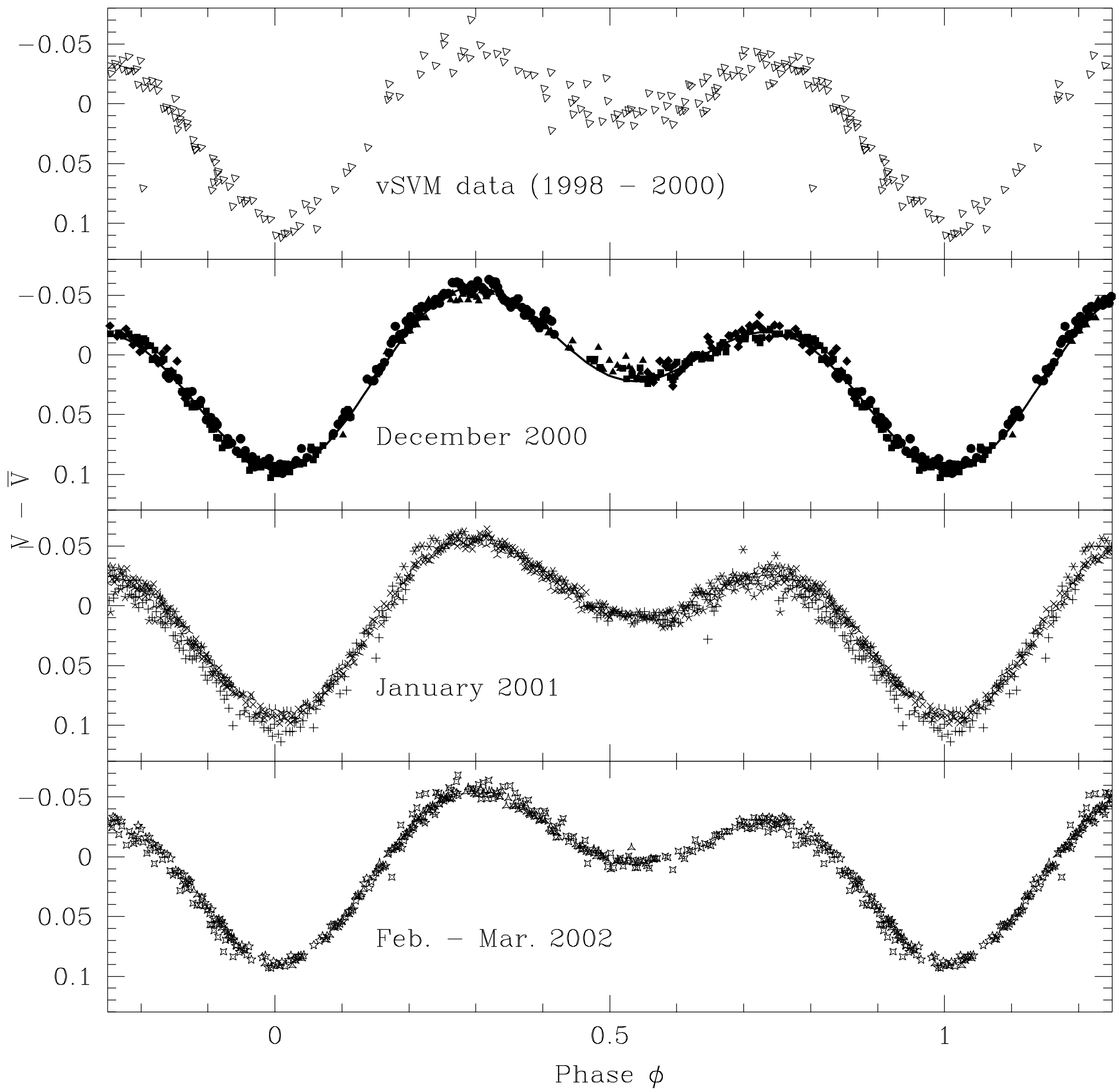

Fig. 5.— Phased V light curves for the contact binary S1036, separated by month of observation. The top panel shows data from van den Berg et al. (2002). Zero phase was chosen to be the photometric minimum. Our best-fit light curve model is plotted with the December 2000 data.

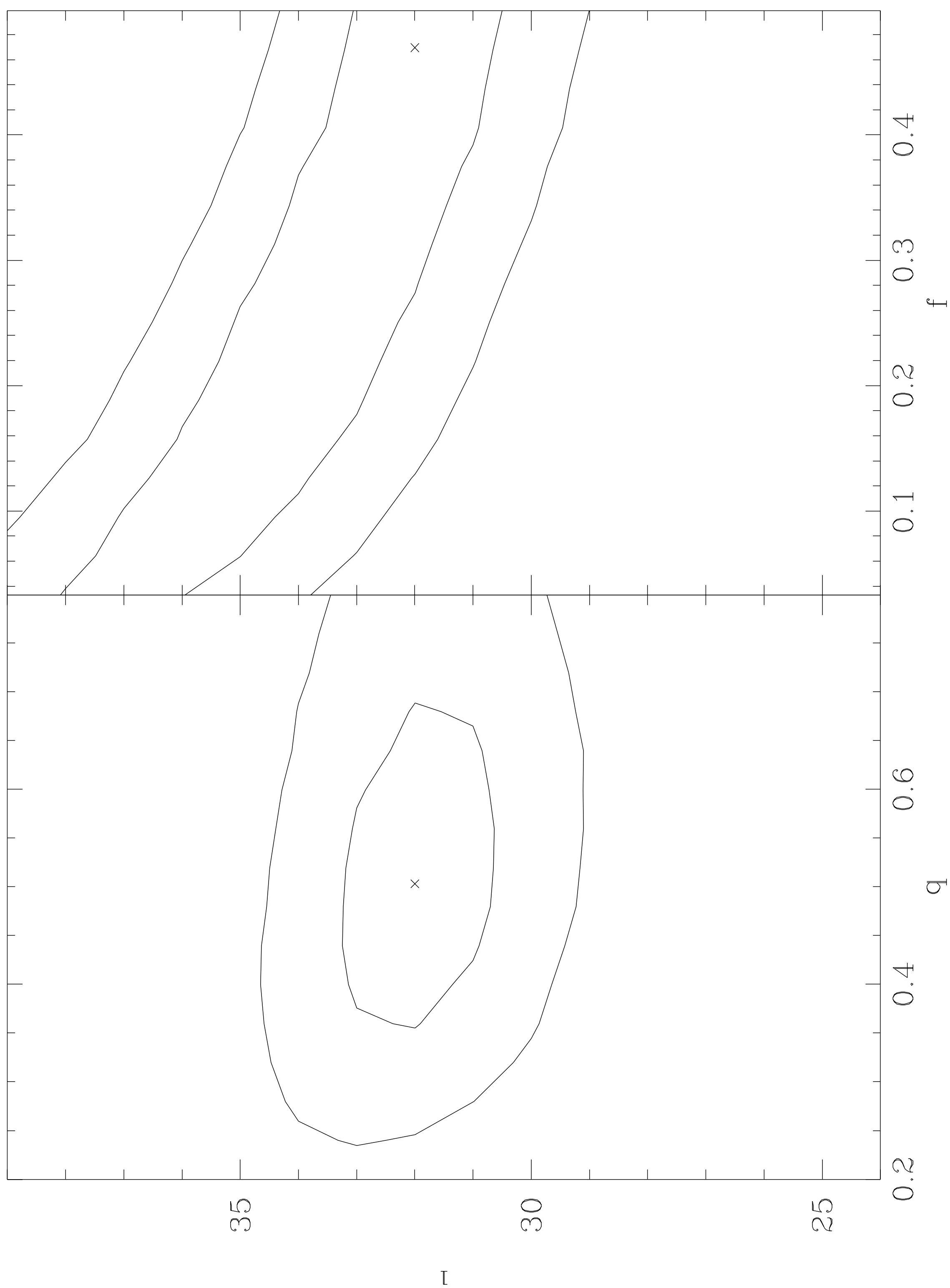

Fig. 6.— χ^2 contours for light curve fits to the December 2000 for S1036. In both cases, the inner contour corresponds to $\chi^2_{min} + 1.0$ and the outer contour corresponds to $\chi^2_{min} + 4.0$, roughly 1 and 2σ boundaries on q and i. $\times$ symbols indicate our baseline solution (described

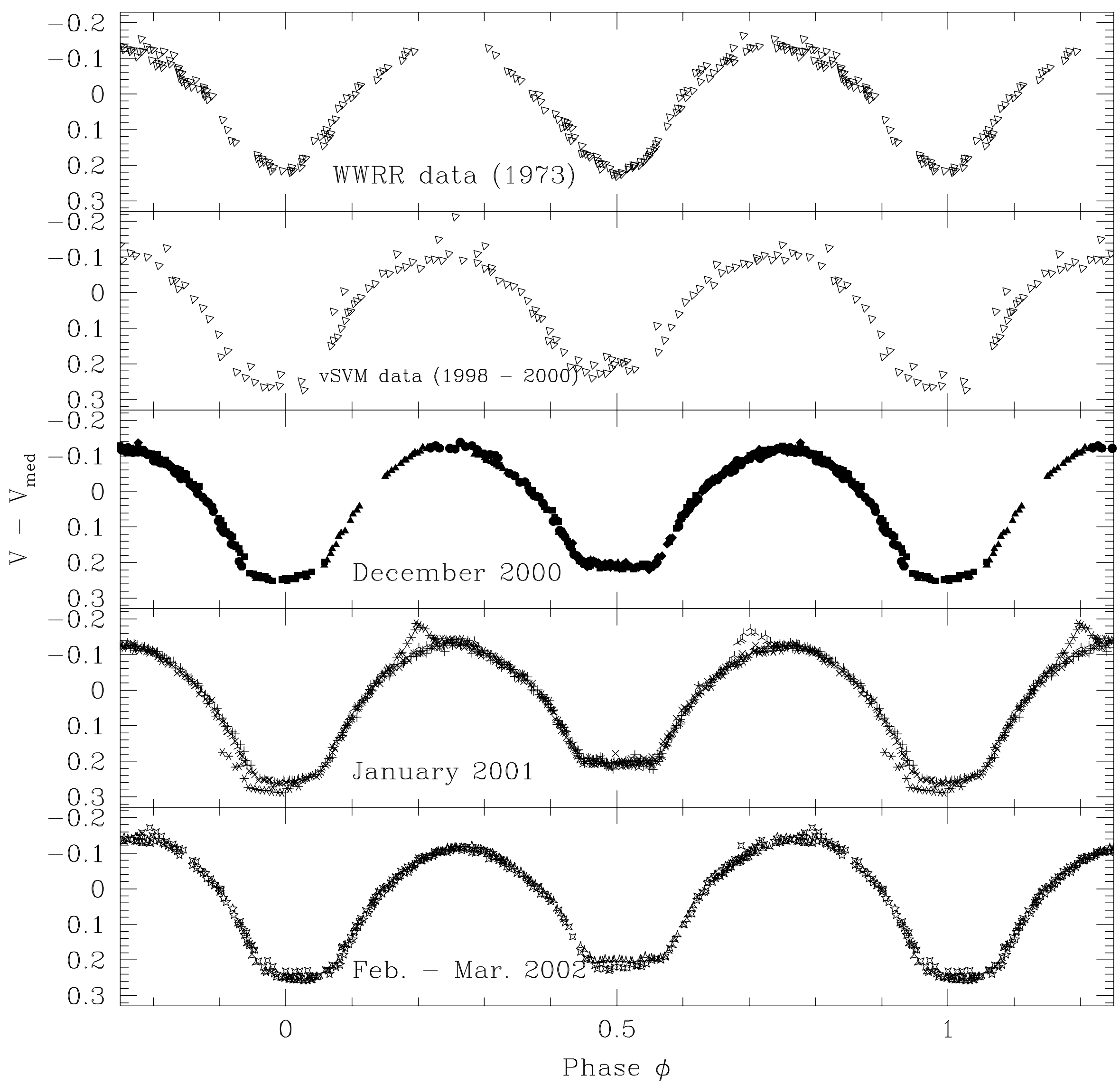

Fig. 7.— Phased V light curves for the contact binary S1282 (AH Cnc) separated by month of observation. The top panel shows data from Whelan et al. (1979), and next panel lower shows data from van den Berg et al. (2002). Zero phase was chosen to be the total eclipse of the least massive star.

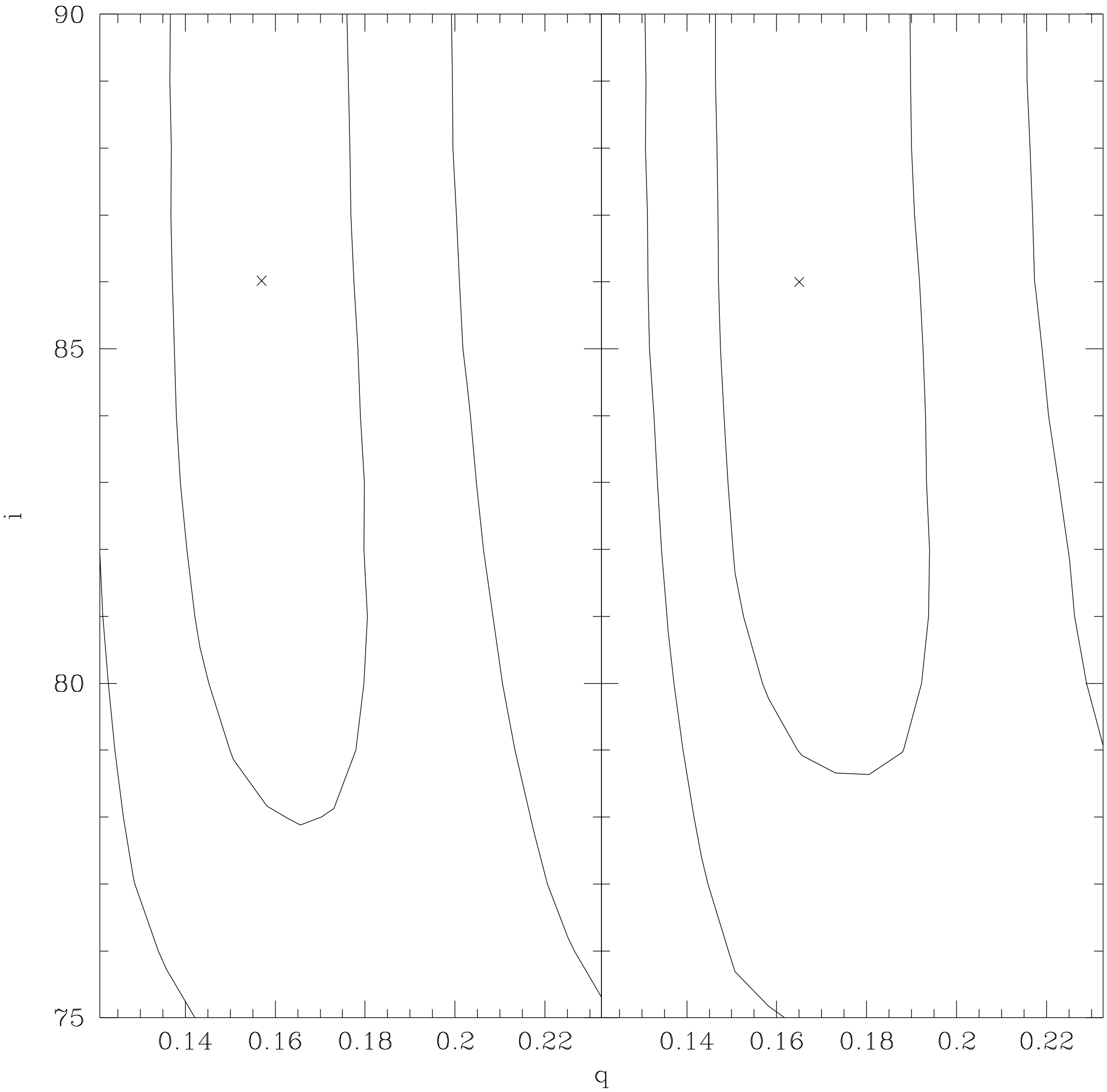

Fig. 8.— χ^2 contours for light curve fits to the December 2000 (*left panel*) and January 2001 (*right panel*) data for S1282. In both cases, the inner contour corresponds to $\chi^2_{min} + 1.0$ and the outer contour corresponds to $\chi^2_{min} + 4.0$, roughly 1 and 2σ boundaries on q and i. $\times$ symbols indicate the best fit solutions.

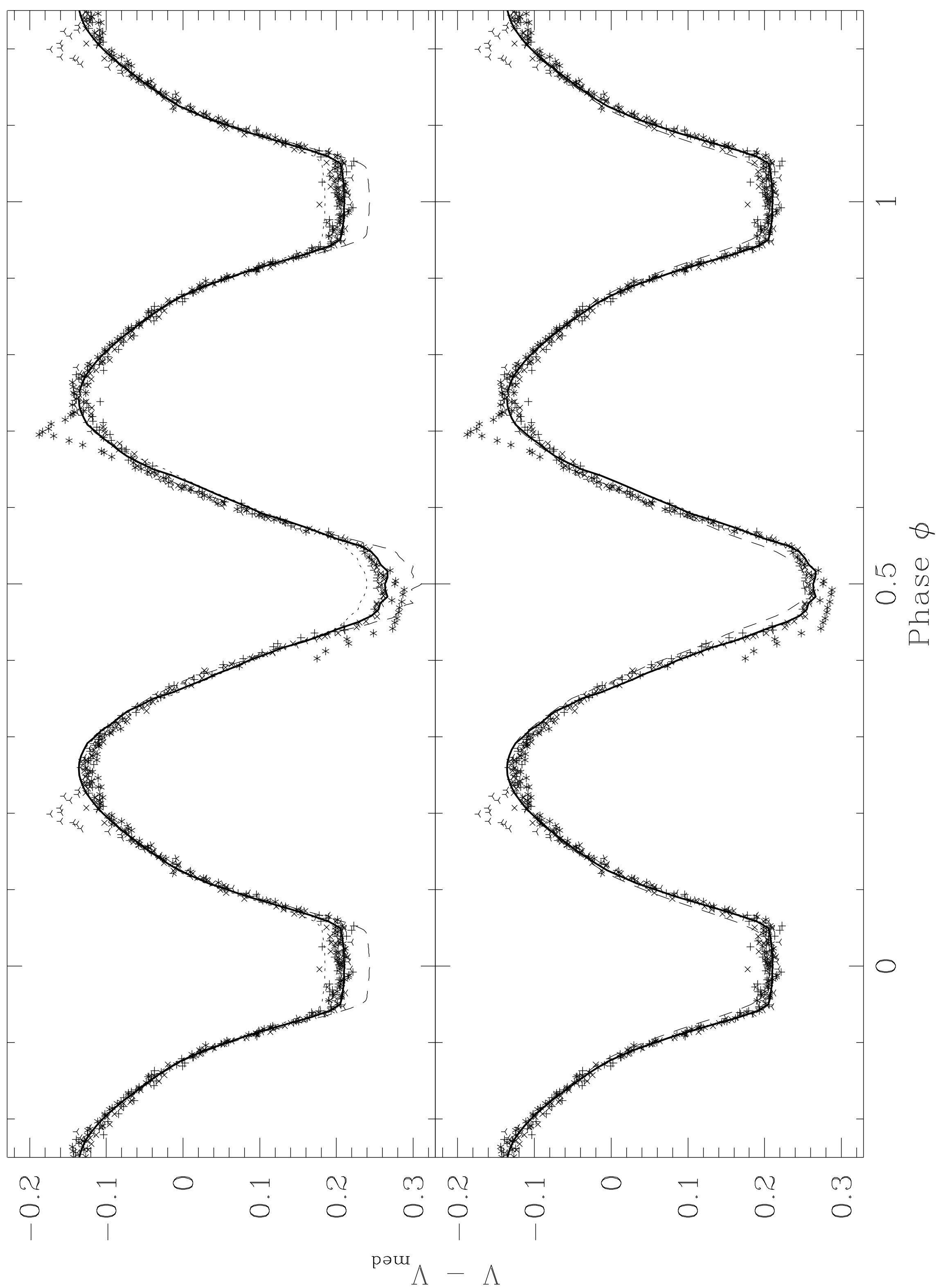

Fig. 9.— Trial light curve fits to the January 2001 data for S1282. In both panels, the heavy solid line is our best fit model ($q = 0.165$, $i = 86°$). Models with constant i are shown in the upper panel: $q = 0.145$ (dotted line) and $q = 0.195$ (dashed line). Models with constant q

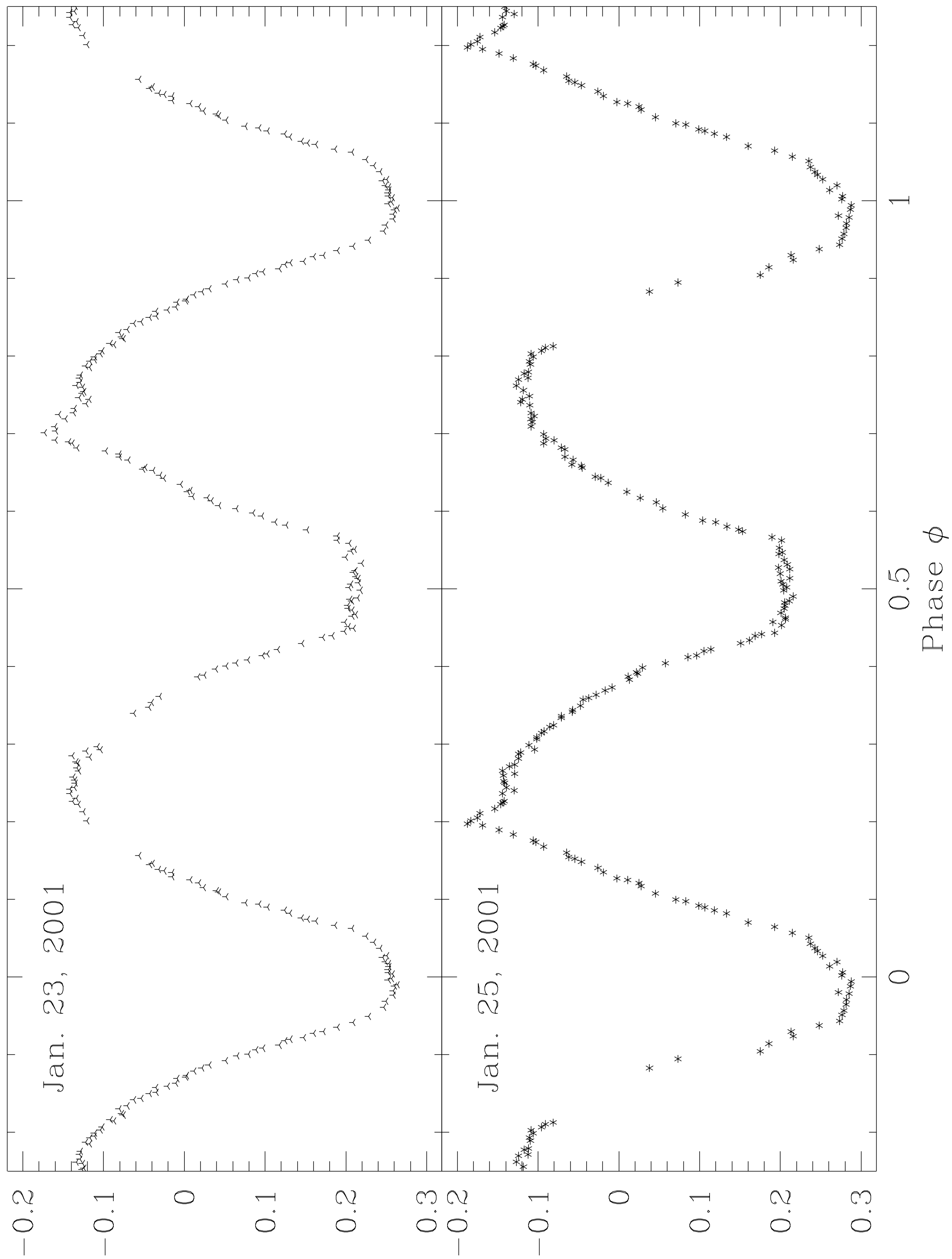

Fig. 10.— Disturbed V light curves for the contact binary S1282 (AH Cnc) in January 2001.

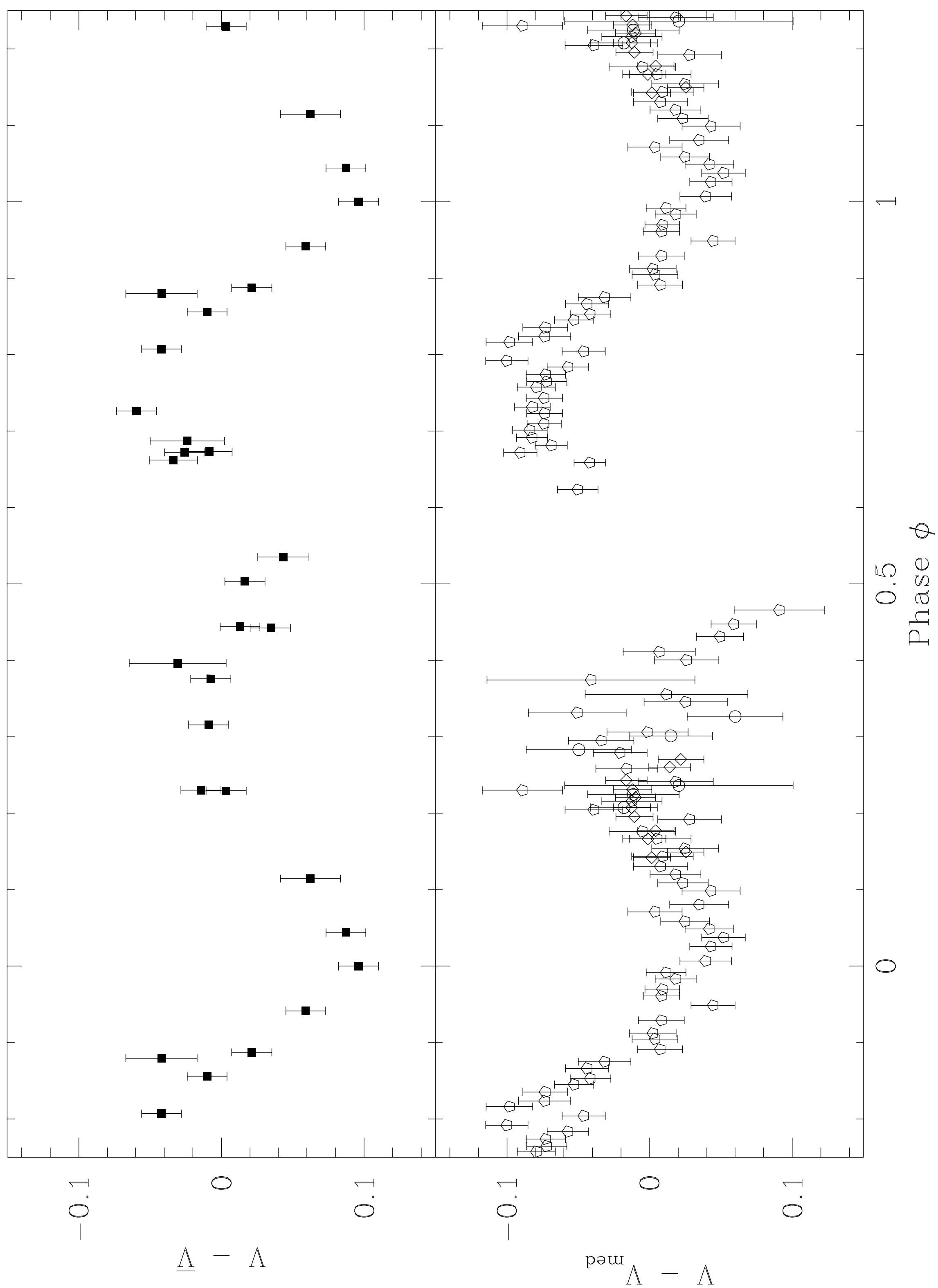

Fig. 11.— Phased V light curves for the contact binary III-79 (ET Cnc). The upper panel shows data from Stassun et al. (2002), and the lower panel shows our measurements from March 2001. Both datasets have been phased to the same linear ephemeris ($P = 0.270505$

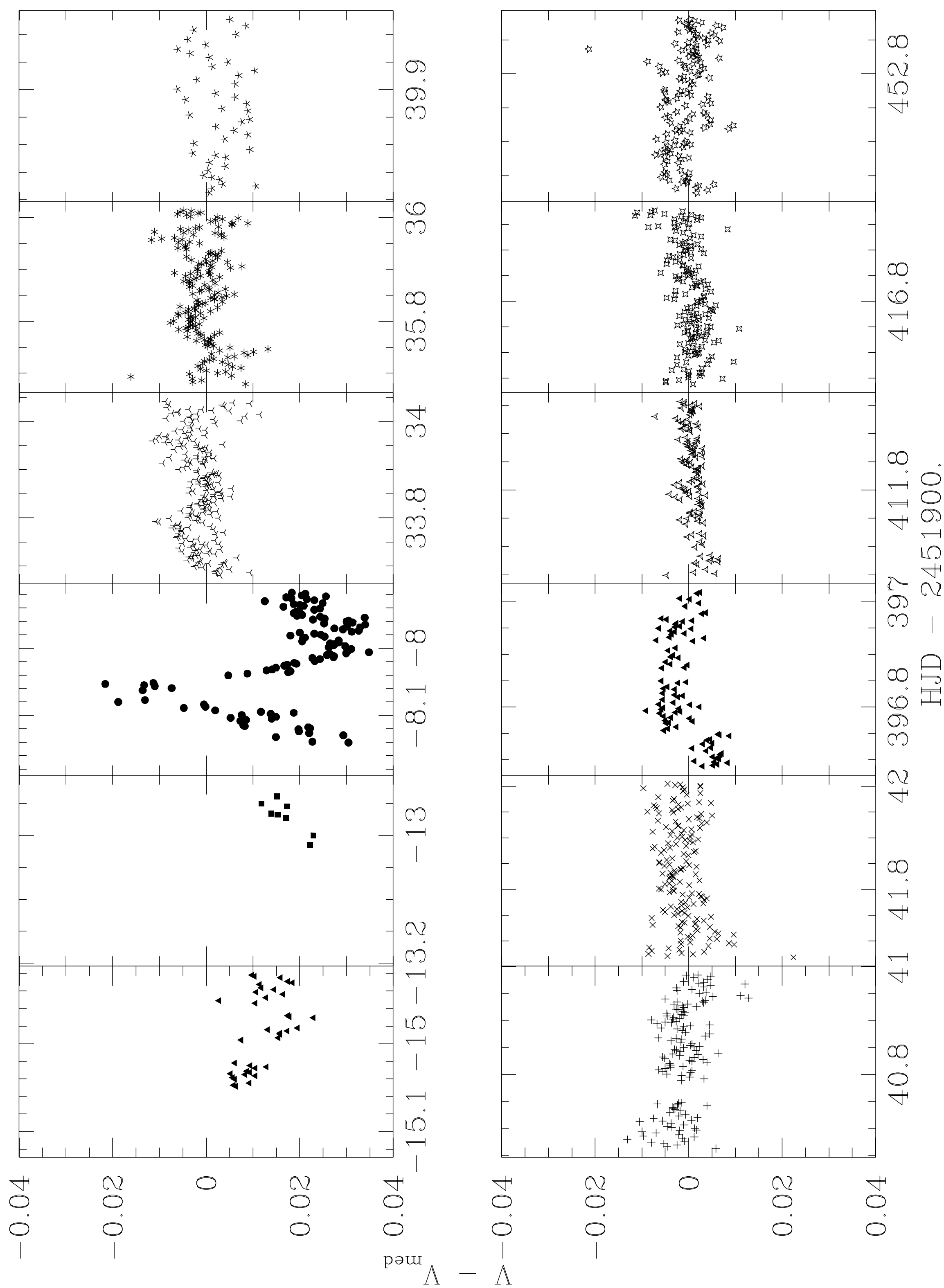

Fig. 12.— V-band time-series photometry for the blue straggler S752. Tick marks on the time axis are spaced by 0.05 d.

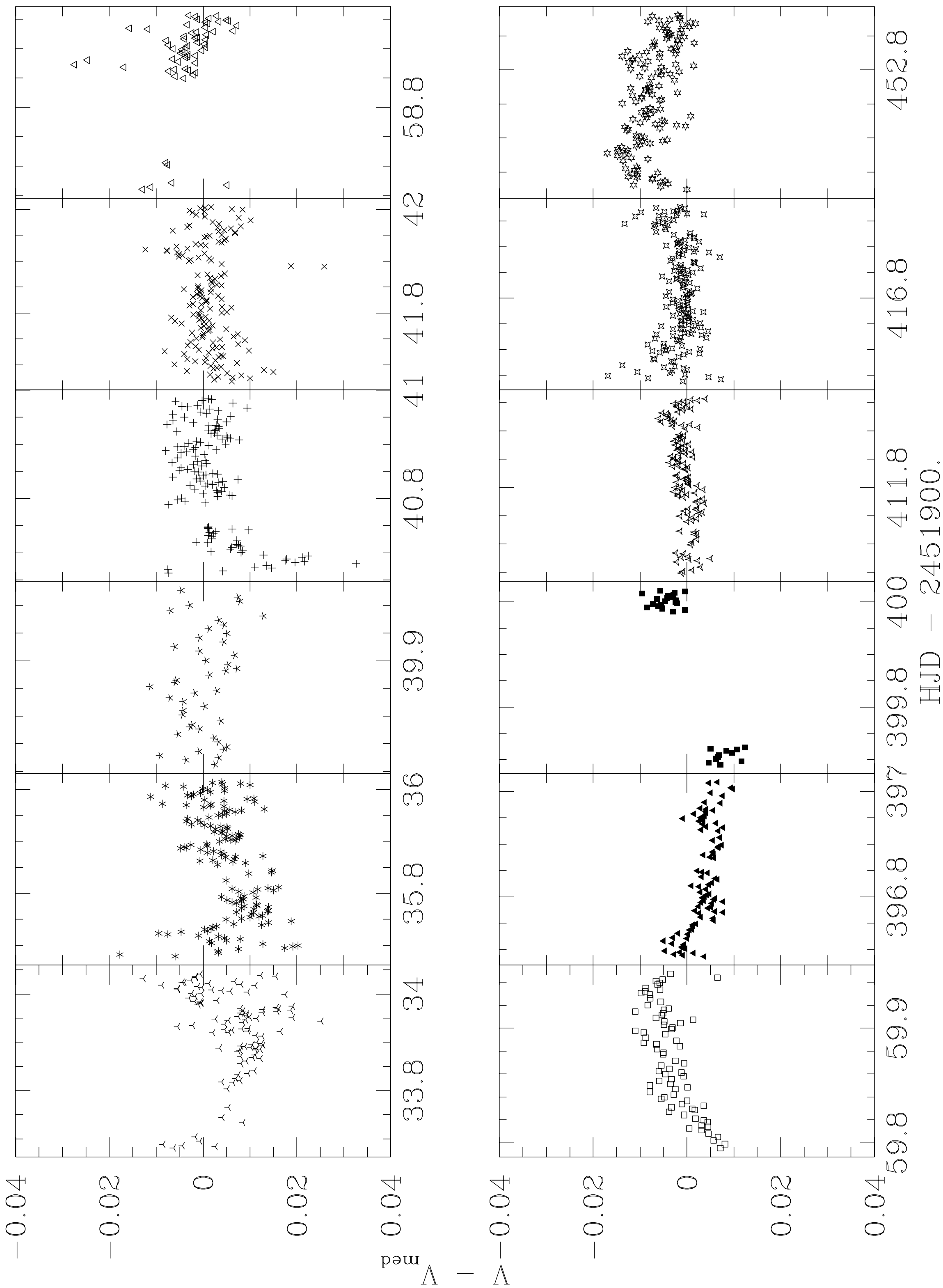

Fig. 13.— V-band time-series photometry for the blue straggler S968. Tick marks on the time axis are spaced by 0.05 d.

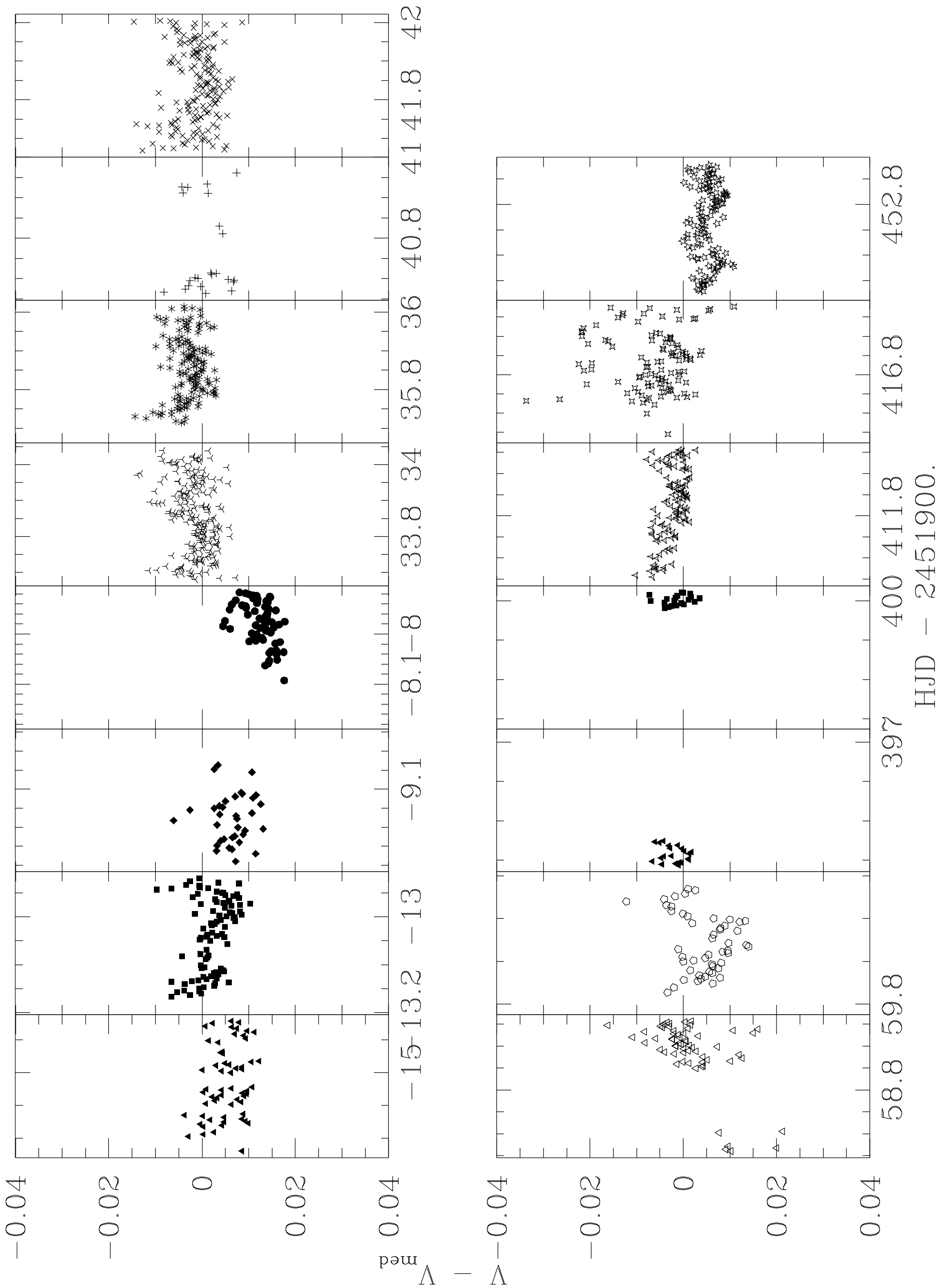

Fig. 14.— V-band time-series photometry for the blue straggler S1263. Tick marks on the time axis are spaced by 0.05 d.

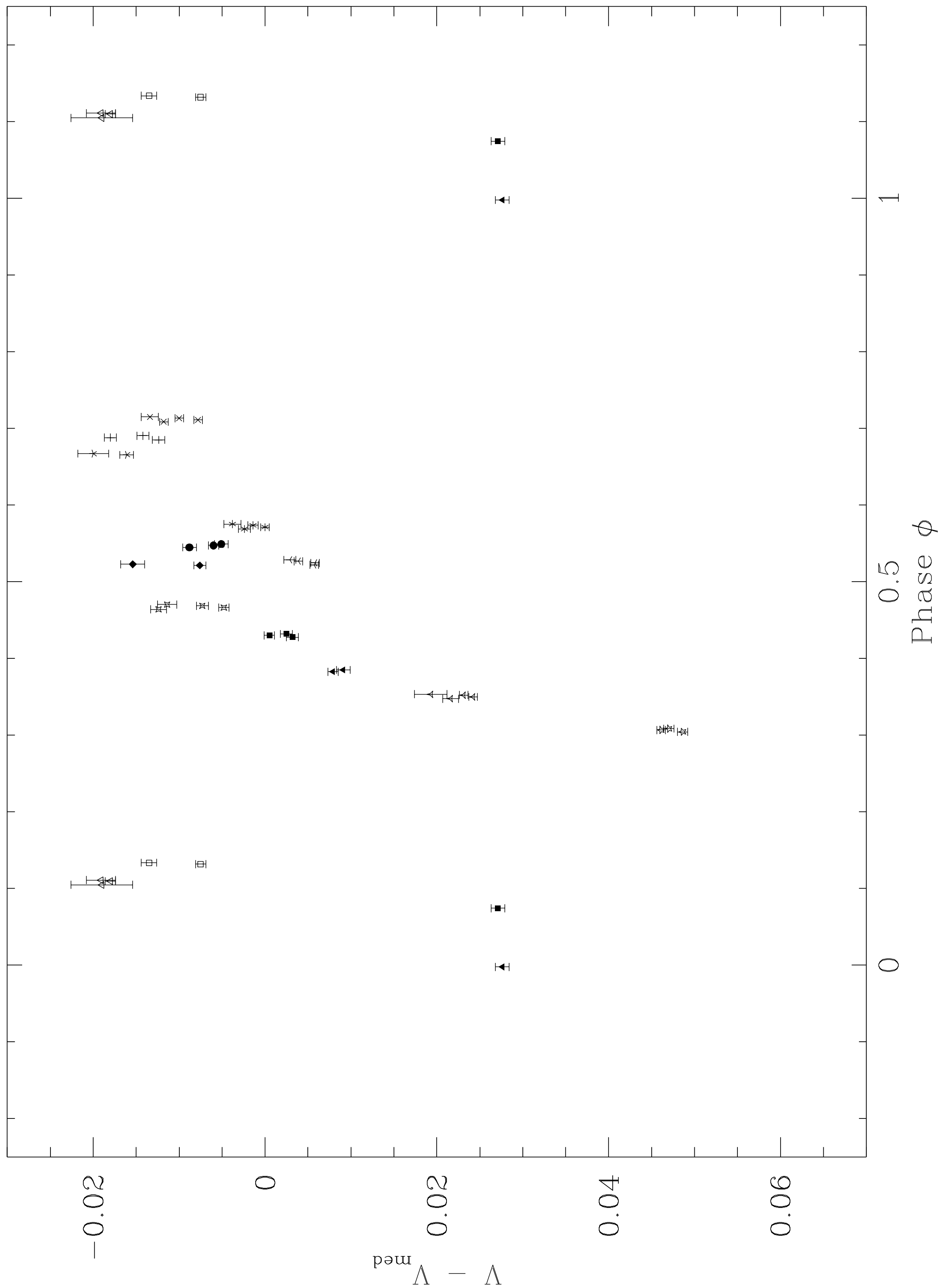

Fig. 15.— The V light curve for the “red straggler” binary S1040. Observations have been averaged in bins 0.1 d in duration. The data has been phased to the spectroscopic ephemeris of Mathieu, Latham, & Griffin (1990). Phase $\phi = 0$ corresponds to maximum positive radial

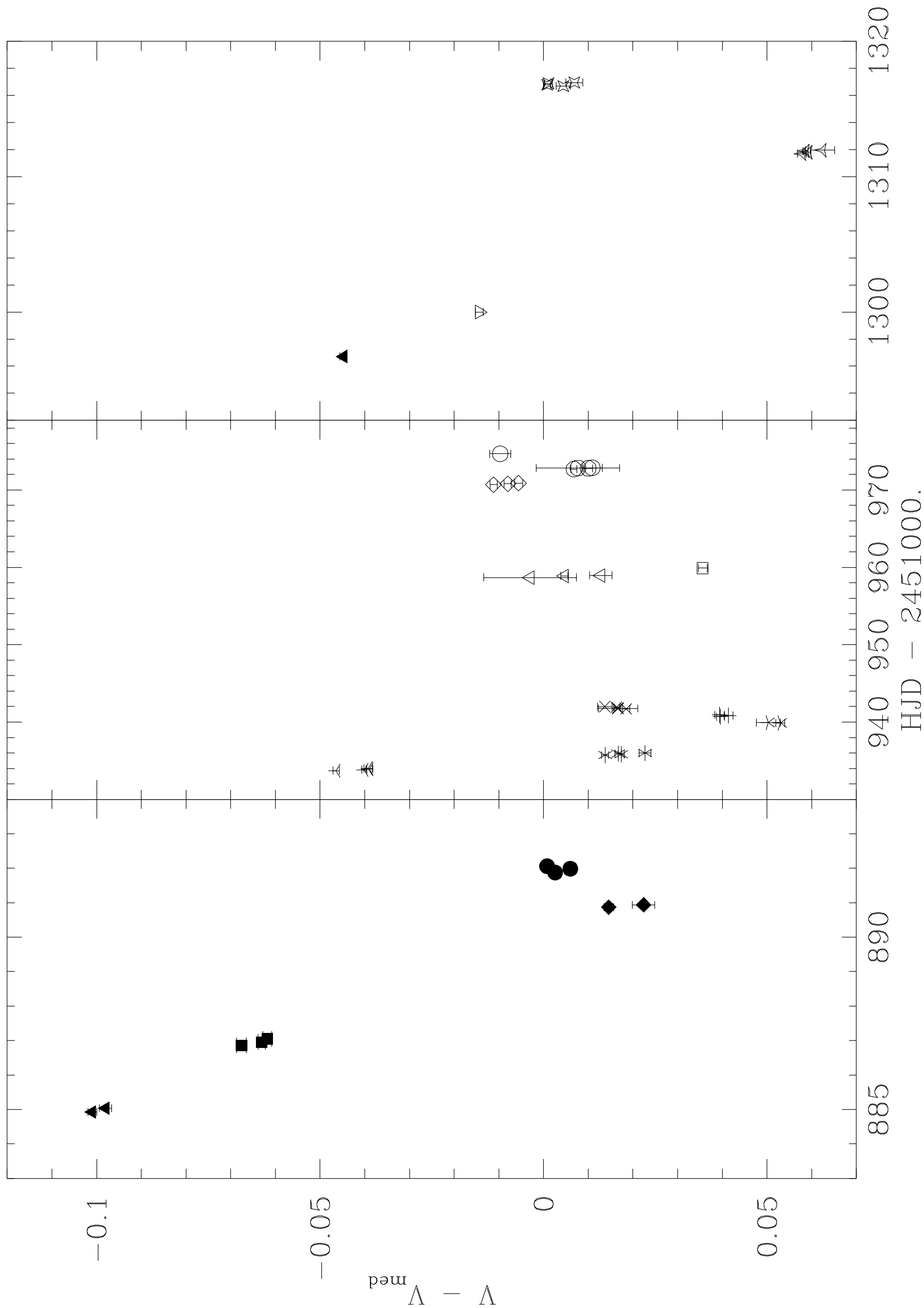

Fig. 16.— V-band time-series photometry for the sub-subgiant branch binary S1063. Observations have been averaged in bins 0.1 d in duration. Note that the time axis in the middle panel is more compressed than those on either side.

Table 1. Observing Log for V Photometry at Mt. Laguna

#	Date	mJD Start[a]	N_{obs}
1	Dec. 5/6, 2000	1884.878	60
2	Dec. 7/8, 2000	1886.806	111
3	Dec. 11/12, 2000	1890.817	57
4	Dec. 12/13, 2000	1891.820	116
5	Jan. 23/24, 2001	1933.675	206
6	Jan. 25/26, 2001	1935.673	176
7	Jan. 29/30, 2001	1939.676	44
8	Jan. 30/31, 2001	1940.657	130
9	Jan. 31/Feb. 1, 2001	1941.663	161
10	Feb. 17/18, 2001	1958.655	63
11	Feb. 18/19, 2001	1959.790	75
12	Mar. 1/2, 2001	1970.619	205
13	Mar. 3/4, 2001	1972.631	205
14	Mar. 5/6, 2001	1974.721	32
15	Jan. 21/22, 2002	2296.687	89
16	Jan. 24/25, 2002	2299.690	124
17	Feb. 5/6, 2002	2311.649	119
18	Feb. 10/11, 2002	2316.638	167
19	Mar. 18/19, 2002	2352.625	131

[a]mJD = HJD - 2450000

Table 2. Properties of M67 W UMa Systems

ID	S757	S1036 EV Cnc	S1282 AH Cnc	III-79 ET Cnc
T_0	2451800.129	2450500.047	[e]	2450000.036
P (d)	0.35967 ± 0.00002	0.441437 ± 0.000003	0.360452 [ce]	0.2704 [d]
ΔV_p	0.08	0.13	0.39	$\gtrsim 0.17$
ΔV_s	0.06	0.06	0.33	0.11
$\overline{V}$ [a]	13.51	12.81	13.44	15.90
$(B-V)$	0.61 [c]	0.50 [b]	0.52 [b]	1.11 [d]
i		$\sim 35°$	$86°^{+4}_{-8}$	
q			$0.16^{+0.03}_{-0.02}$	

[a]Average V magnitudes from observations in this study.

[b]Stassun et al. (2002)

[c]van den Berg et al. (2002)

[d]Gilliland et al. (1991)

[e]Period known to vary with time; see ephemeris of Kurochkin (1979)

Table 3. Best Fits to the Light Curve of S1282

Quantity	Dec. 2000	Jan. 2001
i	86°.0	86°.0
q	0.157	0.165
f	0.73	0.62
χ^2_{min}	0.41	1.31

Table 4. Blue Straggler Observations

ID[a]	V	$B-V$	σ_V	I_{WS}	Nights Observed[b]	N_{obs}	Results
145					none		
277					none		
751	12.70		0.008	0.53	$5-9$	777	no variation
752[c]	11.32	0.30	0.018	0.75	$4-9, 15, 17-19$	1418	Am star; possible flare detected
792	11.99	0.60	0.007	1.01	$5-9, 12, 13, 17-19$	1610	no variation
968[c]	11.25	0.13	0.010	0.74	$5-9, 11, 15, 17-19$	1261	Am star; possible low amplitude timescale $\sim$ days
975	11.05	0.43	0.077	7.26	$1-9, 11, 15, 17-19$	1659	photometry affected by faint com
977[c]	10.02	−0.07	0.006	0.69	$5-9, 18, 19$	504	no variation
984	12.26	0.57	0.014	1.64	$1-9, 11, 15, 17-19$	1732	no variation
997	12.13	0.46	0.006	0.92	$1-9, 11, 15, 17-19$	1655	no variation
1005	12.68	0.52	0.010	1.57	$1-9, 11, 15, 17-19$	1654	no variation
1031	13.29	0.46	0.007	0.32	$1-9, 11, 15, 17-19$	1644	no variation
1036	12.81	0.49	0.046	90.59	$1-9, 11, 15, 17-19$	1651	W UMa variable (EV Cnc)
1066[c]	10.95	0.11	0.003	0.24	$1-9, 11-13, 17-19$	2061	no variation
1072	11.31	0.61	0.006	0.97	$1-9, 11-13, 17-19$	2073	no variation
1082	11.20	0.42	0.024	33.59	$1-9, 11-13, 17-19$	2097	RS CVn variable (ES Cnc)
1165					none		
1183[d]	12.66		0.011	0.07	15	66	no variation
1195	12.29		0.003	0.40	15	78	no variation
1263[c]	11.06	0.19	0.007	0.98	$1-9, 11, 17-19$	1275	possible low amplitude, timescale $\gtrsim$ 10 days
1267[c]	10.90		0.005	0.45	$1-4, 11$	484	no variation
1273	12.25	0.57	0.006	0.63	$1-9, 11-13, 17-19$	1451	no variation
1280	12.23	0.26	0.009	2.55	$1-9, 11-13, 17-19$	1685	δ Scu variable (EW Cnc)
1282	13.44	0.52	0.133	108.08	$1-14, 17-19$	1864	W UMa variable (AH Cnc)
1284	10.93	0.22	0.012	9.41	$1-9, 11-13, 17-19$	2015	δ Scu variable (EX Cnc)
1434	10.70	0.11			none		
1440					none		
1947					none		
2204	12.89	0.45	0.013	1.03	$1-9, 11, 15, 17-19$	1717	no variation
2223	13.30	0.50	0.012	0.92	$1-9, 11-13, 17-19$	2084	no variation
2226					none		

[a]ID from Sanders (1977).

[b]Night IDs given in Table 1

[c]Photometry corrected for color-related errors at the 0.02 mag level

Table 5. Averaged Photometry for S1040

mJD[a]	$\bar{V}$	$\sigma_{\bar{V}}$	N_{obs}
1884.9294	11.5231	0.0006	33
1885.0391	11.5243	0.0008	27
1886.8586	11.5184	0.0007	36
1886.9615	11.5157	0.0006	43
1887.0468	11.5177	0.0007	32
1890.8688	11.5076	0.0007	42
1890.9386	11.4998	0.0014	14
1891.8734	11.5064	0.0008	37
1891.9872	11.5092	0.0006	51
1892.0607	11.5101	0.0008	28
1930.7983	11.5395	0.0058	1
1933.7305	11.5209	0.0005	55
1933.8308	11.5210	0.0005	63
1933.9312	11.5191	0.0005	57
1934.0118	11.5181	0.0007	31
1935.7288	11.5128	0.0007	45
1935.8314	11.5152	0.0005	60
1935.9333	11.5138	0.0006	54
1936.0000	11.5114	0.0010	17
1939.8739	11.4991	0.0008	36
1939.9386	11.4952	0.0018	8
1940.7053	11.5028	0.0007	37
1940.8386	11.4972	0.0007	46
1940.9371	11.5010	0.0007	47
1941.7175	11.5034	0.0005	49
1941.8186	11.5074	0.0005	48
1941.9199	11.5052	0.0005	50
1941.9883	11.5018	0.0010	14
1958.6849	11.4962	0.0036	7
1958.8989	11.4972	0.0006	50
1958.9531	11.4961	0.0017	5
1959.8451	11.5077	0.0006	47
1959.9218	11.5017	0.0009	28
2296.7175	11.5428	0.0008	21
2300.0020	11.5423	0.0008	20
2311.6980	11.5368	0.0009	23
2311.7991	11.5394	0.0005	44
2311.8994	11.5383	0.0005	46
2311.9536	11.5345	0.0010	5

Table 6. Averaged Photometry for S1063

mJD[a]	$\bar{V}$	$\sigma_{\bar{V}}$	N_{obs}
1884.9297	13.4520	0.0010	33
1885.0391	13.4550	0.0014	27
1886.8594	13.4854	0.0011	36
1886.9609	13.4899	0.0008	43
1887.0469	13.4912	0.0010	32
1890.8711	13.5676	0.0011	43
1890.9375	13.5754	0.0025	13
1891.8750	13.5556	0.0012	37
1891.9883	13.5590	0.0010	52
1892.0625	13.5538	0.0015	27
1933.7305	13.5066	0.0007	55
1933.8320	13.5129	0.0006	64
1933.9336	13.5140	0.0007	58
1934.0117	13.5138	0.0010	29
1935.7305	13.5668	0.0008	45
1935.8320	13.5704	0.0007	60
1935.9336	13.5697	0.0007	54
1936.0000	13.5757	0.0013	17
1939.8750	13.6060	0.0010	36
1939.9375	13.6033	0.0027	7
1940.7070	13.5926	0.0009	37
1940.8398	13.5944	0.0010	47
1940.9375	13.5924	0.0011	46
1941.7188	13.5715	0.0008	50
1941.8242	13.5696	0.0007	49
1941.9258	13.5693	0.0007	49
1941.9922	13.5667	0.0016	12
1958.6797	13.5500	0.0104	4
1958.8984	13.5577	0.0008	49
1958.9531	13.5658	0.0025	5
1959.8984	13.5886	0.0010	51
1970.6875	13.5418	0.0008	63
1970.7930	13.5450	0.0008	75
1970.8828	13.5474	0.0009	67
1972.6914	13.5598	0.0007	97
1972.7930	13.5630	0.0010	89
1972.8594	13.5639	0.0022	17
1974.6758	13.5433	0.0024	30
2296.7188	13.5082	0.0008	21

Table 6—Continued

mJD[a]	$\bar{V}$	$\sigma_{\bar{V}}$	N_{obs}
2352.7773	13.5164	0.0006	51
2352.8555	13.5183	0.0008	32

[a]mJD = HJD - 2450000