A DEEP CATALOG OF VARIABLE STARS IN A 0.66 deg$^2$ LUPUS FIELD

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ABSTRACT

We have conducted a wide-field photometric survey in a single 52′ × 52′ field towards the Lupus Galactic Plane in an effort to detect transiting Hot Jupiter planets. The data set also led to the detection of 494 field variables, all of which are new discoveries. This paper presents an overview of the project, along with the total catalog of variables, which comprises 190 eclipsing binaries (of contact, semi-contact, and detached configurations), 51 miscellaneous pulsators of various types, 237 long-period variables ($P \geq 2$ d), 11 δ Scuti stars, 4 field RR Lyrae (3 disk and 1 halo) and 1 irregular variable. Our survey provides a complete catalog of W UMa eclipsing binaries in the field to $V = 18.8$, which display a Gaussian period distribution of $0.277 \pm 0.036$ d. Several binary systems are likely composed of equal-mass M-dwarf components and others display evidence of mass transfer. We find 17 candidate blue stragglers and one binary that has the shortest period known, 0.2009 d ($V = 20.9$). The frequency of eclipsing binaries (all types) is found to be $1.7 \pm 0.4 \times 10^{-3}$ per star, substantially higher (by a factor of 3–10) than previously determined in the halos of the globular clusters 47 Tuc and ω Cen. This indicates that cluster dynamics aid mass segregation and binary destruction.

Key words: binaries; eclipsing – binaries: general – δ Scuti – stars: variables: other

Online-only material: machine-readable table, supplemental data file

1. INTRODUCTION

The discovery rate of field variable stars has dramatically increased in recent years due to the advent of large-scale photometric surveys with wide fields of view. Many such surveys are dedicated to the detection of transiting short-period planets or microlensing events (e.g. Wozniak et al. 2004 and references therein). They are perfectly suited to the detection of variable stars (Soszyński 2006; Alcock et al. 2003), as they incorporate long temporal baselines, high-resolution imagery, and achieve simultaneous high-precision photometry for tens of thousands of stars.

Variable stars provide important information on the frequency, nature, and evolution of stellar variability (of all types) in various regions of the Galaxy. Binary stars provide information on stellar mass–radius relationships across many orders of magnitude, particularly for the little-understood relation for the lowest-mass stars. Pulsating variables (such as δ Scuti stars) offer insights into the internal structure and evolution of main-sequence and post-main-sequence objects. RR Lyrae and Cepheids are often used as distance indicators, and their identification (particularly in stellar clusters) provides additional distance information for comparing stellar properties with that provided by theoretical isochrones.

Unlike microlensing surveys, transit surveys have temporal resolution of several minutes, permitting the detection of variability on very short time-scales, as well as longer-period variability depending on data set properties. Kane et al. (2005) present an example of a variable star catalog from a wide-angle transit survey in the general field, containing the types of variability commonly found. Similarly, Weldrake et al. (2004, 2007a) present the variables identified during a transit survey of the halos of 47 Tucanae (47 Tuc) and ω Centauri (ω Cen). Open clusters have also been targeted (Pepper & Burke 2006 and references therein), and the Permanent All Sky Survey (Deeg et al. 2004) has the goal of permanently tracking variable stars in the whole sky with high temporal resolution.

This paper presents the total catalog of 494 variable stars identified during a deep, wide single-field survey for transiting Hot Jupiter planets (~Jupiter-mass planets with orbital periods of a few days) towards the Lupus Galactic Plane. In addition to searching for transiting planets, this survey acts as a control field for our previous 47 Tuc and ω Cen transit surveys, both of which produced significant null results. One object that is almost certainly a transiting low-mass Hot Jupiter has been identified in our survey (Weldrake et al. 2007b). The survey also serves as an excellent test of the techniques and strategies for use in the soon-to-begin 5.7 deg$^2$ SkyMapper transit survey (Bayliss & Sackett 2007). SkyMapper has the capacity to discover dozens of new transiting planets and thousands of variable stars in the near future.

Here, we present the properties of all 494 variables, and illustrative $V + R$ lightcurves for the majority of the catalog. We detail a preliminary analysis on their occurrence rates and likely nature, particularly in comparison to previous work in the fields of the globular clusters 47 Tuc and ω Cen (Weldrake et al. 2004, 2007a, 2007c). We find a significant difference in the occurrence rate for binary stars, with our field having three times the observed binary frequency of ω Cen and 10 times that of 47 Tuc. This supports mass segregation, particularly for 47 Tuc, and overall binary destruction in globular clusters due to cluster dynamics. Several of our binary systems are likely composed of M-dwarf components, of interest in the study of low-mass stars, and several other binaries display evidence of mass transfer, important for studies into binary system evolution and stellar interactions. We have also identified 17 blue straggler candidates and a binary which very likely contains a δ Scuti component.

Section 2 of this paper details the observational strategy and data reduction techniques. Section 3 describes the production
of the stellar time-series, the removal of data set systematics, resulting photometric accuracy, and stellar colors and astrometry. Section 4 details the variability search methods and data set completeness. Section 5 presents the variable catalog, detailing each main type of variable and provides the derived binary frequency in our field, with a comparison to the globular clusters and distance estimates for our four RR Lyrae stars. We conclude in Section 6.

2. OBSERVATIONS AND DATA REDUCTION

Using the Australian National University 1 m telescope at Siding Spring Observatory, a single 54′ × 54′ Wide-Field Imager (WFI) field was observed for 53 nights, 26 contiguous nights in 2005 June and 27 nights in 2006 June. The WFI detector consists of a 4 × 2 array of 2048 × 4096 pixel back-illuminated CCDs, arranged to produce a total area of 8K × 8K pixels. The detector scale is 0.′8 per pixel at the Cassegrain focus, well matched to the median seeing at the site (mean seeing of 2.′2) allowing a suitable sampling of the stellar point-spread function (PSF). During the course of this survey, only seven of the eight WFI CCDs were operational, resulting in an effective survey field of 0.66 deg².

The survey field is a few degrees from the Galactic Plane and is centered at R.A. = 15h30m36.3s, decl. = −42°53′53.0″ (b = 11° i = 331.5°). The positions of the centers of each individual WFI CCD are given in Table 1. This particular field was chosen as it has excellent visibility during the course of the run, it is permanently located away from the moon, it lacks any stars brighter than V ~ 11, and it is a highly crowded field with low dust extinction.

We require a signal-to-noise ratio of ~200 at V = 18.0 to adequately recover the transits of Hot Jupiter planets. In order to do this, we used a single broad-band filter covering the combined wavelength range of Cousins V and R to increase the signal-to-noise ratio. We took 5 min exposures of the field, which with the V + R filter permitted a photon-noise signal-to-noise ratio of ~220 for a 7 d moon for a V = 18.5 star in 2′′ seeing. With a full moon this signal-to-noise ratio decreases to ~165. A total of 2201 images of the field were obtained over the course of 53 nights. Given the CCD readout time, pointing, and focusing overheads, a mean temporal resolution of 6–7 min was achieved within our observing window (typically 9 h per night in good conditions). This combination of telescope, detector, filter, and observational strategy has been previously used successfully to perform a similar search for planetary transits and variable stars in the globular clusters 47 Tucanae and ω Centauri (Weldrake et al. 2004, 2005, 2006, 2007a).

In addition to the V + R imagery, three images in V and three in I were taken with the same telescope and pointing in order to produce the field color–magnitude diagram (CMD). Observations in V and I of Mark-A standard stars (Landolt 1992; Stetson 2000) were also taken on the same night for accurate CMD calibration.

Image reduction was carried out using the standard MSCRED routines within IRAF. This included region trimming, overscan correction, bias correction, flat-field correction, and dark current subtraction. Low-quality images (poor seeing, poor focus, etc.) were filtered out, and the resulting data set used to produce precise, high-resolution, photometric time-series for as many stars as possible in the survey field.

3. LIGHTCURVE PRODUCTION

A total of 110,372 stars were identified in our survey field, and for each we produced a photometric time-series using an application of Differential Imaging Analysis (DIA), previously described as the optimal PSF-matching package of Alard & Lupton (1998). This code was subsequently modified by Wozniak (2000) for the detection of microlensing events. We direct the reader to the Wozniak paper for a full description of the code and its application.

By matching the stellar PSF throughout a large image data base, the systematic effects resulting from varying atmospheric conditions on the output photometric precision are dramatically reduced. This method allows ground-based observations, the best prospects of detecting small-amplitude brightness variations in faint targets. DIA is also one of the optimal photometric methods when sampling fields with a high degree of crowding, as the large number of stars permits a large number of pixels to contain information on any PSF differences, improving the PSF-matching process. Initial stellar flux measurements are made via profile photometry on a template frame, produced via median combining a number of best-quality images with small offsets. The flux measurement on this template is used as the zero-point of the resulting stellar time-series.

Stellar positions were found on a reference image, which contained the best seeing conditions, and all the subsequent data set images, including the template, were registered. The best PSF-matching kernel was determined, and each registered image was subsequently subtracted from the template, with the residuals generally being dominated by photon noise. Any object in the frame that changed in brightness between the image and the template was recorded as a bright or dark spot in the residual map.

Differential photometry does not automatically produce time-series in magnitude units, rather in differential counts. This is a linear flux unit output in the code from which a constant reference flux (taken from the template image) has been subtracted. In order to convert to a standard magnitude system, the total number of counts for each star was measured using the PSF package of DAOPHOT within IRAF, with the same images and parameters as used in the DIA code. The total database of output time-series was then converted in a standard way into magnitude units via the relation:

$$\Delta m_i = -2.5 \log[(N_i + N_{\text{ref},i})/N_{\text{ref},i}]$$

The “−” symbol is used to define negative magnitudes.

Table 1

| CCD | R.A. (J2000.0) | Decl. (J2000.0) |
|-----|---------------|----------------|
| 1   | 15:31:47      | −42:34:45      |
| 2   | 15:31:49      | −42:47:35      |
| 3   | 15:31:50      | −43:01:04      |
| 4   | 15:31:51      | −43:13:57      |
| 5   | 15:29:30      | −43:14:06      |
| 6   | 15:29:29      | −43:01:07      |
| 7   | −             | −              |
| 8   | 15:29:27      | −42:35:17      |

Note: CCD7 was inoperative and is marked with a “−”.

This combination of telescope, detector, filter, and observational strategy has been previously used successfully to perform a similar search for planetary transits and variable stars in the globular clusters 47 Tucanae and ω Centauri (Weldrake et al. 2004, 2005, 2006, 2007a).
Figure 1. The photometric precision of 90,959 stars across the field resulting from the DIA+SYSREM photometry technique applied to our data set, plotted against $V$ magnitude. The theoretical photon noise for the star (green short-dashed), the sky (blue long-dashed), the residual noise contribution (blue dot-dashed), and the sum of all (red solid line) are overplotted for comparison. Some variable stars are visible as the sequence of higher rms at bright magnitudes.

Figure 2. The CMD for our Lupus field. The locations of all 494 detected variable stars are overplotted. The four panels denote the four main types of variable in the catalog, plotted in various colors to facilitate their visibility. The various types of variable are seen to populate various regions of the CMD. The $\delta$ Scuti (yellow) and RR Lyrae stars (green) are all blueward of the main shoulder defining the limit of A-F type Galactic Disk stars, indicating their early spectral types. The EcB are scattered all over the plot, indicating the different spectral types of the stellar components. The 17 binaries with $V-I \leq 0.5$ are candidate blue stragglers. The overplotted error bars represent the output DAOPHOT errors and the CMD calibration uncertainty added in quadrature.

Figure 3. The astrometry for our field. The spatial distribution of the main types of variable are overplotted (with the same color schemes as in Figure 2). The non-functional CCD7 is clear.

Figure 4. The output AoV significance ($S_{AoV}$) distribution for the whole 110,372 stellar lightcurve data base upon which it was run. The main population at lower significance defines the general population for which no periodicity was detected. A Gaussian was fitted to this population and overplotted along with the resulting mean and standard deviation parameters. Any lightcurve that had an AoV output significance $\geq 3 \times$ the standard deviation of the background (marked as a vertical line) was flagged as a candidate variable. All 9230 candidates satisfying this criteria were searched for variability.

The pixel coordinates of all the visible stars were determined separately from the reference frame via DAOFIND within IRAF, with the resulting profile photometry extracted from the subtracted frames at those determined positions. Due to the chosen filter, the time-series are presented here in $V + R$ differential magnitude units. These can be converted to the standard $V$ system if required via the additional calculation of color terms.

where $N_{tot,i}$ is the total flux of star $i$ on the template image and $N_i$ is the original difference flux in the time-series as produced with the photometric code.
When combining differential fluxes with DAOPHOT-derived photometry on the reference image, we must correct for errors based on the individual apertures used. The scaling between the two fluxes was determined via an aperture correction, which was performed on the DAOPHOT magnitudes for the stars. This method is described in appendix B of Hartman et al. (2004). We found that our PSF magnitudes were consistently 0.06 mag brighter than the aperture-derived values (using the same aperture values as in the differential photometry). We corrected for this by shifting our magnitude zero-point to $25.0 - 0.06 = 24.94$. This correction ensures that the amplitude of moderate variation detected by the DIA code is accurately represented in magnitude units.

3.1. Systematics Removal and Photometric Accuracy

All 110,372 time-series as output by DIA were converted to $\Delta V + R$ magnitude units as above. The whole data set was cleaned for systematic effects by running an application of the SYSREM systematics removal code (Tamuz et al. 2005). This algorithm searches for and removes effects common to the stars of a particular data set, using only the time of observation and the respective flux measurements for all stars simultaneously. The result is a dramatic increase in the photometric precision, of vital importance to any search for small amplitude brightness variations. The algorithm works best for brighter stars, where systematic effects dominate in the photometric uncertainties.

Figure 1 presents the output DIA-derived photometric precision for 90,959 stars across the whole of the WFI field, after an application of the SYSREM algorithm. These stars are those for which a post-SYSREM lightcurve, $V$ magnitude, and astrometry have been derived. The $V$ magnitudes for these stars were determined from the field CMD (see next subsection). The $Y$-axis shows the logarithm of the measured root mean square (rms) uncertainty for the whole stellar lightcurve, plotted against the $V$ magnitude of the same star. Some variable stars are visible as a separate sequence above the main rms distribution (particularly for brighter stars). Also overplotted in the figure is the theoretical photon noise due to the star (green short-dashed line) and the sky noise contribution (blue long-dashed line). A further noise contribution arises from residual image-based systematic effects; flat-fielding errors, scintillation, and CCD nonlinearity response. All of these are estimated with an
amplitude of four times the calculated sky noise to represent
the total observed noise when added to the photon noise in the
star and the sky, and is displayed in Figure 1 as a dash–dotted
blue line. The solid red line represents the total of the photon
noise, and this total sky contribution (added quadratically), and
describes the photometric uncertainties well. Our photometry is
photon-noise dominated to a $V$ magnitude of $\sim 18.5$, where it be-
comes sky+residuals dominated to fainter magnitudes.

3.2. CMD and Astrometry

A CMD of $V - I$ against $V$ was produced for the survey
field with the same telescope and detector, in order to place
the detected variables (and transit candidates) onto the standard
magnitude system. The diagram contains a total of 95,358 stars
with both measured $V$ and $I$ magnitudes. This CMD, with all
494 detected variables overplotted, can be seen in Figure 2.
The figure shows four panels, one for each of the main type of
variable star found (overplotted). The four main types can be
seen to populate different regions of the CMD, depending on
their intrinsic spectral type. Our survey has a saturation limit at
$V = 15.0$, and a faint limit of $V = 22.0$. A sharp edge is seen at
$V - I = 0.6$, indicating the Galactic disk main-sequence turn-
off, the limit of the more numerous F, G, K, and M stars (to the
right of the edge) compared to the far less numerous earlier-type
stars (to the left of the edge) at the typical age of the galactic
disk. The DAOPHOT-derived errors and calibration uncertainty
in our magnitude determinations are also overplotted.

The CMD was calibrated via $V$ and $I$ observation of the
MarkA standard stars (Landolt 1992; Stetson 2000), taken at the
same time as the CMD data. A total of 415 standards were cross-
identified in the field via matching of astrometry. The mean and
standard deviation of the shift in magnitude were found for each
CCD and for each filter independently. The resulting calibration
uncertainty is 0.03 mag in $V$ and 0.05 in $V - I$. As an additional
check, the CMD was also cross-correlated with 2000 stars within
20’ of the field center in the NOMAD online catalog (Zacharias
et al. 2004), and, being towards the faint limit of NOMAD,
have $V$ magnitudes within 0.2 mag (1σ) of the NOMAD
results.

The astrometry for all of the stars in our database was
determined via a search of the USNO CCD Astrograph Catalog
(UCA2), to search for astrometric standard stars within the
field. Several hundred such stars were successfully identified,
producing an accurate determination of the astrometric solution
for the stars in each CCD independently; the resulting calibration
accuracy was 0.25” (0.66 pixels). The extent of our field can be
seen in Figure 3, plotted as $\Delta$ R.A. and $\Delta$ decl. in degrees.
The location of the variable stars is overplotted with the same
color scheme as in Figure 2. The non-functioning WFI CCD7 is
clear.

4 MarkA astrometry and photometry downloaded from http://www4.cadc-
cnda.hia-iha.nrc-cnrc.gc.ca/community/STETSON/standards/
4. VARIABILITY SEARCH METHOD AND COMPLETENESS

We used the “analysis of variance” (AoV) statistic to perform the variability search, with Schwarzenberg-Czerny (1989) providing a full description of the method. Via AoV, the data are phase-wrapped to a trial period and grouped into phase bins. A one-way statistical AoV is performed on the result with the output noted. This procedure is repeated for a fixed range of test periods for each star, producing a series of significances and their corresponding periodicities. The final output for each star is the peak periodicity and its corresponding significance.

The output AoV significance is far higher if a periodicity is detected, facilitating the variable identification, and allowing for detection thresholds to be used to increase the search efficiency. Figure 4 shows the output AoV significance ($S_{AoV}$) distribution for the whole time-series data set. The main population at low significances are those stars for which no periodicity was detected. The variable star candidates constitute the long tail to increasingly higher significance. The main population was fit with a Gaussian, overplotted in Figure 4 with a resulting mean $S_{AoV} = 3.904$ and standard deviation (rms) of $S_{AoV} = 0.499$.

Any candidate with a significance $\geq 3 \times$ rms (9230 candidates $S_{AoV} \geq 5.401$) was counted as a candidate variable star, which was then phase-wrapped at the AoV-determined peak periodicity and the presence of any variability noted. This candidate detection threshold is marked in Figure 4 with a vertical line.

We visually searched through all 9230 candidates to detect the variable stars, which were also phase-wrapped to 0.5, 2, and 3 times the detected period to check for the presence of integer aliasing. Out of these, we visually detected a total of 572 variables, corresponding to one real variable per 16.1 candidates. With such a large number, the chance of any real variables being missed in the search and escaping detection via this method is low.

The total candidate list numbered 572 stars that were seen to undergo periodic brightness changes, 77 more than the final variable list. The astrometry for the original 572 was checked for double entries, consisting of candidates that lie within several arcsec of each other in both R.A. and decl., and also variables with the same or very similar ($\leq 0.1$ d) peak periodicity. The majority of the extra 77 were found to be double entries, particularly comprising fainter “variables” which lie close ($\leq 5''$) to a far brighter real variable. We classify these as “blends,” and have lightcurves with the same periodicity as the bright nearby variable, but with only a fraction of the signal. The RR Lyrae stars, being so bright, were particularly responsible for these blended candidates. The remaining few false variables were identified by their common periods to more distant, yet still nearby, bright counterparts. In all, 494 true variables remained in the candidate list and constitute the final catalog.
A small number of the detected variables (∼5%) had significant scatter on the resulting phase-wraps, indicating an incorrect determination of the period. These were then analyzed with a Lomb–Scargle Periodogram (Bretthorst 2001) to provide a secondary estimate to the period. This was then phase-wrapped and the period optimized until a minimum in the scatter was obtained. The change in period needed to obtain the final period was less than 0.1 d in all cases, and is related to the number of data points contained within the periodicity. The small number of these statistical false-period detections is further evidence of the strength of AoV as an accurate periodicity determinator.

Figure 5 presents the total amplitude of the variation for each cataloged variable star, plotted as a function of its corresponding \( V \) magnitude. This provides information on the detection limits of the catalog. The dotted line defines the observed empirical limit in the variable amplitude as magnitude increases. Any variable with an amplitude less than or equal to the position of the dotted line is unlikely to be revealed by the detection method described above. Hence, at \( V = 18.0 \), the observed detection limit is 0.05 mag (4.7%), while at \( V = 22.0 \), the limit is 0.70 mag (91%), and originates from our photometric uncertainties (Figure 1).

5. VARIABLE STAR CATALOG

In total, the catalog contains 494 variable stars. This consists of 190 eclipsing binary (EcB) systems, displaying many examples of detached (e.g. V8), semi-detached (e.g. V26), and contact (e.g. V3) configurations. It also contains 51 pulsating stars (puls) defined as having a sinusoidal variation and period \( \leq 2 \) d; and 237 long-period variables (LPV), which display similar variation to the pulsators but with far longer periods (\( 2 \leq P \leq 100 \) d). We also detected 11 \( \delta \) Scuti stars with extremely short pulsation periods (minutes in many cases) and four field RR Lyrae stars (three type “AB” and one type “C”). We also detected a single irregular variable. The lightcurve data base is available on the online edition of this paper.

The total variable star catalog (in order of R.A.) can be seen in Table 2. This table presents the identification number of the variable, the type of variability (tabulated in order of type: EcB, RR Lyrae, \( \delta \) Scuti, puls, LPV, and Irr), the period in days, the R.A. and decl. (J2000.0), the \( V \) magnitude, \( V \) uncertainty, and finally the \( V - I \) color and associated error. The \( V \) magnitude, uncertainty, and \( V - I \) color are all taken from the CMD data set. The uncertainties include calibration errors. If a particular binary has an orbital period \( \leq 0.385 \) d (from the determined 3σ lower limit to their period distribution, see later) we classify it as a W UMa type system, and is marked as such in the table. Those magnitudes marked with “−” have unknown magnitude in that particular band, the vast majority of which are due to saturation in one filter.

Accurately determined periods are presented to five decimal places. Variables with less certain periods are presented with a number of decimal places appropriate to the uncertainty. Those pulsating variables which could in reality be short-period
Table 2

| ID | Type       | Period (d) | R.A. (J2000.0) (h.m.s) | Decl. (J2000.0) (°′′) | V   | σV  | V − I | σ(V − I) |
|----|------------|------------|------------------------|-----------------------|-----|-----|-------|----------|
| V2 | EcB        | ∼15.15     | 15:28:30.29            | −42:59:51.98          | 18.187 | 0.005 | 0.744 | 0.008    |
| V3 | W UMa      | 0.26837    | 15:28:30.98            | −43:00:17.23          | 18.830 | 0.006 | 0.799 | 0.008    |
| V4 | EcB        | 0.39051    | 15:28:31.49            | −43:07:35.66          | 16.699 | 0.004 | 0.819 | 0.006    |
| V8 | EcB        | 3.84765    | 15:28:34.03            | −42:31:00.60          | 15.739 | 0.005 | 0.838 | 0.013    |
| V10| EcB        | ∼4.31      | 15:28:35.46            | −42:33:17.75          | 15.860 | 0.003 | 0.660 | 0.007    |
| V15| EcB        | ∼6.54      | 15:28:38.99            | −42:33:23.34          | 20.309 | 0.017 | 0.945 | 0.022    |
| V17| EcB        | 5.2915     | 15:28:40.56            | −42:56:54.39          | 19.960 | 0.013 | 0.655 | 0.018    |
| V20| W UMa      | 0.25374    | 15:28:41.36            | −43:05:08.04          | 19.786 | 0.012 | 0.800 | 0.016    |
| V24| EcB        | 1.87920    | 15:28:42.69            | −42:59:47.78          | 18.982 | 0.007 | 1.224 | 0.009    |
| V26| EcB        | 0.44130    | 15:28:43.13            | −43:14:25.41          | 21.052 | 0.034 | 1.924 | 0.036    |

**Notes.**

Tabulated are the Variable Star Identification number, the type of variable, the period, R.A., and decl. (given in J2000.0), $V$ magnitude, $V$ error, $V − I$ color, and its associated uncertainty. Those pulsators with periods marked as * are those which could be eclipsing binaries with twice the tabulated period. Unknown magnitude values are marked as “−.”

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

Eclipsing binaries, indistinguishable in our data, with equal-mass components W Ursae Majoris (W UMa) stars, and hence identical primary and secondary eclipses, have their periods marked with an asterisk. Those longer period variables and binaries with only one single eclipse visible (hence uncertain periods) have their estimated periods presented, which are marked with a “∼.” Those variables classed as pulsators which could be actually eclipsing binaries with twice the tabulated period are marked with a “*.”

The total catalog of variables is overplotted on the data set CMD in the four panels of Figure 2 to facilitate the determination of their likely nature. The EcB stars (top left, blue squares) are...
seen to inhabit all parts of the diagram, indicating the differing component spectral types and distances to these systems. In contrast, the $\delta$ Scuti stars (bottom left, yellow circles) and RR Lyrae (bottom left, green triangles) are all located blueward of the main “shoulder” seen at $V - I = 0.6$. This indicates that these types of variability are associated exclusively with stars of earlier spectral types ($\leq A - F$). No faint $\delta$ Scuti stars were seen in our data due to the low amplitude of their variability. In comparison, all but two of the LPV (V200 and V401) (red triangles) are located redward of the $V - I = 0.6$ shoulder, indicating the association of this type of variability with later spectral types ($\geq G - M$). All but four of the pulsators (bottom right; V291, V319, V338, and V491) are located redward of $V - I = 0.5$.

5.1. Eclipsing Binaries

A total of 190 EcB systems were found in our data. These include many examples of contact, semi-detached, and detached systems. The vast majority of the binaries have accurate periodivities determined, with the exception being those long-period fully detached systems with only one or two eclipses visible during our observing run. We classify those 17 binaries blueward of $V - I = 0.5$ (V36, V44, V76, V113, V117, V168, V228, V253, V257, V294, V296, V317, V385, V405, V442, V467, and V476 as seen in Figure 2) as candidate blue stragglers. Particularly, V385, V405, and V467 have “blue” $V - I$ magnitudes of 0.244, 0.272, and 0.253, respectively. Some binaries (e.g., V10 and V31) are difficult to phase-wrap accurately due to the low number of eclipses visible in our data.

5.1.1. Selected Binary Systems

Several of our binary systems are of particular interest for follow-up studies. V413 is the brightest binary detected in this search, with $V = 14.595 \pm 0.008$ and orbital period 1.7962 d. The total phase-wrapped lightcurve for this semi-detached system is seen within Figure 14 and in greater detail in Figure 6. It displays a very deep primary eclipse ($\Delta V + R \sim 2$ mag) and a far shallower secondary eclipse. This indicates that the two stellar components are of very different spectral types and luminosities.

Closer examination of the V413 lightcurve reveals a secondary pulsation variation with a period of only a few minutes, typical of a $\delta$ Scuti star. The amplitude of this pulsation is $\geq 5$ mmag and can be seen in both panels of Figure 6 (phase-wrapped in the bottom panel to five times the periodicity for ease of visibility). Such variations indicate the presence of a small-scale surface variability similar to solar surface oscillations. The period of this secondary oscillation is comparable to the exposure time of the observations, hence the amplitude presented here carries uncertainty. Furthermore, the period of this oscillation is seemingly $1/500$th the binary orbital period, perhaps indicating that it may originate with surface jitter induced by the binary companion. A second theory, and perhaps more likely, is that one component of this binary is a $\delta$ Scuti star.
Follow-up photometry and spectroscopy are planned to fully understand this interesting system.

V161 displays a long-period sinusoidal variation with a superimposed eclipse with the same period. The system is quite red \((V - I = 0.96)\) and is perhaps composed of a pulsating red variable, which is in turn orbited by a stellar companion. Alternatively, the system could contain a red giant which has been significantly distorted by a nearby massive companion.

As our survey field was observed for 27 nights in 2005 June and 26 nights in 2006 June, changes in any variability during the course of that year can be seen in our lightcurves. V130 (orbital period 1.22086 d) displays a consistent change in system brightness (out-of-eclipse zero-point) of \(\sim 0.1\) mag \((V + R)\) during this time; the system is brighter in 2007. This can be seen in the phase-wrapped lightcurve for this system in Figure 9. We attribute this variation to one component being an LPV in itself. As the change is stable over the course of a month, we cannot attribute this to starspots or flare activity. If the components are interacting with each other, as the out-of-eclipse ellipsoidal variations seem to indicate, then an accretion scenario may be present in this system.

A number of our binaries are likely composed of low-mass M-dwarf components, as such they are of importance to studies of stellar mass and radius relationships for late-type stars. These systems were chosen based on their \(V\) magnitude and \(V - I\) color, along with their short orbital periods and the evidence for only a small degree of interaction between the components in their lightcurves. We classify V26, V115, V184, V297, V304, V352, V355, V402, V418, and V438 as likely low-mass systems. Particularly interesting are V304 and V402 as detached systems. V232 is extremely faint \((V = 21.99)\) with a \(V - I\) of 2.91, and is almost certainly composed of very low mass stars.

A number of the longer period systems could also contain a low-mass component again based on the amplitude of gravity effects and the difference in primary and secondary eclipse depths (e.g. V144 and V312). Indeed, the systems classified as W UMa stars (seen in Table 2) almost certainly contain low-mass components. Interestingly, these W UMa stars are seen as mostly blue straggler systems in old globular clusters (Weldrake et al. 2004, 2007a) rather than late-type stars expected for the (younger) general field. The shortest period binary detected in this survey is V344, with an orbital period of 0.2009 d \((V = 20.9)\), and if confirmed will become the shortest period binary known (beating shorter than the previous 0.215 d binary found in 47 Tuc by Weldrake et al. 2004).

5.1.2. EcB Period Distribution

Figure 7 displays the \(n(P)\) \(dP\) EcB period distribution, to a maximum limit of 1 d, which contains all the binaries we define as contact binaries. The number of binaries can be seen to generally increase as period decreases, with a population of
Figure 14. Binary lightcurves, continued.

5.1.3. Binary Frequencies and Comparison to Globular Clusters

In the halos of the globular clusters 47 Tuc and ω Cen, Weldrake et al. (2004, 2007a) determined an observed EcB frequency of $1.7 \pm 0.4 \times 10^{-4}$ and $5.3 \times 10^{-4}$, respectively (the cluster cores are saturated). The value for 47 Tuc is substantially lower than that observed in the cluster core (Albrow et al. 2001), and this has been taken as evidence for mass segregation in 47 Tuc. Binary destruction due to cluster dynamical processes would produce a substantially higher binary frequency in the general Galactic field.

In our Lupus field, we determine an EcB frequency of $\frac{190}{110372} = 1.7 \pm 0.4 \times 10^{-3}$, with the error being 3σ, derived from the Poisson error in both the binary and total star number and applied with standard quotient error propagation. This equates to one detected binary per $\sim 600$ stars, 10 times the value for 47 Tuc and three times the value for ω Cen. This strengthens the argument that binaries are less common (particularly long-period detached binaries) in the outskirts of globular clusters, being mainly due to mass segregation, and also due to binary destruction. Mass segregation is not thought to be prevalent in ω Cen (which has three times the observed binary frequency of 47 Tuc, yet only 1/3rd that of our Lupus field). All three surveys contain a similar total number of stars (within 10%) and have very similar detection thresholds, due to similar global data set properties. Clearly, the general galactic
field contains a higher rate of detectable binary stars than is contained within the halos of these two globular clusters.

5.2. δ Scuti and RR Lyrae Stars

A total of 11 δ Scuti stars and 4 RR Lyrae stars (three type “AB” and one type “C”) were detected in our data. The δ Scuti stars (also known as a Dwarf Cepheids, AI Velae stars, or AI Velorum stars) undergo both radial and non-radial pulsations on short time-scales. They were classified as such in this work from their pulsating nature, bluer $V - I$ values, and very short periods. The tabulated data for these variables can be seen in Table 2 and their lightcurves are presented in Figure 15.

The determined periods range from 0.003919 d (V459, 5.6 min) to 0.08953 d (V270, 2.1 h). They (along with the RR Lyrae) are located blueward of the main stellar type “shoulder” seen in Figure 2, indicating their classification as stars of earlier spectral type (typically A to F). The moderate amplitude of the V459 pulsation precludes it from being composed of solar-like convection-driven surface oscillations. From the total stellar data base of 110,372 stars, we estimate an apparent $δ$ Scuti occurrence frequency in our field of $11/110,372 = 10.0 \pm 3.0 \times 10^{-5}$. This corresponds to one $δ$ Scuti per 212 arcmin$^2$.

RR Lyrae are pulsating horizontal branch stars that are generally old and with relatively lower mass ($\sim 0.8 M_\odot$). Their identification in the field (particularly in large field surveys targeting the Galactic halo) is important to trace the extent of halo streams. Three of the four detected here are very likely disk stars, due to their apparent brightness, and have pulsation periods and lightcurve shapes typical of the two main classes of RR Lyrae (Vivas et al. 2001). Similarly, their data are presented in Table 2 and Figure 13. None show evidence of the little understood Blahzko effect (Blazhko 1907). We estimate an apparent occurrence frequency of $4/110,372 = 3.6 \pm 0.1 \times 10^{-5}$ ($\sim 1$ RR Lyrae per 583 arcmin$^2$) for field RR Lyrae towards Lupus. None of the rare AHB RR Lyrae (Sandage et al. 1994) were seen in our data.

RR Lyrae is a well-known class of variable due to their usefulness as distance indicators; however their absolute magnitude depends on their metallicity (Sandage 1981a, 1981b). From studies of RR Lyrae and horizontal branch stars in the Milky Way, the LMC, and M31 clusters, this relation has been adopted with a slope $0.20-0.23$ mag/dex (Clementini et al. 2003; Cacciari & Clementini 2003; Gratton et al. 2004). Rich et al. (2005) adopted a relation of the form $M_V = 0.20 \pm 0.09[Fe/H] + 0.81 \pm 0.13$, which was also used to estimate the distance to ω Cen by Weldrake et al. (2007a). The metallicity must be determined spectroscopically before the distance can be estimated with any certainty.

However, if we assume solar metallicity ([Fe/H] = 0) for all four RR Lyrae, using the above relationship, we determine an absolute $V$ magnitude of $0.81 \pm 0.22$. By applying the maximum degree of reddening for the field ($E(B - V) = 0.182$ mag; Schlegel et al. 1998), the $V$ magnitudes of the stars...
would be altered by \( V_{\text{obs}} - 3.315 \times E(B-V) \). Hence, for the four RR Lyrae and their corresponding \( V \) magnitudes \((V_{\text{obs}})\) as listed in Table 2, we derive minimum reddening-corrected apparent \( V \) magnitudes of 14.602 \( \pm \) 0.003, 15.063 \( \pm \) 0.002, 14.907 \( \pm \) 0.002, and 17.146 \( \pm \) 0.005 for the four stars.

We determine distance modulus \((m - M)_0\) upper limits of 13.80 \( \pm \) 0.22, 14.25 \( \pm \) 0.22, 14.10 \( \pm \) 0.22, and 16.34 \( \pm \) 0.22 \((\sim 5.7, \sim 7.0, \sim 6.6, \text{ and } \sim 18.5 \text{ Kpc})\) for our four RR Lyrae, with equal uncertainties throughout as they are strongly dominated by the uncertainty in the absolute magnitude. The faintest RR Lyrae (V387) is likely a background halo star. Actual metallicity measurements will permit more accurate distances for these stars, rather than the upper limits presented here.

5.3. Miscellaneous Pulsators

Our catalog also contains 51 pulsating stars of various types and one irregular variable. We define the pulsators as stars displaying regular pulsation brightness variations with periods less than two days. The global properties of these stars are presented in Table 2, and the lightcurves for the first 20 pulsators (for illustrative purposes, as visually they appear very similar) can be seen in Figures 16 and 17. Longer-period pulsators are classified here as LPV (see below). Their position on the CMD is mostly scattered (Figure 2) although the majority are quite red, indicating their makeup as later spectral types. The irregular variable (V134) is quite blue \((V - I = 0.35)\) indicating it likely is of A-F spectral type and may contain both radial and non-radial pulsations. Their apparent occurrence frequency is 4.6 \( \pm \) 0.3 \( \times \) 10\(^{-4}\) (one pulsator for every 46 arcmin\(^2\)).

The majority of the pulsators display regular radial sinusoidal variations, with periods in the range 0.4 \( \rightarrow \) 0.6 d, with the lowest being 0.12377 d (V238). We classify them as “pulsators,” or red variables, being stars passing through the instability strip during their later evolution. V295 has a period of only 0.04159 d, a typical period for a \( \delta \) Scuti star; however the \( V - I \) color is 0.932, unusually red for a \( \delta \) Scuti, hence its inclusion here.

5.4. Long-Period Variables

We also detected a total of 237 LPV, by far the most common type of variable seen in our Lupus field, with an observed occurrence frequency of 2.2 \( \pm \) 0.3 \( \times \) 10\(^{-4}\) (one LPV per 10 arcmin\(^2\)). We define these as displaying regular sinusoidal (or slightly sawtooth) variations with various periodicities greater than an arbitrarily chosen lower limit of two days. The global properties of these stars are also seen towards the end of Table 2. The LPV are in the vast majority very red stars, indicating their likely nature as red giant stars of late spectral types. The lightcurve data themselves can be accessed as online data.

Many of the periods presented in Table 2 are uncertain, and marked appropriately with a “\( \sim \)” This is due to the limitations imposed by our 53-night data set, variables with significantly
longer periods (Mira variables) would be flagged as variable but have indeterminate final periods. Further photometry spanning a long baseline (months) is needed to determine accurate periods for these stars, and is outside the scope of the project. The lightcurve data (in ASCII format) for all 494 variables in the catalog are available in the online journal.

6. CONCLUSIONS

We present a variable star catalog, along with a preliminary analysis of the stars, detected during a long-baseline (53 nights: 26 contiguous nights in 2005 June and 27 in 2006 June) high temporal resolution (6–7 min) photometric survey to detect transiting short-period planets towards Lupus. A total of 494 variable stars were detected in our 0.66 deg$^2$ field, all of which are new discoveries. The catalog comprises 190 eclipsing binaries (of contact, semi-detached, and detached configurations), 51 miscellaneous pulsators, 237 LPV, 11 δ Scuti stars, 4 field RR Lyrae, and a single irregular variable.

We determine a period distribution of 0.277 ± 0.035d for our detected short-period W UMa binaries (to $V = 18.8$). Several binaries appear to be composed of equal-mass M-dwarf components, and others display evidence of mass transfer. We detected 17 candidate blue straggler stars, and we also detected a binary with period 0.2009 d ($V = 20.9$), which constitutes the shortest period EcB known. Our brightest binary likely harbors a δ Scuti component.

We have used this catalog to determine the occurrence frequencies of the various types of variable in our field, and compared the overall frequency of detected binary stars to that previously determined for the halos of the globular clusters 47 Tuc and ω Cen. We find that the frequency of binary stars is significantly larger in our field than that found in either cluster (10 times for 47 Tuc and three times for ω Cen). This favors the scenario in which binaries are readily mass segregated into the cluster cores and/or destroyed by cluster dynamical processes.

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