New Northern-Hemisphere Variables

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Abstract A survey looking for previously unknown variable stars has been carried out in the declination range 30–39 degrees and in the R.A. range 0–24 hours. The survey was done in I-band, and was carried out from October 2003 to December of 2004. Seventy-five new and previously suspected variable stars were detected. This paper presents a brief description of the survey and identifies the new variables.

1. Introduction

CCD technology continues to improve, with larger and cheaper CCD cameras available every year. This means that many amateurs and professionals upgrade, with the result that their older cameras are either sold or put to use elsewhere in the observatory. One obvious use would be as an external guide camera for the main telescope. However, another use is to combine the older CCD camera with a photographic camera lens, creating a system capable of a wide-field survey. This paper describes such a system.

The data were obtained with a very simple hardware configuration: Cookbook CCD camera (Berry *et al.* 1994), Edmonds IR long-pass filter (RG 715, cut-on at 715 nm), Nikon 50 mm focal length f/1.8 lens, with the whole assembly rigidly attached to a building. There was no tracking of the sky—the camera pointed straight up at the zenith. The unchanging orientation of the optics was one piece of the stability needed to do the night-to-night comparison to detect variability. Exposures of 4–6 seconds were obtained every 15 seconds throughout the night on suitably clear nights. The field of view is 5.5 degrees in the R.A. direction and 7.3 degrees in Dec. Stars took 100 frames (25 minutes) to cross the array, and a typical full night had 2500 frames of data. The observing location was 118 degrees 20 minutes west, 33 degrees 48 minutes north.

The CCD device used in the Cookbook Camera is the Texas Instruments TC245. This chip has reduced response areas between the picture elements that can cause errors in photometry. This effect was minimized by choosing an integration time that corresponded to the time taken for the star to move exactly one pixel, and by clocking the focal plane so that the projection of the focal plane on the sky was oriented a few degrees from the short axis of the array, (to average out the periodic non-uniformities in the long-axis direction; the non-uniformities in the short-axis direction are averaged out by the main motion of the stars across the focal plane).

The camera was controlled with the standard Cookbook Camera program CBWINCAM in 378 pixel mode, generating a series of 378×242 pixel 16 bit integer FITS images. In this readout mode the pixel size is 1.4×1.2 arcminutes. Typical seeing at the site is poor, running 2–5 arcseconds. However, at this large pixel size, seeing is a small fraction of a pixel.

2. Software and processing

In contrast to the simple hardware configuration, the software and data processing were complex. All software used in the analysis after the initial data acquisition with CBWINCAM was written for this project.

As part of the night's data acquisition sequence, a series of dark frames was obtained. These frames were averaged and a variance image generated to detect any frames with cosmic ray hits. These frames were then removed from the sequence and a new average dark frame generated.

Each frame was checked to eliminate frames with airplanes, cosmic rays, clouds, satellites, meteors, birds, bugs, and such. A program was written that automatically stepped through the frames, subtracting off the average dark frame, generating a "movie-like" display. When a bad frame was detected (by the operator), it was entered into a list of bad frames for that night.

The night's frames are assembled into a single R.A./Dec. strip image ("Scan Image"). Input to this program is the average dark frame, a flat field (an average of short exposures of the sky taken early evening with an associated dark subtraction), the list of bad frames, the individual FITS images, and geometric parameters such as the optical axis of the lens, its clocking angle, pixel pitch, and frame rate. These parameters are used to project each frame onto an equatorial coordinate grid that allows the individual frames to be laid down on the R.A./Dec. strip image. Each pixel in the image is normalized by the number of frames that contributed to that pixel; that number typically is 100. These output images are typically 6000 pixels in R.A. (~10 hours) and 350 in Dec. (~7 degrees), and retain the 16-bit integer type. The pixel size in the grid was 1.3 arcminutes square (i.e. 1.3 arcminutes in declination and a corresponding size in R.A. at the nominal 33 degree declination).These Scan Images are used in all subsequent processing. This and subsequent programs run off of control files containing night-specific data so they are able to automatically process multiple nights' data.

Note that a Scan Image is really a R.A./Dec. brightness map in which different R.A. areas are measured at different times of the night. Any particular point in the image is built up from ~100 frames taken over 25 minutes. The absolute time accuracy on the frames going into the scan image is about 1 minute. A R.A./Dec. calibration file is generated for each scan image by locating a reference star in the field and noting its coordinates in the Scan Image.

Peaks are detected in each Scan Image and their integrated intensity, pixel coordinates, and R.A./Dec. coordinates are output into a "Peak" file associated with the Scan Image. The peak detection and integration is a multi-step process where a first pass is made with a low detection threshold in order to identify even low S/N peaks. These peaks, and a region around them whose size depends on the integrated peak intensity, are removed from a copy of the Scan Image. This image, which now looks like Swiss cheese, becomes the Background Image. The Scan Image is again searched for peaks, this time with a higher s/n threshold. For each peak found, the integrated signal is calculated out to a fixed radius from the peak pixel (typically ~2 pixels) and the Background Image is used to define the background under the peak. This background is computed by defining an area in the background image within N pixels of the star, calculating the mean and standard deviation of all of the background pixels in that area, eliminating those pixels that are > 2 standard deviations from the mean, and re-computing the mean. Since I did not want the noise in the calculation of the background to dominate the noise in the star photometry, I had to chose N large enough to get a good background estimate, even in the presence of lots of background stars (i.e., the Milky Way). N=20 pixels radius was used for the processing.

A reference night is picked. This is a night with a long run, and no detectable clouds. Four reference nights were used to cover 0–24 hours of R.A. Candidate variable stars are associated with one of the reference nights (LCD, LCE, LCF, and LCG).

In order to obtain a better matching of stars from night to night, a Differential Geometry Calibration file is generated for each night. This is computed as a R.A./Dec. correction as a function of R.A. This correction is applied to the basic R.A./Dec. calibration files. These offsets are calculated by allowing the correlation to be off by a few pixels and finding the best match as a function of R.A.

2.1. Peak correlation step

The peaks are matched up using the R.A./Dec. calibration files (including the corrections indicated by the Differential Geometry Calibration file) and an intensity ratio is formed with the peak intensity measured on the reference night. A single file is output that has the ratios of all of the different nights' intensity measurements for an individual star on the same line, with a line for each peak detected in the reference night (many thousand stars). This line also includes the integrated intensity for the star on the reference night.

2.2. Photometric calibration step

Since the extinction can vary from night to night, and even hour to hour, even a constant star will not have a constant intensity ratio of 1.0. A relative extinction calibration factor is computed by calculating the mean brightness ratio as a function of R.A. (proxy for time) for each night relative to the reference night (Moving average, 30 minute bin size, 15 minute step size). Stars with grossly inconsistent ratios are detected and removed from the calculation (mis-identifications and true variables). This extinction correction is then applied to the individual star brightness to generate the final light curves for the stars (text file, one line per star). Note that by pointing at the zenith and operating in the 700–900 nm band, the extinction is minimized.

2.3. Variability detection

The light curves for all of the stars are automatically examined for deviation from a ratio = 1 by a fixed amount (e.g., 20%) and a S/N on that variability greater than, e.g., 20. The reference image is displayed and the candidate variables are highlighted in red. In addition, stars from the *General Catalogue of Variable Stars* (GCVS, Kholopov *et al.* 1985) and the *New Catalogue of Suspected Variable Stars* (NSV, Kholopov *et al.* 1982) are indicated on the same image. Clicking on a star in the reference image will bring up its light curve. Stars that the program detected as potentially variable, and that did not have an entry in the variable star catalogue, were candidates for newly identified variables. These were examined manually and the ones that appeared to be convincing are included as candidate new variables. This final filtering was somewhat subjective; a well-isolated star (avoiding contamination) and a slowly-varying light curve were considerations. This meant that a star with a period of a few days was more likely to be rejected than one with a period of months if it was near the 0.2 mag, S/N=20 thresholds that were typically used for automatic initial selection.

3. Results

The 24-hour R.A. range was covered with the 4 reference nights (Figure 1). The plot shows a 2-degree Dec. shift that occurred when the mount was modified to increase its stability.

As an example of the relative photometric precision and long-term stability, Figure 2 shows the photometry of a known variable (Cepheid variable RT Aur), in which the data have been folded with the known period (3.72819 days). These points were taken over a period of 144 days, so adjacent points in this plot are many weeks apart. In this fairly bright, non-blended star, the precision and stability of the data is better than 0.02 magnitudes rms. Note that in Figures 2 and 3 the magnitudes are relative to those of the Reference Day values.

As an example of the data on newly detected variables, Figure 3 shows the light curve for GSC 2379-0496 (α: $4^h\,15^m\,35^s$; δ: +33° 49' 46" (J2000)). The light curve shape, period, and very red color are all consistent with this star being a Mira-type variable. Why wasn’t it detected previously? The answer may be related to the period. An estimate from Figure 3 gives a period of 365 days. A period of one-half of that cannot be completely ruled out from the data.

Table 1 lists the variable stars identified in this work. The first column is an identifying name that carries over to the text files that have the light curves and the JPG files that have light curves and finder charts. These files are available electronically on the AAVSO web site at http://www.aavso.org/vstar/davies/starplots.shtml.

Stars were identified by matching the image of the star field (shown in the associated JPG file) with a map generated in SKYMAP PRO (Marriott 2005). This comparison resulted in positional uncertainties for the variable star of about 2 arcminutes. This was usually accurate enough to identify the variable star. The second column has the tentative identification of the star against the HST *Guide Star Catalog* (Space Telescope Science Institute 1992), with columns 3 and 4 having the J2000 R.A. and Dec. for that star. Whenever more than one detectable star are blended together, the reddest star has been chosen as most of these new variables are long period. The next four columns are the VJHK magnitudes for the selected star, taken primarily from Tycho2 (Hog *et al.* 2000) and 2MASS (Skrutskie *et al.2006)*. The final column has comments, mainly referring to questionable identification when there was more than one star candidate or giving the NSV identification.

Note that many previously known variables fall within the 9-degree sky stripe of this survey. The data for those stars will be submitted to the AAVSO for inclusion in the AAVSO International Database as time permits.

4. Acknowledgements

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References

Berry, R., Kanto, V., and Munger, J. 1994, *The CCD Camera Cookbook*, Willmann-Bell, Richmond.

Høg, E., *et al.* 2000, *The Tycho-2 Catalogue of the 2.5 Million Brightest Stars*, *Astron. Astrophys.*, **355**, L27.

Khopolov, P. N., *et al.* 1985, *General Catalogue of Variable Stars*, 4th ed., Moscow.

Khopolov, P. N., *et al.* 1982, *New Catalogue of Suspected Variable Stars*, Moscow.

Marriott, C. 2005, SKYMAP PRO software, http://www/skymap.com

Ochsenbein, F., Bauer, P., and Marcout, J. 2000, *Astron. Astrophys., Suppl. Ser.*, **143**, 23.

Piquard, S., 2001, Ph.D. dissertation, University of Strasbourg.

Skrutskie, M. F., *et al.* 2006, *The Two Micron All Sky Survey*, *Astron. J.*, **131**, 1163.

Space Telescope Science Institute 1992, *The Guide Star Catalog*, Version 1.1, STScI, Baltimore.

Table 1. List of new variable stars.

Name	GSC	R.A. (J2000) h m s	Dec. ° ' "	V	J	H	K	Notes
LCG52	2781-2115	00 01 02.4	38 30 15	11.66	3.54	2.63	2.08	
LCG51	2664-1366	00 16 33.1	33 15 29	9.87	4.85	3.85	3.56	
LCG50	2273-0746	00 23 11.1	36 11 20	9.61	4.70	3.68	3.25	
LCG49	2284-0024	00 49 39.4	34 40 28	10.25	4.37	3.47	3.01	
LCG48	2304-0024	01 26 50.7	36 33 08	9.02	8.33	8.24	8.22	dbl
LCG47	2319-0970	01 54 19.4	37 08 15	9.94	3.62	2.78	2.31	NSV 656
LCG46	2832-2209	02 30 18.3	38 08 02	8.82	8.60	8.61	8.56	
LCG45	2329-1311	02 42 12.4	32 24 38	9.04	3.54	2.59	2.21	Piquard (2001)750.2d
LCG43	2351-0808	03 04 34.2	35 51 42	10.94	3.30	2.29	1.76	
LCG44	2343-2169	03 04 34.3	33 44 44	10.62	8.30	7.72	7.56	
LCG42	2340-0371	03 10 04.6	31 47 54	11.87	5.02	3.94	3.62	
LCG41	2345-1366	03 18 04.0	32 55 15	9.63	8.66	8.30	7.95	
LCG40	2345-0600	03 22 54.8	31 52 32	11.68	5.29	4.36	4.00	
LCG39	2349-0915	03 24 36.0	35 18 37	10.99	5.17	4.30	3.98	
LCG38	2861-1100	03 26 44.0	37 52 49	10.26	4.89	4.09	3.74	
LCG37	2346-1197	03 28 10.5	33 28 44	11.60	3.44	2.51	1.97	NSV 1151
LCG36	2359-0434	03 44 44.1	33 14 02	12.56	8.65	7.94	7.69	
LCG34	2364-1325	03 52 55.6	35 28 52	10.34	5.15	4.19	3.88	
LCG33	2379-0496	04 15 34.9	33 49 46	11.30	4.62	3.28	2.57	
LCG32	2383-0526	04 20 09.1	36 35 18	10.10	4.59	3.40	2.89	
LCG29	2391-0963	04 51 03.3	32 09 54	11.8	5.28	4.11	3.84	
LCE51	2390-1549	05 16 21.2	30 42 32	10.50	8.97	8.37	8.22	
LCG28	2415-0742	05 25 44.8	35 38 50	8.43	7.94	7.85	7.65	NSV 1971
LCG27	2407-1332	05 30 35.5	32 47 43	10.60	4.13	3.11	2.63	
LCG26	2413-1390	05 50 37.6	33 48 27	10.97	5.39	4.19	3.80	
LCG25	2414-0524	05 52 40.1	33 55 03	6.05	3.07	2.33	1.94	NSV 2681
LCG24	2427-1312	06 01 24.3	33 51 16	10.7	4.66	3.59	3.06	
LCG23	2427-1309	06 01 37.9	34 50 25	11.18	4.31	3.24	2.62	
LCG22	2428-1010	06 09 03.8	34 53 37	7.64	2.82	1.93	1.56	NSV 2841
LCG21	2424-0864	06 10 19.3	33 36 29	10.26	3.64	2.62	2.20	
LCG19	2430-0183	06 28 22.2	35 10 14	11.20	5.34	4.43	3.97	
LCG17	2426-0398	06 34 46.6	32 29 43	11.70	5.64	4.69	4.24	
LCG16	2447-0589	06 40 54.9	36 47 06	11.05	4.99	3.94	3.60	
LCG15	2941-1597	06 43 57.5	38 29 21	11.60	4.74	3.70	3.30	
LCG14	2447-0670	06 44 51.9	36 49 25	10.21	4.47	3.36	2.94	
LCG54	2448-0740	06 48 41.6	36 04 51	12.00	5.32	4.37	3.98	
LCG13	2444-1056	06 53 45.8	34 46 32	10.22	3.83	2.90	2.48	

(Table 1 continued on following page)

Table 1. List of new variable stars, continued.

Name	GSC	R.A. (J2000) h m s	Dec. ° ′ ″	V	J	H	K	Notes
LCG11	2438-0347	07 06 59.6	31 36 17	11.68	4.32	3.26	2.85	
LCG10	2459-1738	07 14 45.2	34 06 33	11.37	4.74	3.64	3.23	
LCG08	2456-0008	07 22 30.0	33 07 26	10.85	4.71	3.79	3.26	NSV 17442
LCG07	2457-0279	07 38 24.6	32 32 55	10.66	4.14	3.23	2.75	NSV 17530
LCG55	2466-1642	07 39 26.5	36 47 07	11.90	4.12	3.14	2.58	
LCG06	2458-1496	07 47 51.9	33 03 49	11.33	5.47	4.70	4.21	
LCG05	2471-1881	07 55 54.2	32 58 29	11.10	5.01	4.04	3.73	
LCG04	2490-2178	08 40 25.5	35 36 24	10.65	4.96	4.07	3.66	
LCG03	2490-0113	08 46 12.6	36 54 42	10.49	5.15	4.27	3.90	
LCG02	2505-0812	09 52 09.0	34 23 29	10.72	6.36	5.47	5.17	
LCG01	2521-0910	10 48 34.1	36 17 34	10.26	3.26	2.33	1.91	NSV 4977
LCD31	2538-0744	13 14 32.5	34 20 56	10.94	5.60	4.84	4.68	NSV 6154
LCD25	2576-0839	16 02 40.8	33 25 12	9.92	8.79	8.50	8.45	
LCD23	2586-0963	16 13 03.6	25 26 20	10.06	5.04	4.12	3.87	
LCD20	2588-2765	16 36 01.0	36 30 26	10.88	4.98	4.17	3.93	NSV 7859
LCD19	2585-0715	16 41 58.8	32 55 30	11.00	3.92	2.83	2.36	
LCD14	2614-0093	17 36 10.5	35 23 26	10.78	3.97	2.95	2.65	
LCF28	2650-1908	18 50 18.9	37 23 56	10.06	5.38	4.55	4.33	
LCF27	2646-0819	18 50 58.4	34 40 36	10.84	4.67	3.77	3.45	
LCF25	2643-0286	18 57 34.3	33 23 29	10.36	4.83	3.95	3.53	
LCF23	2661-1058	19 12 10.0	35 23 19	9.76	4.59	3.71	3.41	NSV 24710
LCF22	2661-1168	19 20 43.5	35 20 38	9.14	5.08	4.20	3.90	
LCF21	2681-0677	19 49 02.0	37 21 56	9.94	5.04	3.99	3.69	
LCF20	2690-0058	20 41 04.9	33 34 22	10.77	5.06	3.89	3.51	NSV 13231
LCF19	2695-3508	20 50 15.0	34 10 50	11.62	4.41	3.37	2.75	NSV 25359
LCF18	2710-2179	21 14 59.9	34 36 01	12.6	11.64	11.27	11.26	Questionable identification
LCF17	2711-1461	21 23 13.5	35 14 29	10.95	4.46	3.40	2.85	
LCF15	2727-0700	21 58 59.0	35 36 53	11.96	4.19	3.01	2.68	
LCF14	3199-1844	22 17 57.1	37 54 32	13.0	5.63	4.72	4.27	
LCF12	2746-0790	22 24 26.2	36 20 37	10.80	3.47	2.52	2.03	
LCF13	2742-0161	22 28 18.0	35 32 48	10.04	3.16	2.18	1.71	
LCF11	2739-1344	22 37 19.3	32 32 21	11.61	4.48	4.78	4.32	
LCF29	2744-1956	22 46 54.5	35 35 03	10.86	4.86	3.69	3.26	
LCF08	2754-0630	22 57 25.8	33 42 10	11.57	4.23	3.33	2.74	
LCF07		22 59 26.8	35 09 48					No ident.
LCF05	2755-2025	23 07 55.3	32 23 57	9.79	4.01	3.98	3.60	
LCF04	2764-0623	23 16 24.4	37 04 06	10.88	4.67	3.57	3.09	
LCF02	2777-0084	23 24 34.2	36 15 08	10.8	5.87	4.90	4.58	

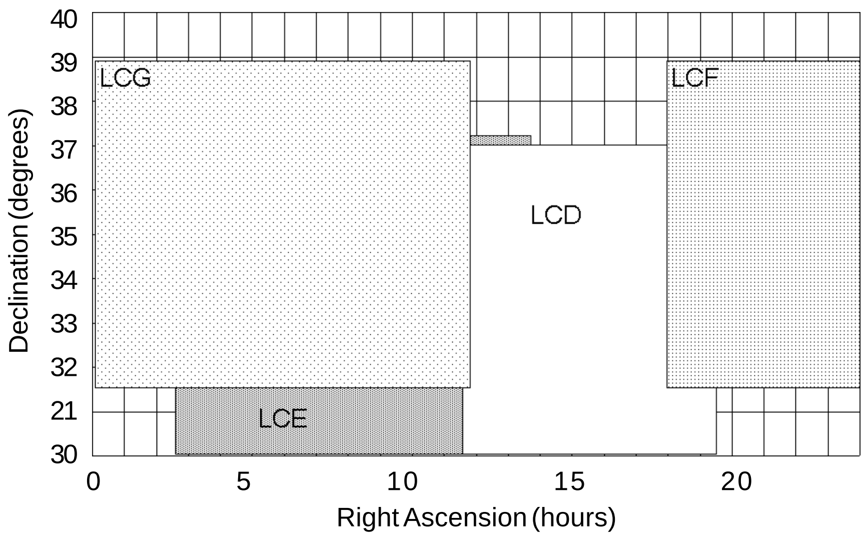

Figure 1. R.A./Dec. coverage. Each block (e.g. LCG) represents the R.A./Dec. coverage for a particular reference night.

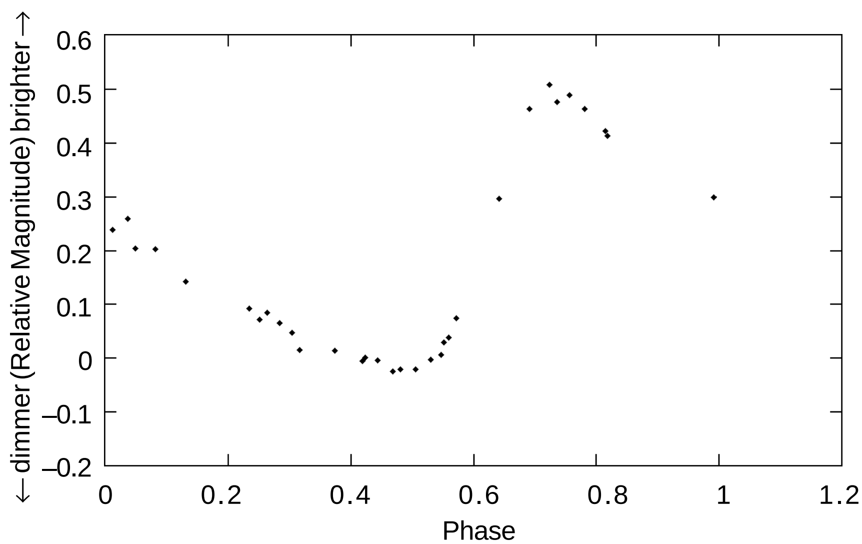

Figure 2. RT Aur light curve, showing the precision and repeatability of the measurements. The period of this Cepheid variable is 3.7 days and the data span 144 days, so adjacent points are weeks apart. Note the relative magnitude scale.

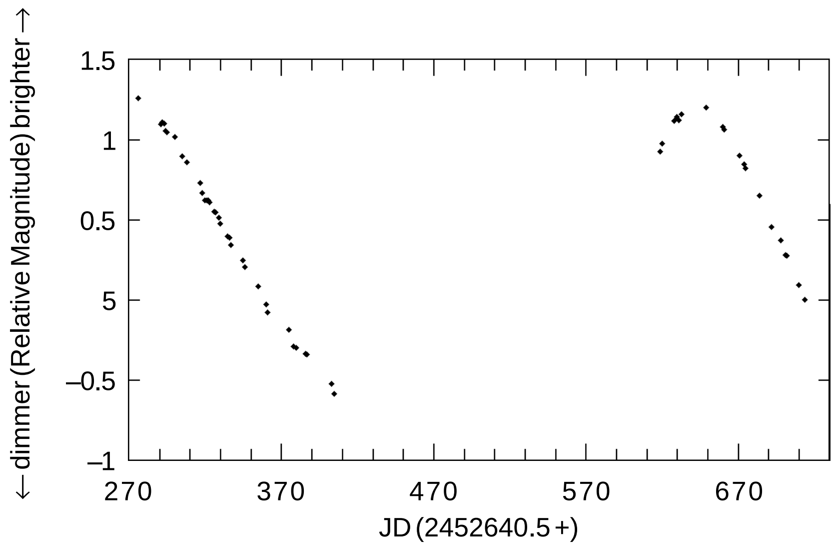

Figure 3. Light curve for GSC 2379-0496. This is a newly-discovered variable with a Mira-like light curve with a period close to 1 year. Note the relative magnitude scale.