Using a Small Telescope to Detect Variable Stars in Globular Cluster NGC 6779

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Abstract The nominal feasibility of utilizing small instruments, in near-urban environments, to detect variable stars in globular clusters is demonstrated through the use of modern CCD cameras and commercially available image processing software. A 0.25-meter telescope and a camera with a 550 × 752 CCD array were used to detect and perform photometry of six of the twelve known variable stars in NGC 6779 (M56). Two commercial image processing and photometric analysis software packages were utilized, and multiple variable detection techniques were examined. The periods of five variables were derived and color magnitude diagrams for the entire cluster were developed.

1. Introduction

While the number of studies of the variable stars in NGC 6779 is quite small, the cluster is readily observable from northern latitudes for more than five months of the year, at relatively high elevation angles. The literature lists this object as a globular cluster of low metallicity, visual magnitude 8.4, and an integrated *B–V* color index of 0.86. It has an angular diameter of approximately 8.8 arc minutes and is at a distance of 32,900 light-years. NGC 6779 has an average magnitude of 15.31 for the 25 brightest stars, an overall spectral type of F5 (Wehlau and Hogg 1985).

Early work by Helen Davis (1917) and by Harlow Shapley (1920) indicated only two confirmed variables in the cluster but later observations (Sawyer 1939; Rosino 1944; Wehlau and Hogg 1985) show that at least eleven variables are in or near the cluster, with an additional star (V2) whose variability remains in question (Russeva 1999). Table 1 reproduces the entry for NGC 6779 from the *Catalog of Variable Stars in Globular Clusters* (Clement 2000), where the elements for the individual variables in this cluster have been taken from Wehlau and Hogg (1985).

This table describes each variable in terms of: the x and y offset from the cluster center (in arcseconds), the minima and maxima of variability, the epoch and period (if known), and remarks. The remarks field includes the type of variable, alternate periods, and whether it is a suspected field star (f) or member of the cluster (mem); a "u" denotes unknown or uncertain cluster membership. The Min. and Max. values given in Table 1 are Visual Magnitudes.

Previous research and observations of this and other clusters have utilized telescopes in the 1.0–2.0 meter range (Russeva 1999, 2000; Sawyer 1939). With the advent of modern CCD cameras, amateur telescopes of relatively modest size can take images of deep sky objects that easily reach 17th magnitude and more. Additionally, recent releases of image processing and photometry software make the calibration and photometric analysis of CCD images very rapid and straightforward. Rowe (2001) has suggested taking advantage of these two developments to perform photometry of deep sky objects with small telescopes. Consequently, an observational project was begun to determine the ability of smaller telescopes to detect and analyze variable stars in distant clusters, and thus perform much of the types of work traditionally reserved for large research telescopes.

2. The observations

Observations were obtained using a Meade LX200 10-inch (0.25m) telescope, with a Starlight Xpress MX 716 CCD camera, which has a 550×720 pixel array. Observations were taken from a location on the edge of San Jose, California, a metropolitan area with a population of approximately three million, and approximately twenty miles from the Lick Observatory. The site has correspondingly substantial light pollution in the western and northern sky areas, and to a lesser degree in the east and south. Observations of NGC 6779 were made on 14 different nights, chiefly during the summers of 2003 and 2004. Earlier exposure tests indicated that a series of sixteen stacked 30-second exposures for each data set would provide sufficient magnitude depth in the resulting combined image, while being short enough in overall time duration (eight minutes) not to mask the variability of any short-period variable stars.

Exposures were taken at *f*-ratios of $f/10$ (approximately 6×9 arcminutes) to maximize the cluster image size on the CCD array, and $f/6.3$ (approximately 11×14 arcminutes) to provide as wide a field of view as possible. Exposures taken primarily for variable star detection and period analysis were taken with no photometric filter, in order to maximize the depth of the CCD images. Other exposures were taken with Johnson V, B, and I filters. Typical seeing conditions for this low-altitude site were between 3.5 and 4.5 arcseconds FWHM for stars in each image. All exposures were dark current and bias subtracted, and flat-fielded (using a twilight sky) according to established procedures. Table 2 shows a list of these observations.

Photometric transformation equations were also developed using observations (over three separate nights) of eight Landolt standards (selected from the "Mount Hamilton Standard Stars List," Univ. California Obs., undated), shown in Table 3.

3. Data reductions

Using the techniques outlined by Romanishin (2002), linear fits of the observations of the Landolt standards were performed, and both the $B-V$ and $V-I$ transform equations were developed. The $B-V$ transformation equation was determined to be:

$$(B-V)_s = 0.92\,(B-V)_i - 0.04 \quad (1)$$

Similarly, the $V-I$ transformation equation was determined to be:

$$(V-I)_s = 1.25\,(V-I)_i + 2.35 \quad (2)$$

As mentioned, a series of sixteen 30-second individual images were summed to produce a single image, equivalent to an eight-minute image, for each data set. These images were then aligned, eliminating any translation or rotation between the various frames. The commercial software product MAXIMDL/CCD was used to produce these stacked, aligned, and calibrated images.

To extract individual star photometry data, another commercial package, AIP4WIN, was utilized, using its "Extractive Photometry" tool. Additionally, several field stars in each image have measured visual and blue magnitudes, and these were used to set the respective photometric zero points for M56, allowing the other stars in the image to be calibrated in magnitude for a selected filter using the appropriate AIP4WIN tools.

The AIP4WIN extractive photometry tool was used at a "high" sensitivity level. The output of this tool is a text file that includes the X Centroid, the Y Centroid, the FWHM in X, the FWHM in Y, a Roundness parameter, the Maximum Pixel Value, the Sky Background, Raw Instrumental Magnitude for a given aperture radius, and the formal error in magnitudes. Approximately 1,000 stars were found on each image, although some data points later proved to be image artifacts.

As a check on the AIP4WIN photometry tool, the SPS Stellar Photometry Software package by Janes and Heasley (1993) was also utilized. While the AIP4WIN photometry tool uses aperture photometry, and the SPS program uses point spread fitting (PSF), the two reduction methods gave similar results. While PSF-based tools are usually better in crowded fields such as globular clusters, comparison of AIP4WIN data and SPS data did not show a significant difference in the number of stars detected in the central core. This is likely because the smaller aperture of our telescope limits the number of stars that can be effectively resolved in the core.

4. Variable star detection methods

Unfortunately, the cluster center-offset coordinates given in Table 1 could not be used for direct variable identification. Because the center coordinates and epochs are not entirely clear from previous studies, Clement notes the given "x-y coordinates can be used to aid in identifying the variables, but they can not be used for finding the precise locations." Clement (2000). Thus it was necessary to employ other techniques in order to determine which, if any of the processed stellar data contained variable stars.

Two scatter techniques were tried:

(1) The first search was performed using a χ^2_ν variability statistic (Saha and Hoessel 1990):

$$\chi^2_\nu = \sum_i^n \frac{(m_i - \overline{m})^2}{\nu \sigma_i^2} \tag{3}$$

where n is the number of data points (images) available, $\overline{m}$ is the mean magnitude of the star across all images, m_i and σ_i are the individual magnitude measurements and their uncertainties, and $\nu = n - 1$. Stars with $\chi^2_\nu \geq 1.75$ were identified as possible variable star candidates (Rawson *et al.* 1997). A computer program was developed that read in the text files generated by either SPS or AIP4WIN, matched stars for each image, and developed the variability statistic for each star.

Two detection cycles were run. The first, concentrating on detecting long period and irregular variability, was run over all the images, while the second, concentrating on detection of short period variables, was run over consecutive three-night sets of observations. Possible candidates were confirmed or eliminated using differential photometry techniques on each image.

(2) A second search was performed using a variation of this statistical technique, measuring a star's calibrated magnitude against the mean calibrated magnitude of all stars in the cluster for each image. For a large number of images, the difference between a star's calibrated magnitude and the average magnitude of the cluster on each image will form a Gaussian distribution. For all of images of NGC 6779, any difference falling outside of two standard deviations from the mean was identified as a variable candidate. A similar computer program was developed to automate the identification process. Again, possible candidates were confirmed or eliminated using standard differential photometry techniques on all images.

Neither method provided a clear advantage over the other. Since both were scatter techniques, a number of false positives had to be eliminated. In most cases, these false positives were found to be artifacts resulting from the image stacking and alignment process. After eliminating the false positives, the variables that could easily be detected using these scatter techniques were V1, V3, V4, and V6. V2 and V5 were found by considering candidates with lesser statistical differences and searching the image area in and around the offset coordinates given in Table 1.

Rowe (2001) suggested an additional technique, "Image Subtraction," and this was attempted using the ISIS program developed by Alard and Lupton (1998). This technique did not seem as robust in determining the faint variables in the images from this study, presumably because the dynamic range of the images is quite small in some cases. Only V6 was detected via this method.

Periods of the detected stars were obtained by using the period analysis tool PERANSO (Vanmunster 2005).

5. The variable stars in NGC 6779

Table 4 shows the detected variables in the globular cluster NGC 6779, their color indices, and their period (if found) for this study. Color Indices for V4 and V5 could not be obtained because of field of view limitations. Light curves for the regular period variables are shown in the associated figures. These light curves are matched against those from Wehlau and Hogg (1985). Error bars for the data represent a total of 0.1 magnitude.

V1: Wehalu and Hogg (1985) indicates that this is a BL Her type star and show the period as 1.51 days. This study found good agreement with this period as 1.48 days. The Simbad data on M56 list V1 as an A6 star and allows a calculation of the *B–V* index of V1 as 0.3, although Wehalu and Hogg (1985) gives a $(B-V)_{avg}$ value of 0.55. For this study, the calibrated *B–V* value of V1 is 0.22. The calibrated *V–I* color index found is 0.30. A light curve for the data collected is shown in Figure 1.

V2: The data in Table 1, compiled from various sources (Clement *et al.* 2001), list this as a variable star with an irregular period. Russeva (1999) indicates in his study that "the analysis of the data for V2 has not indicated any variability." Wehlau and Hogg (1985) indicates that the range of variability is from 15.2 to 15.55 visual magnitudes. Our data indicated some variability, within a range of 0.5 magnitude, although no regular period could be deduced from the data. Wehalu and Hogg (1985) gives a $(B-V)_{avg}$ value of 1.56. We obtain a calibrated *B–V* index for V1 of 1.57 and a *V–I* calibrated color index of 1.74.

V3: Russeva (1999) gives the period of this variable as 42.12 days. Other studies shown in Table 1 lists the period of this star as semiregular. Our study found this period to be 39.01 days with an uncertainty of 5.1 days. The SIMBAD data on M56 allow a calculation of the *B–V* index of V3 as 1.97. Wehalu and Hogg (1985) gives a $(B-V)_{avg}$ value of 1.87. Joy (1949), and in turn Simbad, list the spectral type for this variable as F8, which is inconsistent with the *B–V* value, which should be closer to 0.60. Wehalu and Hogg (1985) also notes this inconsistency and concludes that it may be due to the metal weakness of the cluster. We obtain a calibrated *B–V* index for V1 of 1.85.

V4: Wehalu and Hogg (1985) lists this star as a possible RR Lyrae variable, with a period of 0.42 day, with an alternate period of 0.73 day. Our study found good agreement with this alternate period of 0.70 day. Wehalu and Hogg (1985) gives a $(B-V)_{avg}$ value of0.38. Our study could not determine the *B–V* and *V–I* color indices for this star because of field of view limitations. A light curve for the data collected is shown in Figure 2.

V5: Wehalu and Hogg (1985) lists the period of this star as semiregular. Russeva (1999) gives the period of this variable as 31.3 days. Our study found this period to be 29.65 days with a considerable uncertainty of 14 days. Wehalu and Hogg (1985) gives a $(B-V)_{avg}$ value of 1.76. We obtain a calibrated *B–V* index for V5 of 1.59. We could not determine the *V–I* index for this star because of field of view limitations.

V6: Russeva (1999), together with Wehalu and Hogg (1985), indicates that this is a RV Tauri type star, with a period of 90.0 days. Our study found good agreement with a period of 90.01 days. Wehalu and Hogg (1985) gives the $(B-V)_{avg}$ index as 0.8, although the SIMBAD data on M56 list V6 as a G0 star and allow a calculation of the *B–V* index of V3 as 1.25. We obtain a calibrated *B–V* index of 1.37, and a calibrated *V–I* color index of 1. A light curve for the data collected is shown in Figure 3.

V7–V12: These variables were either not detected, or were out of the field of view of the CCD camera for this study. Wehlau and Hogg (1985) indicates that variables V7, V8, V9, and V11 are probable field stars and not members of the cluster. The Rishel *et al.* (1981) analysis of the proper motions in this field tends to confirm that these stars (at extended distances from the cluster) are not cluster members.

6. The color magnitude diagrams

Color magnitude diagrams (CMD) were created for both *B–V* and *V–I* color indices of NGC 6779. These are shown in Figures 4 and 5. Each detected variable is highlighted in each diagram. Since these indices were taken from two different sets of observational data, and the measured visual magnitudes of the variables are different, the Y coordinate of the same variable is not exactly the same on each diagram. Additionally, the *V–I* data for V4 could not be obtained since it was at the edge of the CCD frame. It can be noted that the scatter toward the bottom end of each CMD indicates the point at which the photometry became too noisy to be useful.

The average integrated *B–V* index for NGC 6779 was found to be 1.16. This is larger than value of 0.86 by Rosenberg *et al.* (2000) because this diagram does not contain the large number of bluer stars found in other, deeper color magnitude diagrams. However, the overall shape of the diagram is consistent with other studies (Hatzidimitriou *et al.*2004).

The average integrated *V–I* index for NGC 6779 was found to be 1.60. Again, this is larger than the given value found in the literature (1.16), for the same reasons as the *B–V* color magnitude diagram. Similarly, the overall shape of the diagram is consistent with other studies (Hatzidimitriou *et al.*2004) and (Rosenberg *et al.* 2000).

7. Conclusion

Almost none of the known variables in NGC 6779 are located within the central core of stars. Only V2 and V4 are on its edge. Nearly half of the known variables are outside the field of view of a moderately-sized CCD camera. It is highly probable that use of a wider field CCD or a mosaic approach, and deeper magnitude images, could have been used to detect the other variables, although their inclusion as members of NCG 6779 is questionable for four of them.

In any case, detection of six of the known variables proved straightforward, given a sufficient number of observations of adequate magnitude depth and careful differential photometry of the calibrated images. Several variable star detection techniques were utilized to independently detect and determine the positions of the variables within the cluster. A scatter technique ultimately proved the most successful, although it is prone to a fair number of false positives.

Periods were accurately developed for the variables V1, V4, and V6, and these periods correlate well with previous studies. With a lesser degree of certainty, the periods for V3 and V5 were found, although additional study will be required to determine whether this uncertainty is due to the semi-regularity in their periods.

The variable type of V2 remains uncertain, although the data in this study lend credence to the idea that it is an irregular variable.

The *B–V* and *V–I* indices of V1, V2, V3, and V6 were found. The over all shape and content of the *B–V* and *V–I* color indices for the entire cluster are entirely consistent with the upper portion of previously published respective indices.

It seems clear that small telescopes and modern CCD equipment, together with commercially available image processing programs, operating within an urban environment, can effectively be used to perform much of the variable star work being done on globular clusters. A wider survey of more clusters would seem warranted and can be undertaken by any number of amateur astronomers.

8. Acknowledgement

This research has made use of the SIMBAD database, operated at Centre de Données astronomiques de Strasbourg.

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Table 1. Elements of all variables from Clement (2000), and Wehlau and Hogg (1985). The remarks field includes the type of variable, alternate periods, and whether it is a suspected field star (f) or member of the cluster (mem); a "u" denotes unknown or uncertain cluster membership.

Variable Number	*x″*	*y″*	*V Magnitude Max.*	*Min.*	*Epoch JD2000000+*	*Period (d)*	*Remarks*
V1	+ 44.69	+ 74.10	15.4	16.6	45252.316	1.510019	Cep, mem
V2	+ 18.16	+ 33.09	15.2	15.8		irregular	u
V3	+ 25.10	+ 91.69	14.3	15.2		semiregular	mem
V4	– 112.13	–159.46	16.2	16.9	45250.403	0.423096	alt 0.734873, u
V5	+ 6.79	–134.78	14.4	15.2		semiregular	u
V6	– 2.02	+ 37.06	12.9	14.9	42256.734	90.00	RV Tau, mem
V7	+ 293.48	–213.24	15.7	16.7		irregular	f
V8	– 97.63	–335.90	16.0	16.9		irregular	f
V9	+ 177	+525	15.7	16.5		irregular	f
V10	– 431.53	+ 88.33	16.8	18.3:	45277.308	0.598890	RR0, f
V11	– 415.58	+283.80	15.6	16.7	45250.331	0.07562534	SX Phe?, f
V12	– 243.96	– 95.41	16.3	17.3	45582.594	0.90608	RR0/Cep?, u

Table 2. NCG 6779 observations.

Date JD2452800+	*Air Mass*	*Number of Images*
24.78	1.10	21
47.75	1.03	30
48.74	1.03	29V, 24B, 32
67.68	1.01	60
68.75	1.01	40
69.71	1.01	36B, 36V
72.70	1.01	60
75.69	1.01	50
76.67	1.01	109
338.83	1.53	24V, 24I
406.70	1.01	180
407.68	1.10	180
408.68	1.10	180

Table 3. Landolt standards.

Name	*V mag*	*B–V*	*V–I*
HD 79097	7.60	1.628	2.087
HD 84971	8.64	–0.159	–0.152
HD 97503	8.70	1.178	1.317
SAO 102381	7.91	0.309	0.346
SAO 102472	8.75	1.014	1.011
SAO 10258	9.38	0.060	0.060
SAO 102625	8.89	0.552	0.621

Table 4. Detected variables.

Var.	*R.A.*	*Dec.*	*B–V*	*V–I*	*Period*
V1	19 16 41.3	30 12 48.4	0.22	0.30	1.5d ± 0.4d
V2	19 16 38.4	30 11 45.0	1.57	1.81	No regular period found
V3	19 16 39.3	30 12 15.4	1.85	1.18	39.1d ± 5.0d
V4	19 16 26.7	30 07 20.4	—	—	0.7d ± .007d
V5	19 16 38.2	30 07 42.0	1.59	—	29.65d ± 14.3d
V6	19 16 35.7	30 11 40.6	1.37	1.83	90.0d ± 0.1d

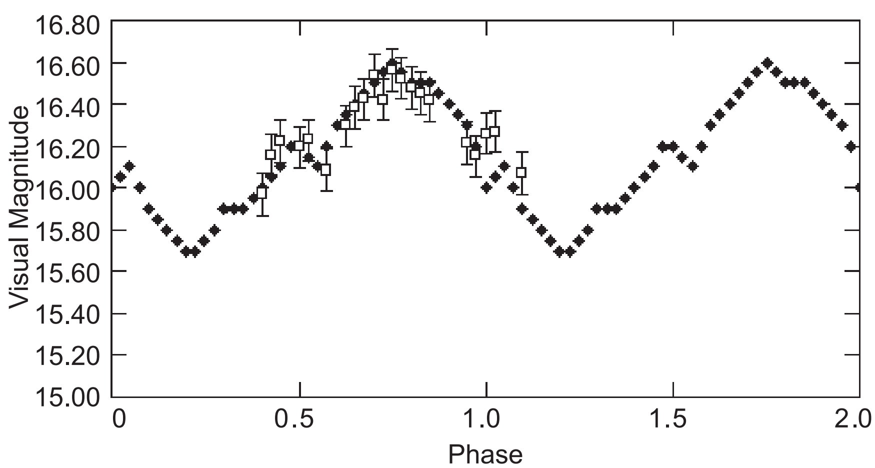

Figure 1. Light curve for the variable star M56 V1, (from observations made by Wehlau and Hogg 1985 (black diamonds), compared with observations made by the author in 2004 (open squares).

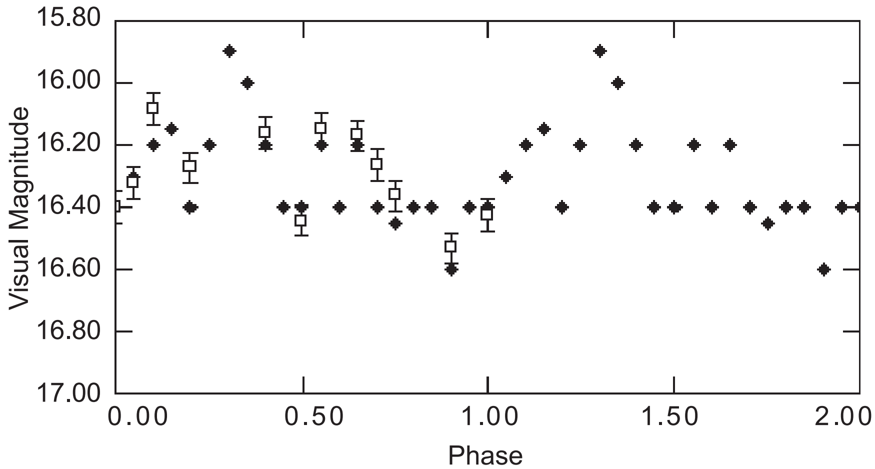

Figure 2. Light curve for the variable star M56 V4, from observations made by Wehlau and Hogg 1985 (black diamonds), compared with observations made by the author in 2003 (open squares).

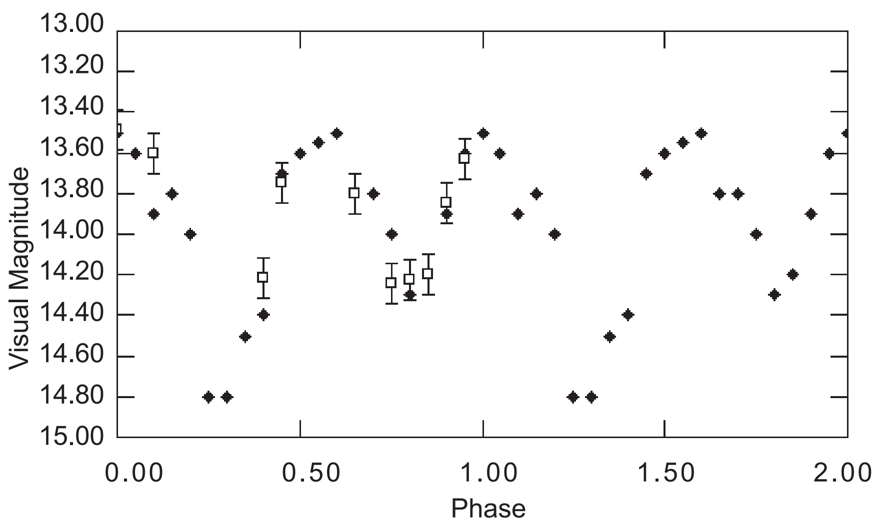

Figure 3. Light curve for the variable star M56 V6, (from observations made by Wehlau and Hogg 1985 (black diamonds), compared with observations made by the author in 2003 (open squares).

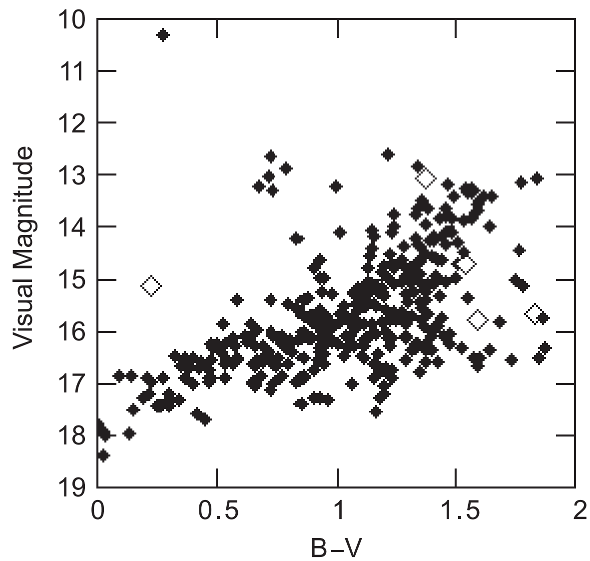

Figure 4. *B–V* color magnitude diagram for NGC 6779, from observations made by the author in 2003. The black diamonds are the cluster stars, with detected variable stars shown as open diamonds.

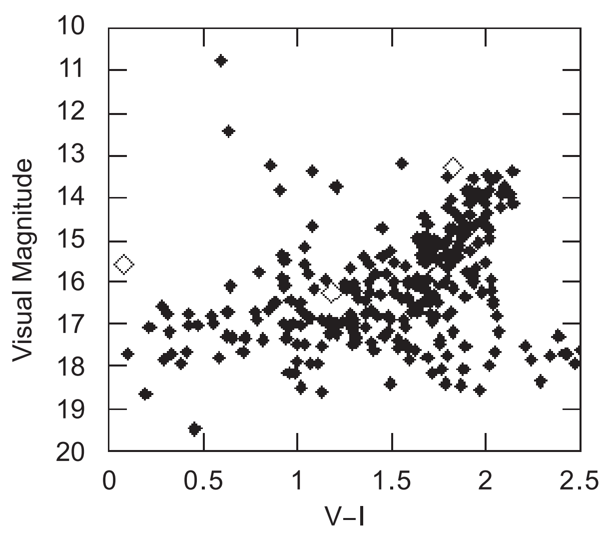

Figure 5. *V–I* color-magnitude diagram for NGC 6779, from observations made by the author in 2004. The black diamonds are the cluster stars, with detected variable stars shown as open diamonds.