

VARIABLE STARS IN THE FIELD OF THE GLOBULAR CLUSTER NGC 3201

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ABSTRACT

We report on the discovery and analysis of 14 short-period variable stars in the field of the southern globular cluster NGC 3201, located within roughly 2 mag on either side of the main-sequence turnoff. Eleven of these variable stars are eclipsing binaries, one is an RR Lyrae, and two are thus far unclassified systems. Among the eclipsing binary stars, nine are of the W Ursae Majoris (W UMa) type, one an Algol (EA) system, and one a detached system. Using spectroscopic follow-up observations, as well as analysis of the variables' locations in the color-magnitude diagram of the cluster, we find that only one variable star (a W UMa type blue straggler) is actually a member of NGC 3201. We present the phased photometry light curves for all the variable star systems, as well as their locations in the field of view and in the color-magnitude diagram.

Key words: binaries: eclipsing — blue stragglers — color-magnitude diagrams — dust, extinction — globular clusters: individual (NGC 3201) — stars: variables: general

On-line material: color figures

1. INTRODUCTION

Variable stars have historically served as important tools and “laboratories” in our understanding of star formation, the formation of stellar clusters, the calibration of distance determination methods, and a variety of other areas. In particular, the study of eclipsing binary stars (EBs) in a globular clusters (GCs) can provide a method of examining certain aspects of the GC itself, and it may be used to obtain a value for the cluster's distance and a constraint concerning turnoff masses of the GC stars (see, e.g., Paczyński 1996).

Simply detecting EBs in the fields of GCs and confirming cluster membership is a straightforward—though data-intensive—task. These systems expand the relatively meager sample of EBs that are currently confirmed GC members (see for example Mateo (1996); McVean et al. (1997); Rubenstein (1997); Rucinski (2000), and references therein). A statistical evaluation of the number of known member EBs in GCs can help in the determination of physical quantities such as the binary frequency in GCs as a parameter in the study of dynamical evolution of GCs (see, for example, Hut et al. 1992), or in the calibration of methods such as the Rucinski magnitudes of and corresponding distances to W UMa binaries (see § 4.3, and Rucinski 1994; Rucinski 1995; Rucinski 2000).

Moreover, the detection of blue straggler (BS) binary systems would assist in shedding light on the binary frequency among this subclass of stars, which in turn could help understand their formation and evolution. Some hypotheses in the study of the formation of blue stragglers claim that they have formed by collisions between single stars, coalescence of binary systems, and/or interactions between binary systems. Getting a handle on the frequency of binary blue stragglers in a certain GC would therefore present a tool for probing into the dynamical past and even the star formation history of the GC itself (see, for example, Leonard & Linnell 1992; Hut 1993; Livio 1993; Sills & Bailyn 1999; Sills et al. 2000).

The simultaneous analysis of photometric and spectroscopic data for individual EB systems can provide a direct estimate of the distance to the system (see, for example,

Andersen 1991 and Paczyński 1996) and thus, if the EB is a GC member, to the GC itself. The main sources of error in the distance determination are (1) the relation between surface brightness and effective temperature of the binary and (2) the precise determination of the interstellar reddening along the line of sight to the EB. The method itself, however, is free of intermediate calibration steps and can provide direct distances out to tens of kiloparsecs. In turn, the knowledge of the distances to GCs can then be used to calibrate a variety of other methods, such as the relation between luminosity and metallicity for RR Lyrae stars.

The very same analysis can in principle be used to obtain the Population II masses of the individual components of the EB system (see Paczyński 1996). If mass is conserved, the evolution of any EB may be expressed by $M_1 + M_2 = M_{1,0} + M_{2,0} + M_L$, where M_i are the present day masses of the two components, $M_{i,0}$ are their initial masses, and M_L is the total mass loss from the system. If one assumes that $M_L = 0$ (no mass loss), then the difference between present-day masses and initial masses of the components is only due to the mass transfer history between the two stars. This demonstrates the value of detecting *unevolved* EB systems. These are systems where the binary components are detached, no mass transfer has taken place, and the present-day masses are therefore equal to the initial masses.

A direct determination of the ages of the systems, however, remains a challenging task. The reasons for this are described in Paczyński (1996); we will briefly repeat them here. Analysis of various theoretical isochrones (e.g., Bertelli et al. 1994, D. Vandenberg 2000, private communication; based on evolutionary models by Vandenberg et al. 2000) readily shows that at the main-sequence turnoff

$$\text{age}_{\text{MSTO}} \sim \text{Lum}_{\text{MSTO}}^{-1} \sim \text{Mass}_{\text{MSTO}}^{-3.7}. \quad (1)$$

From Kepler's third law, it is apparent that $M_1 \sim K_2^3$, where M_1 is the mass of the first component and K_2 is the radial velocity amplitude of the second component. Combining these two relations gives $\text{age}_{\text{MSTO}} \sim K_2^{11}$, implying a 12% uncertainty in age for a 1% uncertainty in the velocity

amplitude! A perhaps more rewarding approach would therefore be to use the MSTO masses to provide a fundamental check of stellar models at low $[\text{Fe}/\text{H}]$. In order to do this, one needs to either detect detached EB systems (and assume no mass loss, in which case the zero-age masses equal the MSTO masses of the two components), or reconstruct the history of mass transfer between contact EBs to obtain zero-age masses for the two stars.

We are currently undertaking a survey of approximately 10 Galactic GCs with the aim of identifying photometrically variable EBs around or below the MSTO. Our observing strategy, aimed at detecting binaries in the period range of approximately 0.2 to 5 days (see Hut et al. (1992) basically consists of repeated observations of a set of GCs during each night. Multiple observing runs are usually helpful in detecting variables with a period of close to one day (or to a multiple thereof). The more valuable detached systems are generally much harder to detect because (1) they will eclipse each other only within a small range of inclination angles due to the larger distances between the components, (2) their duty cycle¹ is very low, and (3) they vary less in brightness (if at all) in between eclipses than the more distorted components of contact systems. Fairly extensive coverage is therefore usually needed in order to detect detached EB systems.

NGC 3201, by chance one of the first GCs in our sample that we analyzed, has been probed for the existence of binary stars in the past, most recently by Côté et al. (1994). The results of even earlier work on variables in NGC 3201 are summarized in Sawyer-Hogg (1973) and Clement et al. (2001), and references therein. The magnitude and period ranges of the EBs covered in these earlier studies, however, does not overlap with the work presented here.

Details on our photometry observations are given in § 2. We then describe how we detect variable stars in our sample and determine their periods in § 3. These two sections set out the methods we will use for the other clusters in our sample. Section 4.1 contains our results concerning the locations of the binaries in the field as well as in the CMD of NGC 3201. In § 4.2, we present the phased light curves for all the variable stars we find. We calculate distance moduli to our set of W UMa-type EBs using Rucinski's formula (Rucinski 1994, 1995, 2000) in § 4.3. Section 4.4 reports our spectroscopy results concerning the membership of our variable stars. We finally summarize and conclude with § 5.

2. OBSERVATIONS AND PHOTOMETRY REDUCTIONS

2.1. Initial Photometry Observations To Find Variables

The bulk of the photometry observations for NGC 3201 was conducted during three separate observing runs in 1996 June, 1997 May, and 1998 May at the Las Campanas Observatory (LCO) 1 m Swope Telescope. For all three runs Johnson-Cousins *VI* filters were used, and the number of images are approximately evenly divided between the two bands. During the 1996 June run we obtained 17 epochs (600 s exposure time) using a TEK 5 CCD with 24' on the side. For both the 1997 May and 1998 May runs we used a SITE 1 CCD with 23.5' on a side (Fig. 1), and obtained 164 epochs and 89 epochs (all with 600 s exposure time), respec-

tively. During the 1998 May run we took additional shorter exposures of the cluster to complete the CMD in the brighter regions (these shorter exposures were not used to detect variable candidates), as described in von Braun & Mateo (2001, BM01 hereafter).

2.2. Processing and Data Reduction of the LCO Data

The details of the IRAF² processing as well as the basic data reduction of the 1998 May data are described in BM01, § 2.1. The processing of the 1997 May and 1996 June runs was performed in the same way. All data were reduced using DoPHOT (Schechter, Mateo, & Saha 1993) in fixed position mode (see BM01) after aligning every image to a deep-photometry template image created by combining the 15 best seeing frames for each filter from the 1998 May data. The astrometric measurements, application of aperture corrections, as well as photometric calibration of the 1998 May images are outlined in BM01. All data from the other two observing runs were shifted to the coordinates and the photometric system of the calibrated 1998 May 600 s exposures. Since NGC 3201 suffers significant differential reddening across the field of view, the stars were dereddened using the differential extinction map in BM01 so that the E_{V-I} zero point applied to all stars in the field is 0.15. This differential reddening correction is applied to the data presented in Figure 3.

2.3. Additional Photometry

In order to precisely determine the times of quadrature (maximum radial velocity) for two of the variable stars we discovered (V11, the Algol, and V12, the detached system; see § 4.1 and Figs. 7 and 8), we performed additional *VI* 600 s photometry observations at the Cerro Tololo Inter-American Observatory (CTIO) 0.9 m telescope during the nights of 2001 February 25–28 just prior to our spectroscopy follow-up CTIO 4 m run (see § 4.4). The 0.9 m telescope setup included a TEK 2048 CCD, which provided a field of view of approximately 13.5' on the side (Fig. 2). Initial data processing was done with the IRAF QUADPROC package. For each night, 10 bias frames were combined for the bias subtraction. Flat-field images were produced by combining five twilight flats per filter per night. The fields we observed were centered on the approximate locations of the detached candidate (field D: $\alpha_{2000} = 10^{\text{h}}17^{\text{m}}25^{\text{s}}.72$ and $\delta_{2000} = -46^{\circ}20'12''.4$) and the Algol candidate (field A: $\alpha_{2000} = 10^{\text{h}}18^{\text{m}}32^{\text{s}}.74$ and $\delta_{2000} = -46^{\circ}30'42''.5$). Field D fell entirely within our original field of view which was centered at $\alpha_{2000} = 10^{\text{h}}17^{\text{m}}36^{\text{s}}.8$ and $\delta_{2000} = -46^{\circ}20'40''.0$, whereas field A contained stars which we had not observed previously (see Fig. 2). We secured 31 *I* and 27 *V* observations of field A as well as 33 *I* and 35 *V* observations of field D.

Following the publication of this work, we will make our entire photometry data set available to readers over the Internet, using NASA's Astronomical Data Center.³

3. FINDING THE VARIABLE STARS

The starting point for our analysis of the LCO photometry with respect to finding binaries and determining their

¹ The duty cycle of an EB is defined as the fraction of the orbital period during which the system is experiencing an eclipse for an edge-on system (inclination angle $i = 90^{\circ}$).

² IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the NSF.

³ Available at <http://adc.gsfc.nasa.gov>.

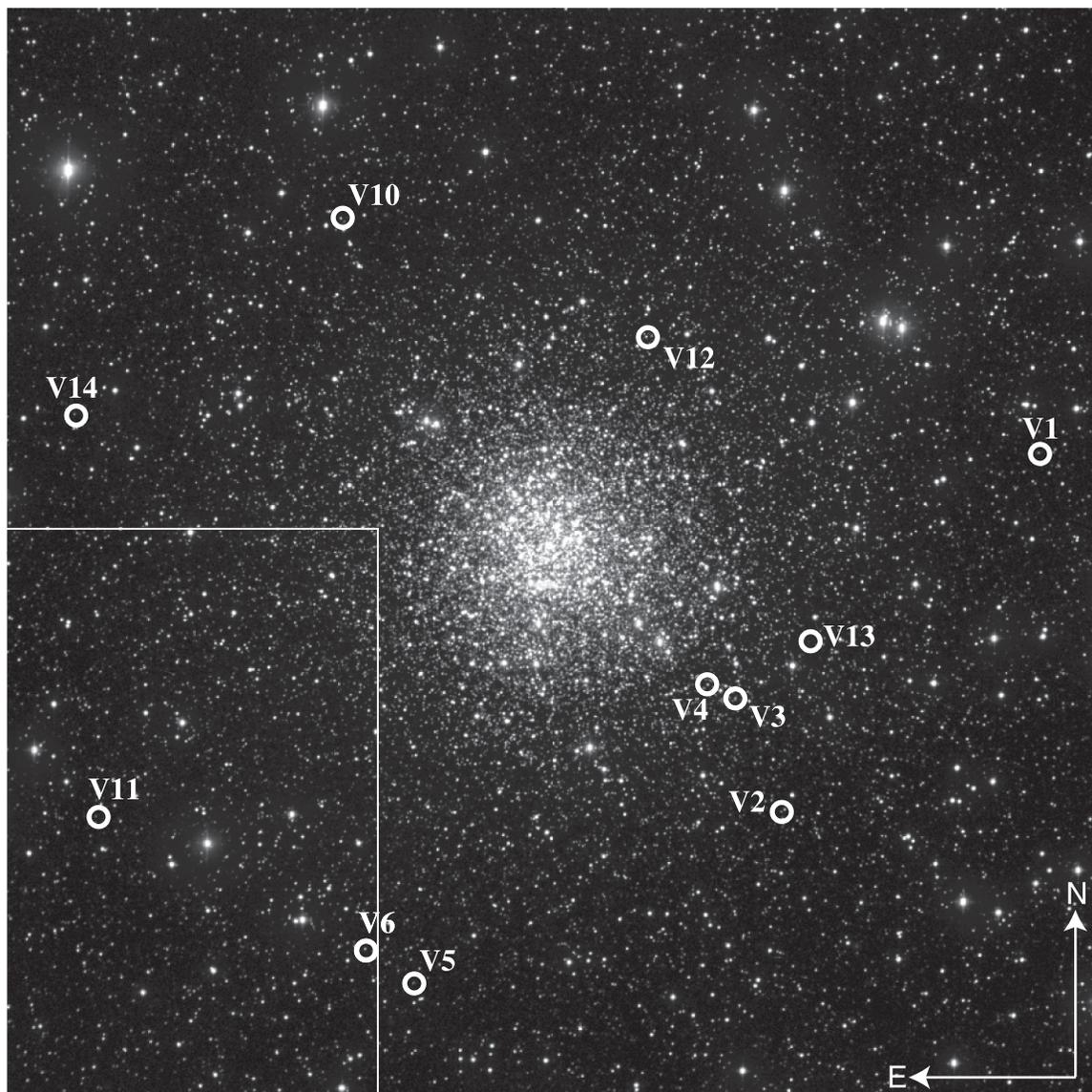


FIG. 1.—Locations of the variable stars in the LCO data. The field of view is 23'5 on the side. North is up, and east to the left. The rectangle toward the bottom left part of the figure represents the approximate boundaries of the overlap region of this figure and Fig. 2, i.e., the northwest part of Fig. 2. [See the electronic edition of the *Journal* for color versions of Figs. 1–8.]

periods was a database which contained the data on approximately 130 observational epochs (600 s exposure time) of 45,000 stars in each filter per image.

3.1. Variability Detection

The criteria we set in order to extract variable star candidates from the list of stars in our database were the following:

1. χ^2 per degree of freedom, calculated based on the assumption that every star is a nonvariable, has to be greater than 3.0. We furthermore set a $\sigma > 0.05$ mag threshold for a star to be taken into consideration as a variable candidate.

2. The star under investigation must appear in at least 75% of the epochs.

3. The detected variability should not be due to only a few outliers (3%–5% of the data points) causing the high χ^2 . Care was taken to avoid deleting possible detached eclipsing systems at this stage (see below).

4. The star under investigation should display a brightness variation in both filters, and the variability signal should be correlated in both filters (this algorithm is very similar to the one described in Welch & Stetson 1993 and Stetson 1996).

Any measurement of stellar magnitude was weighted by the square of the inverse photometric error associated with it. Steps 1 and 2, which were performed simultaneously, returned around 2700 (*V*) and 4500 (*I*) variable candidates. Step 3 reduced both of these numbers by approximately 50%. Step 4 further reduced the number of candidates to a total of 80 candidates. The data for these remaining candidates were then phased and inspected by eye, which is described in the next subsection.

We note that we did not systematically address the issue of completeness in our analysis. The choice of parameters for the steps outlined above was made mainly based on hindsight (e.g., all of our candidates' χ^2 values are well in excess of 100) or trial and error (e.g., the analysis of a set of

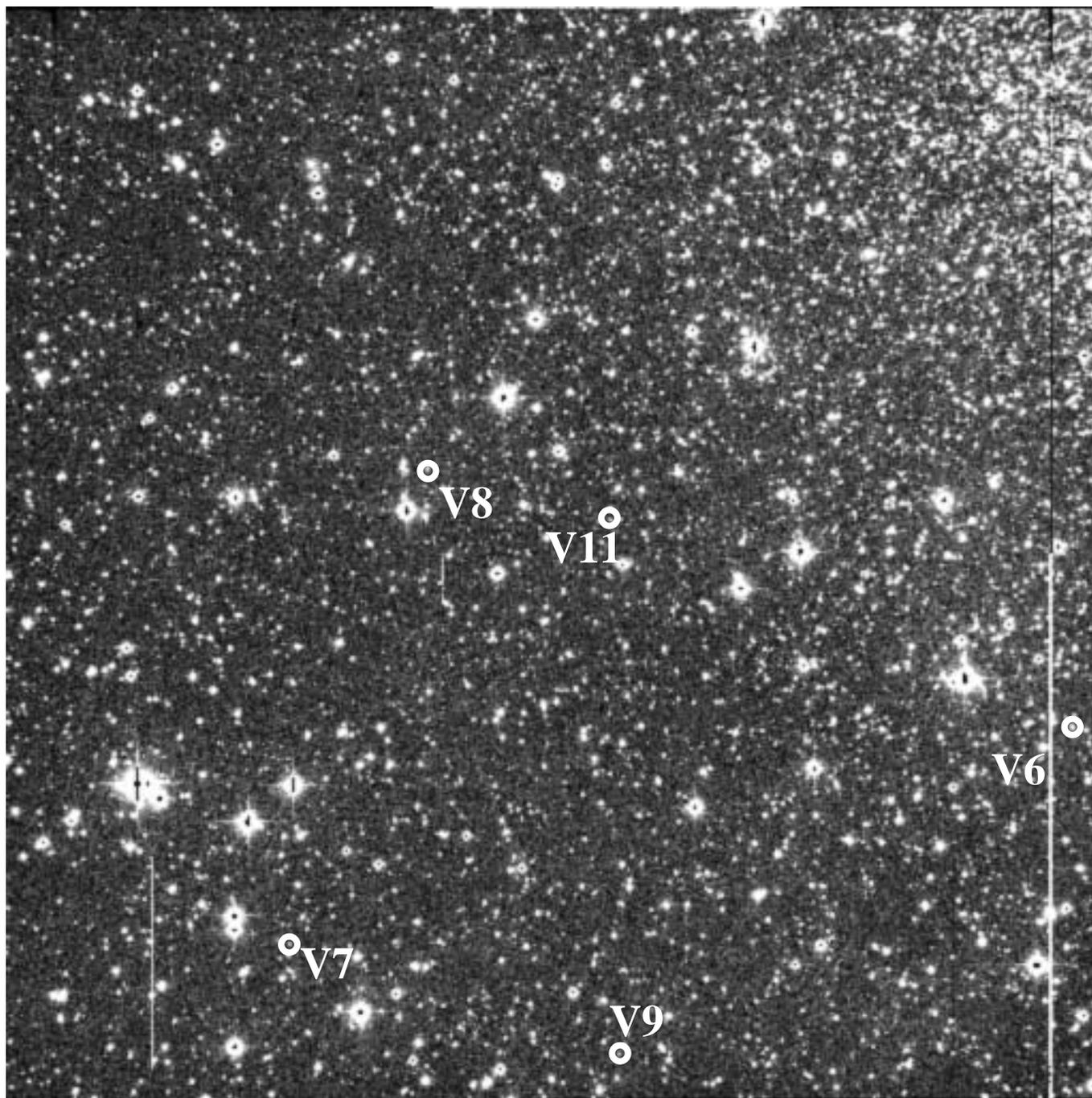


FIG. 2.—Locations of the variables extracted from the CTIO 0.9 m data. The field of view has the same orientation as the one in Fig. 1, but is smaller (13:5 on the side in this figure). V11, toward the center of this image, and V6, toward the right edge of the image, are present in both fields of view. V7–V9 are located outside (southeast of) the field of Fig. 1.

phased light curves before and after a reduction criterion was applied).

One set of binary star system, however, might be prone to being deleted during step 3. A detached system with a period long enough so that eclipses are not very well sampled might show up as a system whose χ^2 is based solely on a few outliers. In order to ensure that we would not miss such a system, we developed a slightly modified set of criteria specifically aimed at detecting detached binary star systems with the basic idea to identify faint “outliers.” which fall next to each other in time.

1. As a first step, the mean magnitude plus standard deviation of the brightest 75% of the data points are calculated.

2. We now try to detect successive (in time) data points which are $n\sigma$ fainter than this mean magnitude. The choice of n depends on the quality of the photometry of the star in question and the number of data points for the star.

3. If the i th data point falls within Δt of data point $i - 1$ (where i indicates succession in time), a merit function is calculated whose value would be $\delta_i \times \delta_{i-1}$. δ_i is defined as the magnitude difference between the i th data point and the average magnitude of the 75% of the brightest stars, divided

by the standard deviation (see step 1). Δt is dependent on the observing strategy followed to detect the binaries (i.e., it would be shorter, perhaps up to an hour, for a strategy where the cluster is observed many times in succession, and longer, perhaps several hours, if the cluster is observed only once every so often). It is obvious that for more than two neighboring faint outliers, the merit function would rapidly increase in value.

4. Candidates for detached systems are selected based on the value of their merit functions.

The application of this algorithm to our data revealed the existence of one detached system in our field of view (V12; see § 4.1 and Fig. 8), which had been eliminated by application of criteria described at the beginning of this subsection.

3.2. Period Determination

The final decision as to whether a star is a true variable candidate (and if so, what kind of variable star it is) was based on the inspection of the phased data (the photometry light curve). The initial estimates of the periods of all our variable star candidates which survived the steps outlined in the previous subsection were determined by two independent algorithms:

1. the minimum string length (MSL) method, based on a technique by Lafler & Kinman (1965) and described in Stetson (1996);
2. the analysis of variance (AOV) method, described, e.g., in Schwarzenberg-Czerny (1989). The basic code for this algorithm was supplied to us by Andrzej Udalski (1998, private communication).

Both of these methods worked very well with our data set to the extent that the periods for a variable star candidate, as independently determined by the two methods, were practically identical. A final tweaking of the precision in the period for a candidate was then done by hand, based on the appearance of the light curve. In the majority of the cases of the smoothly varying variables, such as W UMa stars or the RR Lyrae, the periods as determined by AOV or MSL could, in principle, not be improved by hand, i.e., the period was already determined to the maximum precision possible for our data set. In the cases of the detached system and the Algol, we were able to increase the precision of the periods in general at the $\leq 10^{-4}$ days level. This effort helped ensure that we knew the exact times of quadrature of these systems during our spectroscopic observations.

3.3. Analysis of Additional CTIO Photometry Data

In order to verify that our period estimates for the detached (V12) and Algol (V11) systems were sufficiently precise to accordingly phase our spectroscopic follow-up observations, we reobserved NGC 3201 at the CTIO 0.9 m telescope, as described in § 2.3. Field A and field D provided additional phasing information for the two binaries, enabling us to improve our period estimates for both of these systems. In the case of the detached system, this correction was on the order of five seconds, whereas the previously calculated period for the Algol system proved to be off by less than 0.2 s.

Field A furthermore contained stars we had not observed in our previous monitoring program, giving us the chance to mine additional data of NGC 3201 for the existence of variable stars. Using the algorithms described above, we

detected three additional W UMa systems outside our previous field of view (V7–V9; see Figs. 1 and 2). We made use of the fact that we had repeated V and I observations of the same system (the Algol star) in both the CTIO and the LCO data sets to photometrically shift the CTIO data to the system of the LCO data. The differential dereddening of the CTIO data set W UMa variables (V7–V9) was performed as described above and in BM01.

4. RESULTS

4.1. Locations of Variable Stars in Field and in CMD

Table 1 gives the basic information about the variable stars we detected in the field of NGC 3201. V_{bright} and I_{bright} are the V and I magnitudes at maximum light, respectively. Figure 1 shows the locations of the variable stars in the LCO data set. Figure 2 shows the locations of V11 (the Algol) and the three additional W UMa systems we found in the CTIO photometry data. Finally, Figure 3 indicates where the variables fall within the CMD of NGC 3201. The data shown in Figure 3 are differentially dereddened to a fiducial region within the cluster, as described in BM01. No reddening zero point is applied.

4.2. Photometry Light Curves

The phased light curves for the W UMa systems V1 through V5, detected in the LCO data set, are presented in Figure 4. The three additional W UMa light curves, V7 through V9, extracted from the CTIO photometry data (note the difference in sampling due to the lower number of observational epochs for these stars), are in Figure 5, along with the light curves of V10, the RR Lyrae, and V13 and V14, the two unclassified systems, from the LCO data set. Figure 6 contains the light curve of V6, the only member of NGC 3201 among our set of variable stars. V11, the Algol system, and V12, the detached system, are presented in Figures 7 and 8, respectively. In all of these three last figures, V data are in the bottom panel, I data in the top panel. The error bars represent the photometric errors associated with that particular measurement of the star's magnitude. No reddening correction was applied to the light curves.

4.3. Rucinski Magnitudes

W Ursa Majoris binaries are systems in which the two components are in physical contact with their Roche equipotential lobes and at their inner Lagrangian point (see Mateo 1993 and Rucinski 1985a, 1985b for more detailed descriptions of W UMa systems). Due to the good thermal contact between the two components, the two stars are assumed to have the same surface temperature. The total luminosity of the system can therefore be defined as (Rucinski 1995; Mateo 1996)

$$L = KT^4 S(q, P, f) M_p^{2/3} (1 + q)^{2/3} P^{4/3}, \quad (2)$$

where K consists of well-known constants, T is the common surface temperature, M_p and M_s are the masses of the primary and secondary component, respectively, $q = M_s/M_p$, and P is the orbital period of the system. S represents the total stellar surface area as defined by the Roche geometry, dynamical properties of the binary, and the fill-out factor f by which the stellar surfaces extend beyond the inner critical Roche surface.

TABLE 1
VARIABLE STARS IN THE FIELD OF NGC 3201

Var. No.	Type	R.A.	Decl.	Period (days)	V_{bright}	I_{bright}
V1.....	W UMa	10 16 36.92	-46 22 29.3	0.303587 (28)	18.054 (17)	17.258 (20)
V2.....	W UMa	10 17 07.73	-46 30 18.2	0.345095 (42)	18.237 (14)	17.319 (19)
V3.....	W UMa	10 17 13.75	-46 27 54.7	0.377114 (43)	17.189 (21)	16.352 (21)
V4.....	W UMa	10 17 17.18	-46 27 37.5	0.44179 (55)*	16.850 (17)	15.965 (22)
V5.....	W UMa	10 17 52.93	-46 34 06.7	0.276216 (31)	19.847 (21)	18.380 (32)
V6.....	W UMa	10 17 59.08	-46 33 25.7	0.37307 (39)*	17.270 (13)	16.599 (19)
V7.....	W UMa	10 18 56.03	-46 36 10.4	1.0800 (90)	18.658 (15)	17.064 (19)
V8.....	W UMa	10 18 46.01	-46 30 13.8	0.30642 (75)	18.824 (14)	17.577 (19)
V9.....	W UMa	10 18 31.97	-46 37 32.9	0.33248 (61)	19.609 (22)	18.483 (27)
V10.....	RR Lyrae	10 18 03.86	-46 17 48.7	0.592920 (53)	17.088 (12)	16.446 (22)
V11.....	Algol	10 18 32.74	-46 30 42.5	0.702127 (99)	17.728 (13)	16.932 (19)
V12.....	Detached	10 17 25.72	-46 20 12.4	2.84810 (98)	17.225 (14)	16.301 (22)
V13.....	Unclass. 1	10 17 04.83	-46 26 39.7	1.2080 (44)*	20.203 (35)	18.529 (29)
V14.....	Unclass. 2	10 18 36.28	-46 22 06.2	2.160 (13)*	18.915 (16)	17.108 (21)

NOTES.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds (J2000.0). Errors in parentheses indicate the uncertainty in last two digits, i.e., $0.303587 (28) = 0.303587 \pm 0.000028$ and $2.160 (13) = 2.160 \pm 0.013$. Photometry errors are the result of adding in quadrature the DOPHOT photometry error for the instrumental magnitude and the rms of the standard star solution (see BM01). The error in the period corresponds to the full width at half maximum (FWHM) of the peak in the AOV power spectrum corresponding to the correct frequency. For the determination of this error, only V data were used, except for the cases of V7, V8, and V13, where we used I data. In some instances, the peak in the power spectrum corresponding to the correct period was assigned essentially the same power as directly neighboring peaks (i.e., it would be hard to pick “by eye.” which one is the correct one). In these cases, we estimated the period error to be the distance between the two neighboring peaks (with the peak corresponding to the correct period in the middle). These cases are marked by an asterisk.

Rucinski (1994, 1995, 2000) converted the above equation into the more convenient form

$$M_V^{\text{color}} = a_0 + a_1 \log P + a_2 \text{color}, \quad (3)$$

where M_V is the absolute V magnitude, P is the period in days, and the color is reddening free. For $V-I$ color, this equation is (Rucinski 2000)

$$M_V^{VI} = -4.43 \log P + 3.63(V-I)_0 - 0.31; \quad \sigma \sim 0.29. \quad (4)$$

Table 2 shows the thus calculated absolute magnitudes and distance moduli for the W UMa binaries in the field of NGC 3201. The distance to NGC 3201 was calculated in BM01 to be 4.5 ± 0.03 kpc; the value found in Harris (1996) is 5.2 kpc. The corresponding distance moduli are $V_0 - M_V = 13.58$ and 13.26, respectively.⁴ We note that the absolute magnitudes and distance moduli in Table 2 were calculated under the assumption that the W UMa system under investigation is suffering the full extinction between us and the cluster. Since the spectroscopy results indicated that no W UMa system except V6 is associated with NGC 3201 (see following subsection), and the Rucinski magnitudes for some of the variables indicate that they are foreground stars, this assumption might be incorrect in some cases. That is, for some of the nonmembers, the color might not be the correct, reddening-free value.

The distance modulus of the GC member V6 calculated in Table 2 is 13.873, larger than the NGC 3201 distance moduli in both BM01 (by $\sim 2 \sigma$) and Harris (1996) (by $\sim 1 \sigma$). One way to “force” V6 to be at the correct distance would be to

⁴ These values represent the apparent distance moduli corrected for extinction.

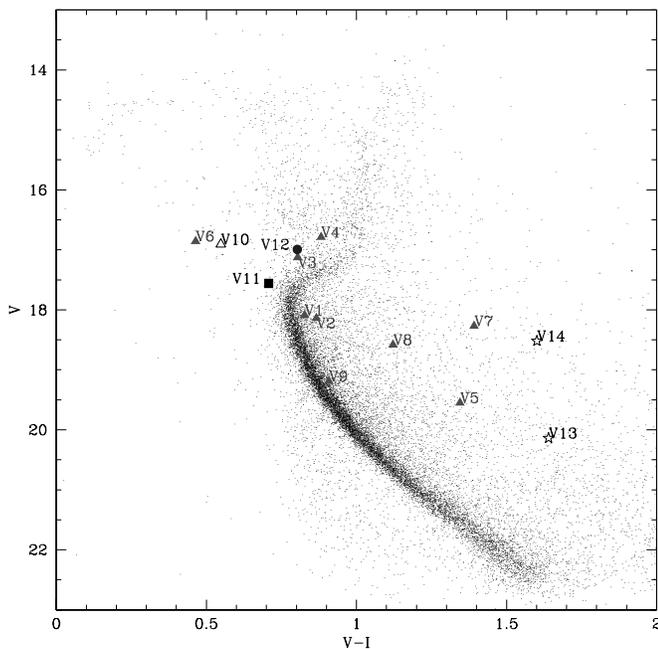


FIG. 3.—Locations of all our variable stars in the field of NGC 3201 in its CMD. The data presented are differentially dereddened to the fiducial region defined in BM01; i.e., no reddening zero point is applied. In BM01, we calculate the E_{V-I} zero point to be 0.15. The variable stars are plotted at maximum brightness and are also differentially dereddened. Filled triangles represent W UMa types, the open triangle the RR Lyrae, the square the Algol system, the filled circle the detached system, and the open star-shaped symbols the unclassified systems.

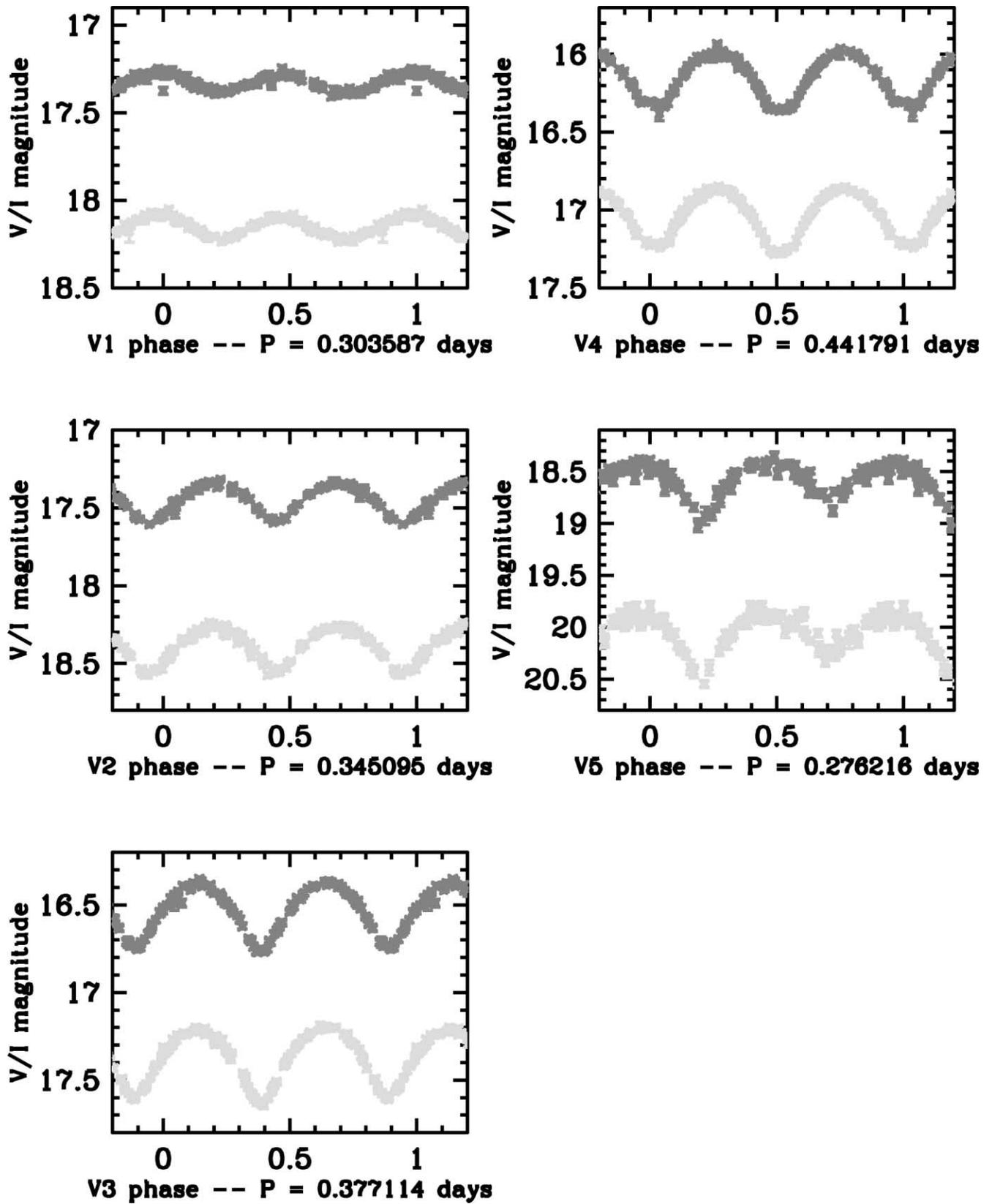


FIG. 4.—*V* and *I* light curves of V1 through V5 (all W UMa-type binaries). The *I* magnitude is the upper curve in each of the panels; no extinction correction is applied. None of these variables is associated with NGC 3201 itself.

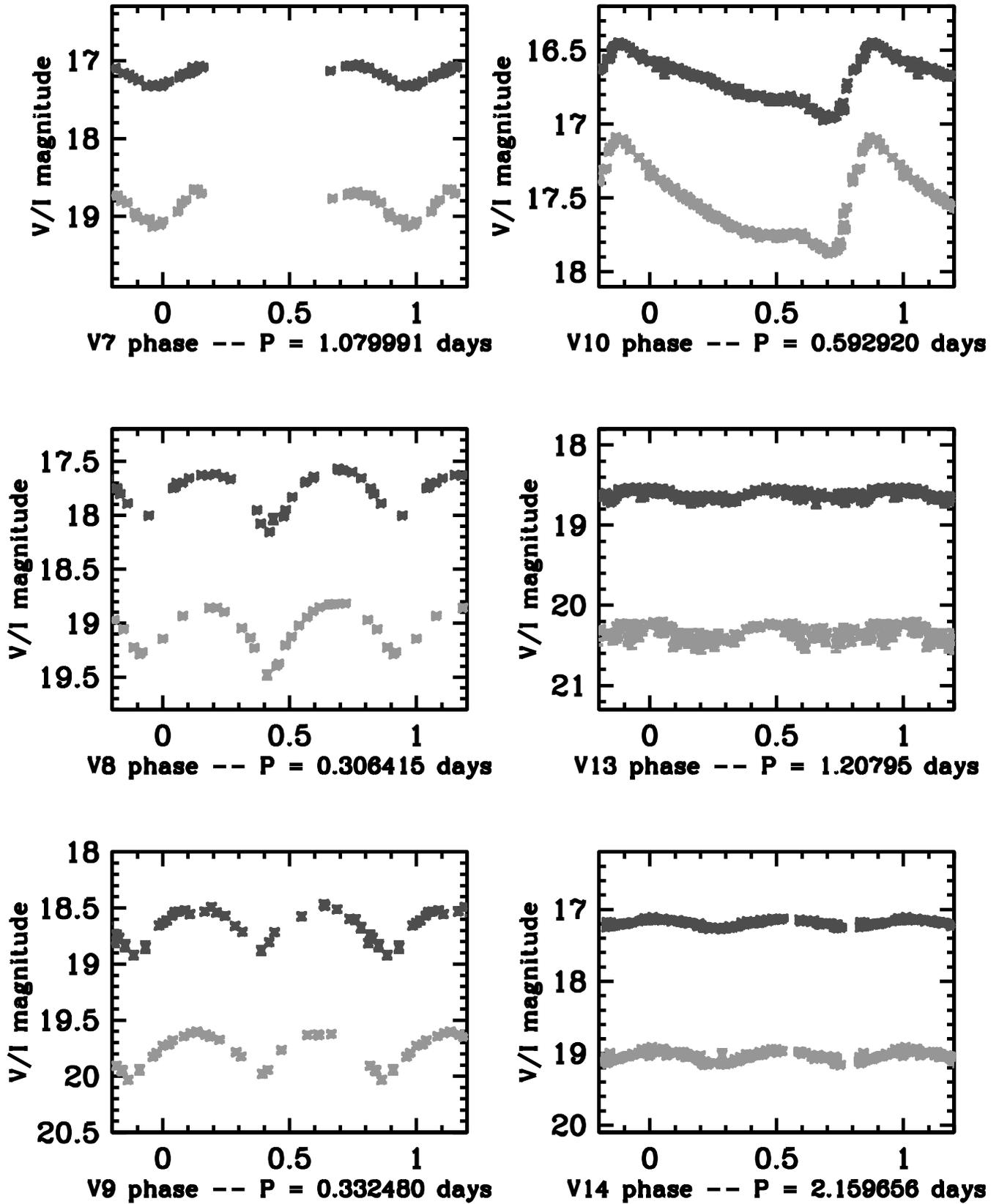


FIG. 5.—V7–V9 are the W UMa systems discovered in the CTIO data set. Note the much sparser sampling of the light curves. V10 is the background RR Lyrae star. Finally, V13 and V14 are the two unclassified systems. Their light curves look similar to the W UMa types, but their periods are much longer and their colors much redder. In each panel, the I magnitude is plotted above the V magnitude. The data are not corrected for extinction.

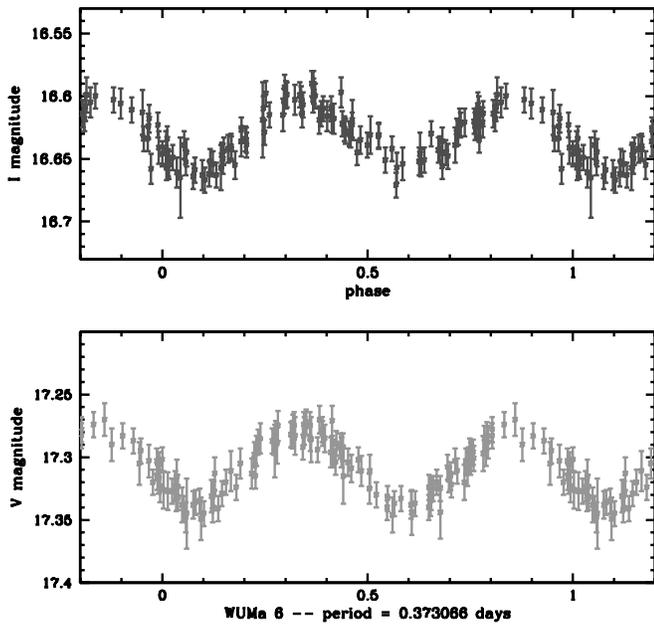


FIG. 6.—Light curve of V6, a blue straggler candidate and the only variable star in our sample that is a member of NGC 3201. No extinction correction is applied.

change the reddening zero point of the cluster and thus change the variable's intrinsic color. Since this correction would force the distance to go down, the reddening zero point obtained this way would decrease to $E_{V-I} \sim 0.02$, significantly below the BM01 value of 0.15. At this point, we can therefore not offer any conclusive reason why V6's distance modulus is slightly too high, other than the possibility that this one particular binary would represent an outlier (by about $1-2 \sigma$) in Rucinski's empirically determined relation.

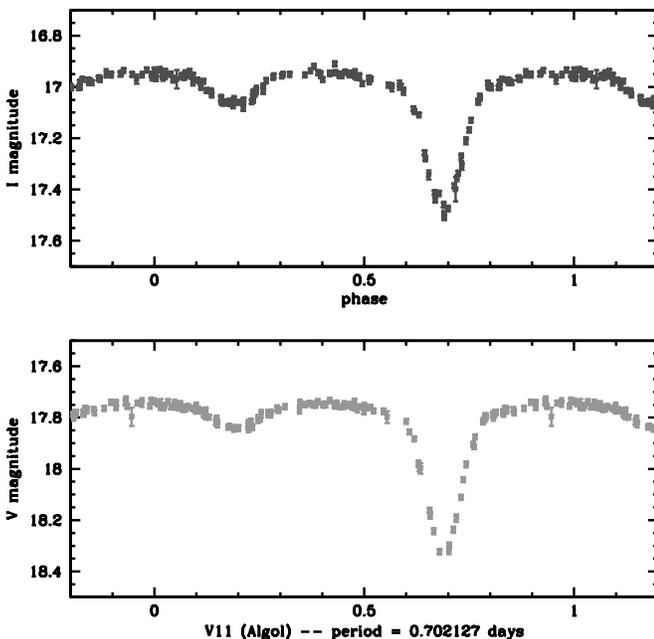


FIG. 7.—Light curve of V11, the Algol system, comprised of data taken at both LCO and CTIO. No reddening correction is applied to the data. V11 is not a member of the globular cluster.

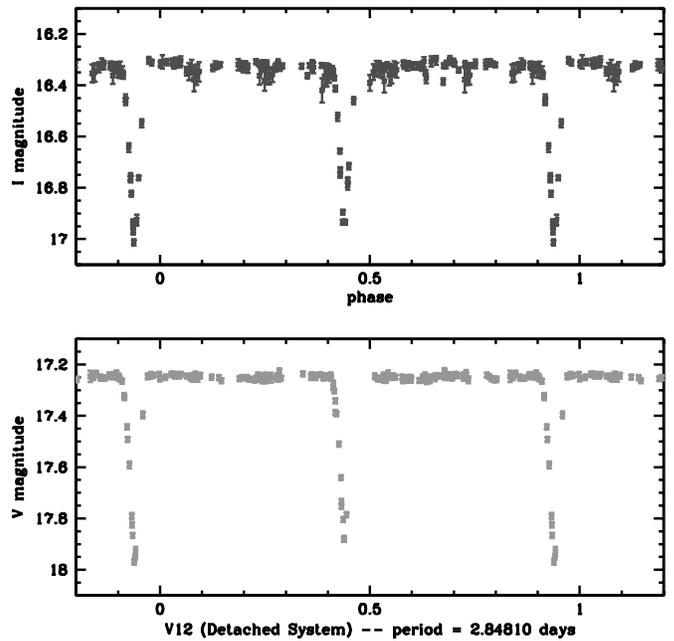


FIG. 8.—Light curve of V12, a detached binary star system. The data for this light curve were taken both at LCO and CTIO, and they are not corrected for extinction. V12 is not associated with NGC 3201.

4.4. Cluster Membership

A first indication of whether an eclipsing binary star system in the field of a globular cluster is associated with that cluster is, of course, its location with respect to the cluster center (we note that we cannot study the very center of the cluster due to crowding). The tidal radius of NGC 3201 is $28'45$ (Harris 1996). Thus, all the binary systems we find are well within the tidal radius. A more powerful membership criterion is a binary's location in the CMD. Based on the CMD of NGC 3201 (see Fig. 3), V5, V7, V8, V10, V13, and V14 are not associated with the cluster. Furthermore, based on their distance moduli, the W UMa systems V3, V4, V5, and V8 seem to be foreground stars while V9 seems to be a background star. V1, V2, and V6, however, seem promising cluster member candidates within error estimates, with the only difference being that the reddening calculated for V1 and V2 is significantly lower than the one for V6 (see Table 2).

The final verdict on membership, however, can only be provided by spectroscopic observations. NGC 3201 has a distinct systemic (retrograde) velocity of approximately 500 km s^{-1} (Harris 1996; Côté et al. 1994), so a single spectrum of a binary system with sufficient resolution and signal-to-noise ratio can be used to establish cluster membership.

During the nights of 2001 March 2–5 we performed spectroscopic follow-up observations of our eclipsing binary star candidates at the CTIO 4 m telescope with ARCON and the RC Spectrograph. Our setup included a $3k \times 1k$ Loral CCD and the KPGLG grating ($860 \text{ lines mm}^{-1}$; first-order blaze = 11000 \AA) in second order. The wavelength coverage extended from 3800 to 5100 \AA , with a resolution of about $0.4 \text{ \AA pixel}^{-1}$. Our observing targets were V1, V2, V3, V4, V6, V11, and V12. V9, a potential cluster member given its location in the CMD, was too faint to observe with our setup at CTIO.

TABLE 2
RUCINSKI MAGNITUDES AND DISTANCE MODULI FOR W UMa-TYPE
BINARIES

System	Period ^a (days)	E_{V-I} ^b	$(V-I)_{0,\text{bright}}$ ^c	$M_V(\text{Rucinski})$	$V_0 - M_V$
V1 ^d	0.303587 (28)	0.131 (55)	0.665	4.397	13.405
V2	0.345095 (42)	0.202 (34)	0.716	4.336	13.513
V3	0.377114 (43)	0.183 (38)	0.654	3.940	12.898
V4	0.44179 (55)	0.183 (38)	0.702	3.810	12.689
V5	0.276216 (31)	0.305 (65)	1.162	6.383	12.878
V6	0.37307 (39)	0.366 (42)	0.305	2.694	13.873
V7	1.0800 (90)	0.352 (81)	1.242	4.050	13.932
V8	0.30642 (75)	0.275 (61)	0.972	5.494	12.802
V9	0.33248 (61)	0.368 (67)	0.758	4.560	14.343

NOTES.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds (J2000.0). Rucinski quotes the scatter in his relation (Rucinski 1994, 1995) to be 0.29 mag in the calculation of the absolute V magnitudes (corresponding to an uncertainty of approximately 13% in distance). Since this uncertainty is far larger than the quadratic sum of all our random errors, we refrain from a detailed error analysis for the Rucinski magnitudes and distance moduli.

^a As in Table 1, errors in parentheses indicate the uncertainty in last two digits. The period errors are the same as in Table 1.

^b E_{V-I} contains the reddening zero point, calculated in BM01 to be 0.15 mag. As mentioned above, this value assumes that the binary suffers the full extinction along the line of sight to the GC (which is not necessarily correct if the binary is not a cluster member). The errors for E_{V-I} are the random errors in the determination of the *differential reddening*. That is, a possible systematic error in the determination of the reddening zero point (described in BM01) is not included in this estimate.

^c $(V-I)_{0,\text{bright}}$ is the dereddened color at maximum light.

^d V1 is located in a region whose differential reddening along the line of sight is lower than the one of the fiducial region whose overall E_{V-I} is 0.15 mag. Its total E_{V-I} is therefore calculated to be lower than the reddening zero point.

In order to check the cluster membership of V9, we obtained three spectra during the night of 2001 March 19 using the Magellan 1 Telescope with the Boller and Chivens spectrograph and a setup similar to the one at the CTIO 4 m telescope, but with lower resolution (approximately 1.4 Å pixel⁻¹). Our wavelength coverage extended from 3900 to 5300 Å.

To our great disappointment, during the first night of the CTIO spectroscopy run, one spectrum after the next eliminated our candidates from cluster membership consideration. The only system with a systemic velocity equal to that of NGC 3201 is V6, a blue straggler candidate (see Fig. 3) with a very small amplitude (see Fig. 6).

Our spectroscopy results are summarized in Table 3. The systemic velocities of the binaries were determined using the IRAF FXCOR package, using radial velocity standards as templates. We estimate our error in the velocity determinations of the candidates to be around 20 km s⁻¹ for the CTIO data (except V6), based on measurements performed on the velocity standards we used. Due to the lower resolution of the spectrum we obtained at Magellan, we estimate V9's velocity uncertainty to be approximately 50 km s⁻¹. The difference in spectral types between V6 and our radial velocity standards made it impossible to determine its velocity using FXCOR. Instead, we calculated its Doppler velocity from line-profile fitting using IRAF's SPLOT package. The error quoted for that star is simply the rms of ~10 individual line measurements from different spectra of the star.

We further note that for all of our variables, except for our CTIO photometry targets (V7–V9, as well as V11 and

TABLE 3
SYSTEMIC VELOCITIES OF MEMBER CANDIDATES

Variable	Systemic Velocity (km s ⁻¹)	Error (km s ⁻¹)
V1	12	20
V2	6	20
V3	9	20
V4	20	20
V6	513	44
V9	24	50
V11	1	20
V12	0	20

NOTES.—The variables not listed in this table but listed in Tables 1 and 2 were considered to be nonmembers based on their location in the CMD. For an explanation on how velocities and errors were determined, see text. The systemic velocity of NGC 3201 is ~500 km s⁻¹ (Harris 1996; Côté et al. 1994).

V12), we do not have phase information obtained more recently than 3 years prior to the spectroscopy run. The propagation of the period determination error (see Tables 1 and 2) therefore makes it impossible to constrain the precise phasing of most of our candidates. The uncertainty in the calculation of the systemic velocities of the binary candidates due to the radial motion of the two components is not accounted for in our estimates.⁵

Since NGC 3201's systemic velocity is so high (500 km s⁻¹), cluster membership based on the comparison between systemic velocity of the variable and the cluster may be determined without phasing information. The velocity amplitudes of the components of a binary system relate to the masses and the period of the system as follows (Paczynski 1996):

$$\frac{K_1 + K_2}{\sin i} = 386.4 \text{ kms}^{-1} \left(\frac{M_1 + M_2}{3M_{\text{Solar}}} \frac{0.5 \text{ days}}{P_{\text{orb}}} \right)^{1/3}. \quad (5)$$

If one assumes that the orbits of the W UMa systems V1–V4 and V9 are circular (which is evidenced by the fact that the minima of the light curves are separated by half a period), that $\sin i = 1$ (the system is seen edge-on), and that the masses and thus velocity amplitudes of the two components are equal, one needs only the sum of the masses and the orbital period to get an estimate of the velocity amplitudes. From the isochrones of D. Vandenberg (2000, private communication; based on evolutionary models by Vandenberg et al. 2000) for a cluster age of anywhere in between 14 and 18 Gyrs and $[\text{Fe}/\text{H}] = -1.41$, one obtains masses for main-sequence stars with $(V-I)_0 \sim 0.7$ of approximately 0.7 M_{Solar} (for each component). Finally, given the average period of these systems of ~0.36 days, we estimate the typical velocity amplitude to be $K_j \sim 165 \text{ km s}^{-1}$. We note, of course, that nonmember binaries might have a different metallicity and thus mass for a given color, but since $K \propto M^{1/3}$ this difference would not significantly

⁵ A binary's period may, of course, also be calculated from the radial velocity curve. Since we were able to eliminate our observing targets (except V6) from cluster membership consideration after obtaining only a few spectra for each system, we refrained from reobserving them and can therefore not determine the phase of the binary at the time of observation.

alter this rough estimate. A deviation from an edge-on configuration would decrease the calculated velocity amplitudes; i.e., the value given above may be regarded as an upper limit.

For V11 and V12, the masses of the individual components are probably slightly higher (bluer $V-I$ color), but the periods are much larger, especially in the case of V12. Retaining the same assumptions as for the W UMa systems, one obtains velocity amplitudes closer to 150 km s^{-1} for V11 and 80 km s^{-1} for V12.

In order for a binary system to be a member of NGC 3201, its systemic velocity would have to fall within $(165 \text{ km s}^{-1} + \sigma)$ of 500 km s^{-1} (NGC 3201's velocity). As one may easily see in Table 3, only V6 survives this criterion.

We obtained approximately 25 spectra of V6 at various phase angles. These results, combined with our photometry data, may be used to calculate the component masses of the binary BS system. The analysis of the radial velocity curve and subsequent calculation of the stellar masses will be addressed in a future publication.

5. SUMMARY AND CONCLUDING REMARKS

The low-latitude GC NGC 3201 was probed for the existence of photometrically variable stars in the magnitude range of approximately $16.5 < V < 20$ and for periods between roughly 0.2 and 5 days. We detected 14 variable star candidates in the field of which most are eclipsing binaries of the W UMa type. Our spectroscopic follow-up observations revealed that only one of the variables, a BS W UMa EB, is associated with the cluster itself. Due to the low-latitude location of the GC, the high contamination of Galactic disk stars in the field of NGC 3201 seems to have manifest itself 13 times in our analysis.

Our confirmation of V6 as a member increases the number of known binary BSs in GCs. Mateo et al. (1990) pre-

dicted that 3%–15% of all BSs in GCs should be photometrically observable binaries. In the case of NGC 3201 there are nine total BSs (Sarajedini 1993). Our detection of one BS member binary is therefore consistent with that prediction. Thus, the membership of V6 supports the basic Mateo et al. (1990) model that BSs evolve from primordial or, at least, long-lived binaries which coalesce after a lifetime of slow angular momentum loss.

Despite the fact that we did not identify a large number of NGC 3201 member binaries, we have nevertheless shown the potential to do just that for the other globular clusters in our survey (provided there are binaries in those clusters). The fact that we successfully identified a BS EB with an V amplitude of around 0.07 mag (see Fig. 6), a detached system with duty cycle of around 0.1 (see Fig. 8), and that we determined periods to a precision of seconds or less (see § 3.3) gives us confidence that we have the data set and the methods to detect a number of EBs in our target GCs. Using the combination of our 1 m telescope photometry data set and the capabilities of Magellan 1 for the spectroscopy follow-up observations, we should be able to determine the cluster membership for binaries in the southern and equatorial GCs of our sample in the near future.

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