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DIRECT DISTANCES TO NEARBY GALAXIES USING DETACHED ECLIPSING BINARIES AND CEPHEIDS. IV. VARIABLES IN THE FIELD M31D[1]

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ABSTRACT

We undertook a long-term project, DIRECT, to obtain the direct distances to two important galaxies in the cosmological distance ladder—M31 and M33—using detached eclipsing binaries (DEBs) and Cepheids. While rare and difficult to detect, DEBs provide us with the potential to determine these distances with an accuracy better than 5%. The extensive photometry obtained in order to detect DEBs provides us with good light curves for the Cepheid variables. These are essential to the parallel project to derive direct Baade-Wesselink distances to Cepheids in M31 and M33. For both Cepheids and eclipsing binaries, the distance estimates will be free of any intermediate steps. As a first step in the DIRECT project, between 1996 September and 1997 October we obtained 95 full/partial nights on the F. L. Whipple Observatory 1.2 m telescope and 36 full nights on the Michigan-Dartmouth-MIT 1.3 m telescope to search for DEBs and new Cepheids in the M31 and M33 galaxies. In this paper, the fourth in the series, we present the catalog of variable stars, most of them newly detected, found in the field M31D [$(\alpha, \delta) = (11^\circ\!.03, 41^\circ\!.27)$, J2000.0]. We have found 71 variable stars: five eclipsing binaries, 38 Cepheids, and 28 other periodic, possible long-period or nonperiodic variables. The catalog of variables, as well as their photometry and finding charts, is available via anonymous ftp and the World Wide Web. The complete set of the CCD frames is available upon request.

Key words: binaries: eclipsing — Cepheids — distance scale — galaxies: individual (M31) — stars: variables: other

1. INTRODUCTION

Starting in 1996 we undertook a long-term project, DIRECT (as in "direct distances"), to obtain the distances to two important galaxies in the cosmological distance ladder—M31 and M33—using detached eclipsing binaries (DEBs) and Cepheids. These two nearby galaxies are stepping stones to most of our current effort to understand the evolving universe at large scales. First, they are essential to the calibration of the extragalactic distance scale (Jacoby et al. 1992; Tonry et al. 1997). Second, they constrain population synthesis models for early galaxy formation and evolution and provide the stellar luminosity calibration. There is one simple requirement for all this—accurate distances.

DEBs have the potential to establish distances to M31 and M33 with an unprecedented accuracy of better than 5% and possibly to better than 1%. These distances are now known to no better than 10%–15%, as there are discrepancies of 0.2–0.3 mag between various distance indicators (e.g., Huterer, Sasselov, & Schechter 1995; Holland 1998; Stanek & Garnavich 1998). Detached eclipsing binaries (for reviews see Andersen 1991; Paczyński 1997) offer a single-step distance determination to nearby galaxies and may therefore provide an accurate zero-point calibration—a major step toward very accurate determination of the Hubble constant, presently an important but daunting problem for astrophysicists. A DEB system was recently used by Guinan et al. (1998) and Udalski et al. (1998) to obtain an accurate distance estimate of the Large Magellanic Cloud.

The DEBs have yet to be used as distance indicators to M31 and M33. (Huterer et al. 1995; Hilditch 1996). According to Hilditch (1996), there were about 60 eclipsing binaries of all kinds known in M31 (Gaposchkin 1962; Baade & Swope 1963, 1965) and only *one* in M33 (Hubble 1929), none of them observed with CCDs. Only now does the availability of large-format CCD detectors and inexpensive CPUs make it possible to organize a massive search for periodic variables, which will produce a handful of good DEB candidates. These can then be spectroscopically followed up with the powerful new 6.5–10 m telescopes.

The study of Cepheids in M31 and M33 has a venerable history (Hubble 1926, 1929; Gaposchkin 1962; Baade & Swope 1963, 1965). Freedman & Madore (1990) and Freedman, Wilson, & Madore (1991) obtained multiband CCD photometry of some of the already known Cepheids to build period-luminosity relations in M31 and M33. However, neither the sparse photometry nor the small

[1] Based on the observations collected at the Michigan-Dartmouth-MIT (MDM) 1.3 m telescope and at the F. L. Whipple Observatory (FLWO) 1.2 m telescope.

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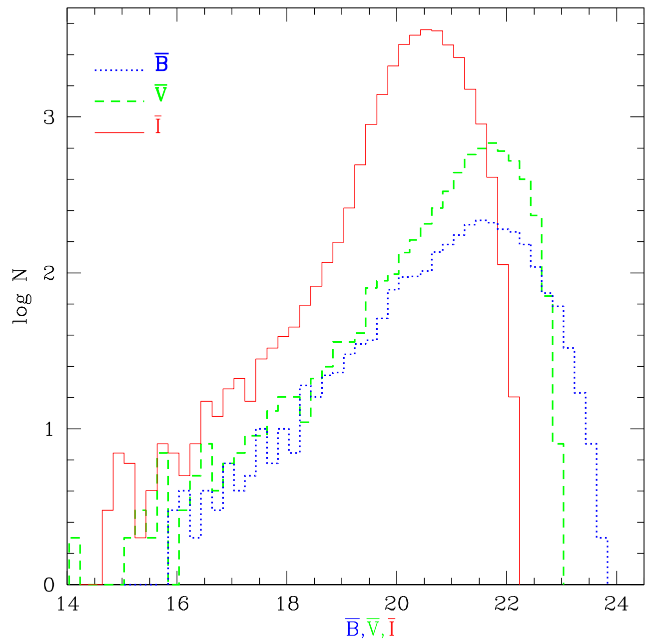

FIG. 1.—Distributions in B (*dotted line*), V (*dashed line*), and I (*solid line*) of stars in the field M31D.

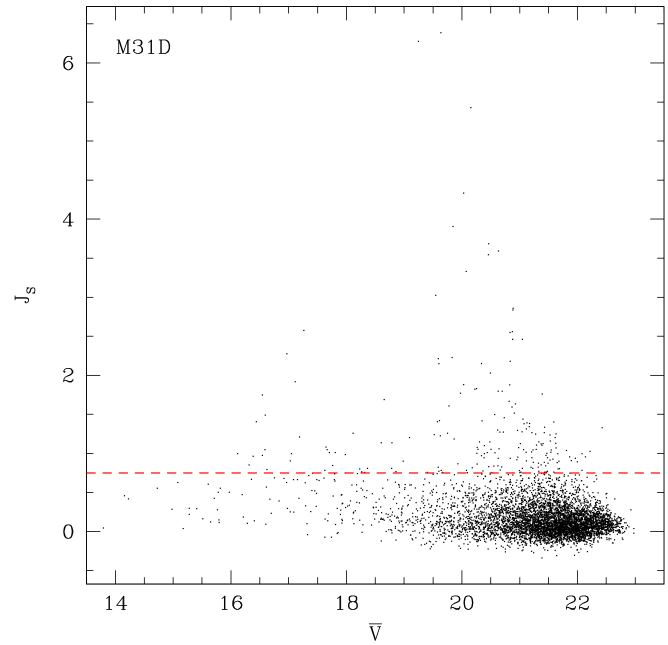

FIG. 2.—Variability index J_S vs. mean V magnitude for 5813 stars in the field M31D with $N_{good} > 45$. Dashed line at $J_S = 0.75$ defines the cutoff applied for variability.

samples (11 Cepheids in M33 and 38 Cepheids in M31) provide a good basis for obtaining direct Baade-Wesselink distances (see, e.g., Krockenberger, Sasselov, & Noyes 1997) to Cepheids. The need for new digital photometry has been long overdue. Recently, Magnier et al. (1997) surveyed large portions of M31 that have previously been ignored and found some 130 new Cepheid variable candidates. Their light curves are, however, rather sparsely sampled and in the V band only.

In Kaluzny et al. (1998, hereafter Paper I) and Stanek et al. (1998, 1999, hereafter Papers II and III, respectively), the first three papers of the series, we presented the catalogs of variable stars found in three fields in M31, called M31B, M31A, and M31C. Here we present the catalog of variables from the next field, M31D. In § 2, we discuss the selection of the fields in M31 and the observations. In § 3, we describe the data reduction and calibration. In § 4, we briefly discuss the automatic selection we used for finding the variable stars. In § 5, we discuss the classification of the variables. In § 6, we present the catalog of variable stars, followed by brief discussion of the results in § 7.

2. FIELDS SELECTION AND OBSERVATIONS

M31 was primarily observed with the 1.3 m McGraw-Hill Telescope at the Michigan-Dartmouth-MIT (MDM) Observatory. We used the front-illuminated, Loral 2048^2 pixel CCD "Wilbur" (Metzger, Tonry, & Luppino 1993), which at the f/7.5 station of the 1.3 m telescope has a pixel scale of 0$''$.32 pixel^{-1} and field of view of roughly 11$'$. We used Kitt Peak Johnson-Cousins *BVI* filters. Data for M31 were also obtained, mostly in 1997, with the 1.2 m telescope at the F. L. Whipple Observatory (FLWO), where we used "AndyCam" (Szentgyorgyi et al. 1999), with a thinned, back-illuminated, AR-coated Loral 2048^2 pixel CCD. The pixel scale happens to be essentially the same as at the MDM 1.3 m telescope. We used standard Johnson-Cousins *BVI* filters.

Fields in M31 were selected using the MIT photometric survey of M31 by Magnier et al. (1992) and Haiman et al. (1994) (see Fig. 1 in Paper I). We selected six 11$'$ × 11$'$ fields, M31A–M31F, four of them (A–D) concentrated on the rich spiral arm in the northeast part of M31, one (E) coinciding with the region of M31 searched for microlensing by Crotts & Tomaney (1996), and one (F) containing the giant star formation region known as NGC 206 (observed by Baade & Swope 1963). Fields A–C were observed during 1996 September and October five to eight times per night in the V band, resulting in a total of 110–160 V exposures per field. Fields D–F were observed once a night in the V band. Some exposures in B and I were also taken. M31 was also observed, in 1996 and 1997, at the FLWO 1.2 m telescope, whose main target was M33.

TABLE 1
DIRECT ECLIPSING BINARIES IN M31D

Name (D31D)	α (J2000.0) (deg)	δ (J2000.0) (deg)	P (days)	V_{max}	I_{max}	B_{max}	R_1	R_2	i (deg)	e
V4520.........	11.0001	41.3004	2.8235	19.53	19.52	19.34	0.56	0.35	83	0.03
V7214.........	11.0840	41.2994	2.8848	19.76	19.46	19.85	0.57	0.42	90	0.00
V7175.........	11.0824	41.2991	5.6958	19.60	19.13	19.90	0.63	0.36	59	0.01
V5186.........	11.0158	41.2888	11.8003	19.50	19.08	19.70	0.53	0.47	75	0.01
V7221.........	11.0845	41.2973	14.2052	19.56	19.52	19.37	0.64	0.36	63	0.14

TABLE 2

DIRECT CEPHEIDS IN M31D

Name (D31D)	α (J2000.0) (deg)	δ (J2000.0) (deg)	P (days)	⟨V⟩	⟨I⟩	⟨B⟩	A	Comments
V7706	11.1179	41.3130	5.365	20.99	20.11	21.73	0.30	Ma97 82
V7671	11.1144	41.3341	6.149	20.83	20.26	21.48	0.20	Ma97 81
V883	10.9315	41.1969	7.459	20.92	19.90	21.57	0.33	
V6311	11.0487	41.2732	9.172	21.69	20.38	...	0.34	
V1219	10.9364	41.2504	9.173	21.09	19.43	...	0.24	
V4503	11.0004	41.2835	9.261	20.71	19.91	21.54	0.23	Ma97 71
V2879	10.9716	41.2127	9.790	21.24	19.69	...	0.27	
V5343	11.0218	41.2345	10.290	21.22	20.13	...	0.30	
V3773	10.9875	41.2405	10.938	21.09	19.74	21.72	0.30	
V7381	11.0925	41.3213	10.943	20.70	19.76	21.53	0.30	Ma97 78
V4134	10.9927	41.2956	11.632	20.67	19.63	...	0.24	
V952	10.9332	41.1849	12.318	20.80	19.72	...	0.26	
V1599	10.9419	41.3027	13.170	20.78	19.33	21.98	0.43	
V5794	11.0322	41.2944	13.317	21.40	19.75	...	0.33	
V5146	11.0166	41.2315	13.523	20.97	19.66	22.00	0.24	
V7353	11.0908	41.3220	13.658	20.54	19.79	21.45	0.39	
V6037	11.0401	41.3103	14.925	21.77	20.16	...	0.51	
V635	10.9252	41.2489	15.255	20.58	18.95	21.65	0.36	
V2286	10.9576	41.2227	15.464	21.77	19.90	...	0.42	
V6164	11.0443	41.2838	16.155	20.38	19.31	...	0.40	Ma97 73
V3198	10.9772	41.2348	16.345	21.04	19.75	...	0.49	
V3551	10.9835	41.2373	16.699	20.49	19.36	21.33	0.48	
V7122	11.0783	41.3468	16.706	20.92	19.29	...	0.47	V7557 D31C
V5565	11.0238	41.3485	17.599	21.07	...	22.29	0.42	V3277 D31C
V1848	10.9455	41.3269	17.628	19.87	18.78	20.88	0.38	
V3583	10.9849	41.2176	17.703	20.21	19.13	20.95	0.34	
V4202	10.9952	41.2509	17.838	20.95	19.61	22.13	0.31	
V5594	11.0272	41.2675	19.084	20.55	19.06	...	0.24	
V5392	11.0209	41.3162	19.611	20.16	19.22	...	0.19	
V1980	10.9496	41.2656	20.260	21.40	19.26	...	0.47	
V6962	11.0732	41.2807	20.654	20.69	19.51	21.79	0.53	Ma97 74
V4960	11.0106	41.2787	21.892	20.20	19.14	...	0.50	Ma97 72
V4449	10.9984	41.3149	22.238	19.50	18.32	20.38	0.38	Ma97 70
V4970	11.0119	41.2402	25.330	20.19	19.00	21.26	0.35	
V4231	10.9960	41.2386	27.885	20.77	19.40	22.07	0.44	
V7483	11.0995	41.3533	36.011	20.03	...	...	0.28	V9029 D31C
V836	10.9290	41.2476	43.371	19.57	18.12	20.69	0.41	
V164	10.9177	41.1856	56.116	20.27	18.52	21.42	0.21	

NOTE.—V7122 D31D (Ma97 75) was found in Paper III as V7557 D31C, with $P = 16.726$ days, $\langle V\rangle = 20.85$, $\langle I\rangle = 19.14$, and $\langle B\rangle = 21.98$; V5565 D31D was found as V3277 D31C, with $P = 17.599$ days, $\langle V\rangle = 21.02$, $\langle I\rangle = 19.60$, and $\langle B\rangle = 22.29$, V7483 D31D was found in Paper III as V9029 D31C, with $P = 35.861$ days, $\langle V\rangle = 20.31$, $\langle I\rangle = 18.62$, and $\langle B\rangle = 21.39$.

In this paper we present the results for the M31D field. We obtained for this field useful data during 23 nights at the MDM, collecting a total of 24 × 900 s exposures in V and 2 × 600 s exposures in I. We also obtained for this field useful data during 35 nights at the FLWO, in 1996 and 1997, collecting a total of 67 × 900 s exposures in V, 43 × 600 s exposures in I, and 5 × 1200 s exposures in B.[3]

3. DATA REDUCTION, CALIBRATION, AND ASTROMETRY

The details of the reduction procedure were given in Paper I. Preliminary processing of the CCD frames was done with the standard routines in the IRAF CCDPROC package.[4] Stellar profile photometry was extracted using the DAOPHOT/ALLSTAR package (Stetson 1987, 1992). We selected a "template" frame for each filter using a single frame of particularly good quality. These template images were reduced in a standard way (Paper I). Other images were reduced using ALLSTAR in the fixed-position mode using as an input the transformed object list from the template frames. For each frame, the list of instrumental photometry derived for the given frame was transformed to the common instrumental system of the appropriate "template" image. Photometry obtained for the B, V, and I filters was combined into separate databases. M31D images obtained at the FLWO were reduced using MDM "templates." In case of B-band images obtained at FLWO,

[3] The complete list of exposures for this field and related data files are available from the authors via anonymous ftp on cfa-ftp.harvard.edu in the pub/kstanek/DIRECT directory. Please retrieve the README file for instructions. Additional information on the DIRECT project is available on the World Wide Web at http://cfa-www.harvard.edu/~kstanek/DIRECT/.

[4] IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

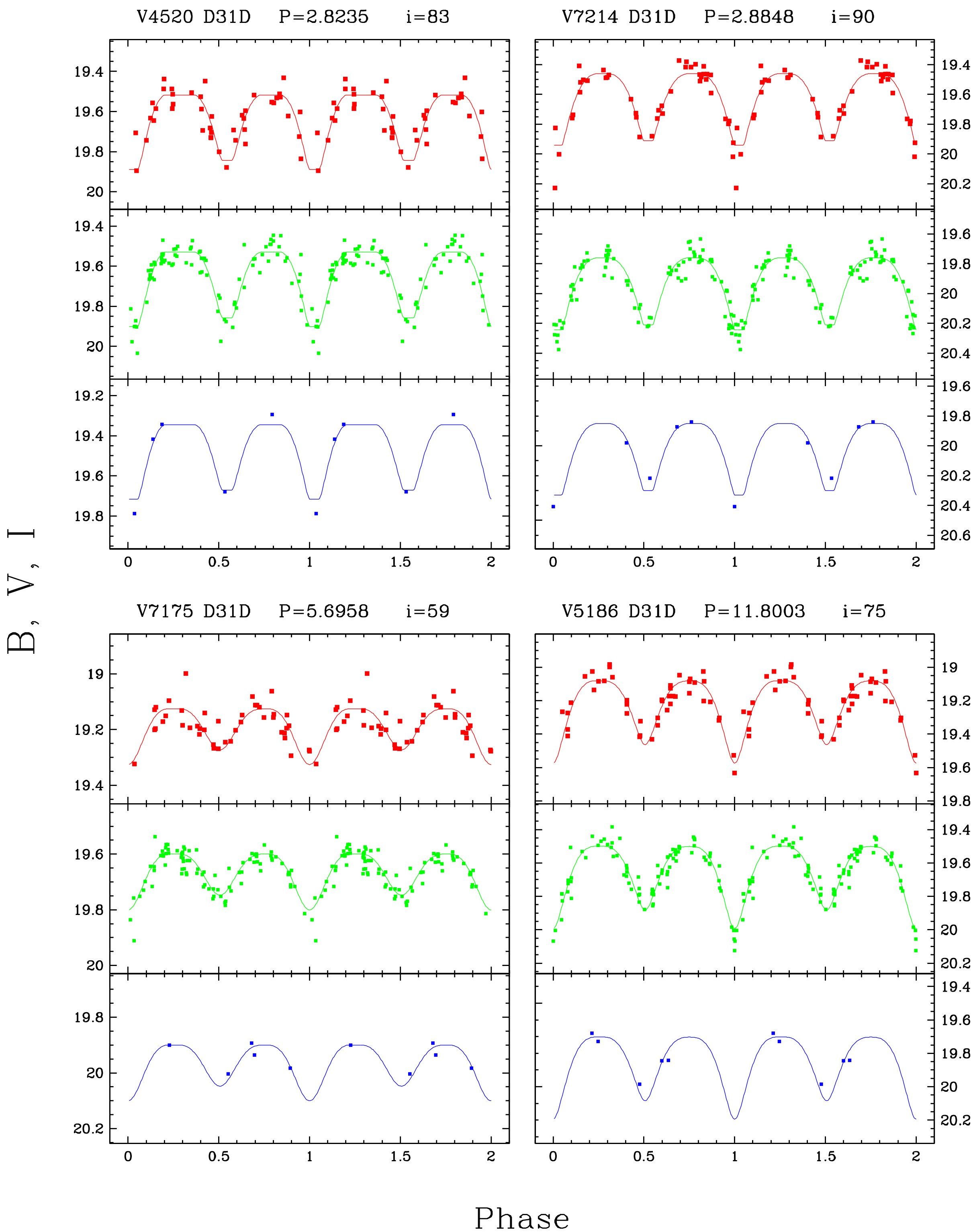

FIG. 3.—*BVI* light curves of eclipsing binaries found in the field M31D. The thin continuous line represents the best-fit model for each star and photometric band. *B*-band light curve is shown (*bottom*), and (when present) the *I*-band light curve is shown (*top*).

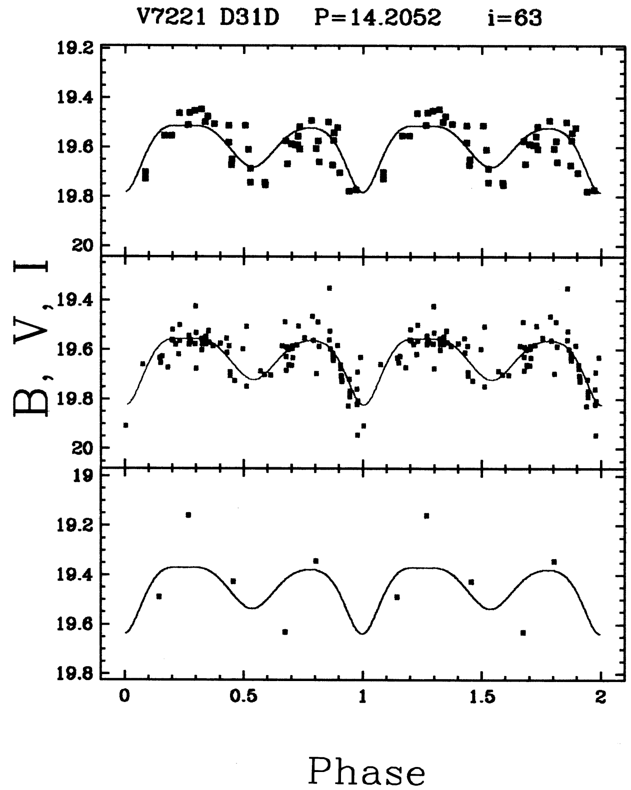

FIG. 3.—*Continued*

we used the V-band MDM template to fix the positions of the stars.

The photometric VI calibration of the MDM data was discussed in Paper I. In addition, for the field M31D on the night of 1997 October 9/10 we have obtained independent BVI calibration with the FLWO 1.2 m telescope. There was an offset of -0.014 mag in V and 0.047 mag in $V-I$ between the FLWO and the MDM calibration, that is, within our estimate of the total 0.05 mag systematic error discussed in Paper I.

To check the internal consistency of our photometry, we compared the photometry for 55 $V < 20$ and 100 $I < 20$ common stars in the overlap region between the fields M31C and M31D. There was an offset of -0.063 mag in V, -0.040 mag in I, and 0.007 mag in B. We also derived equatorial coordinates for all objects included in the databases for the V filter. The transformation from rectangular coordinates to equatorial coordinates was derived using 196 stars identified in the list published by Magnier et al. (1992).

4. SELECTION OF VARIABLES

The procedure for selecting the variables was described in detail in Paper I, so here we only give a short description, noting changes when necessary. The reduction procedure described in the previous section produces databases of

TABLE 3

DIRECT OTHER PERIODIC VARIABLES IN M31D

Name (D31D)	α (J2000.0) (deg)	δ (J2000.0) (deg)	P (days)	$\bar{V}$	$\bar{I}$	$\bar{B}$	σ_V	σ_I	σ_B	Comments
V3994.........	10.9898	41.2932	3.0	18.12	18.24	17.90	0.05	0.05	0.06	EB?
V2395.........	10.9578	41.2977	9.1	21.23	20.26	...	0.29	0.25	...	W Virginis?
V4569.........	11.0043	41.1923	31.4	21.25	19.75	21.66	0.24	0.20	0.22	
V7519.........	11.1053	41.2513	33.9	21.44	20.68	...	0.35	0.23	...	
V2227.........	10.9565	41.2106	35.0	21.12	20.17	21.57	0.33	0.28	0.39	RV Tauri
V5816.........	11.0352	41.2298	35.1	20.82	19.68	21.64	0.23	0.16	0.35	
V5762.........	11.0333	41.2120	56.6	21.30	...	...	0.51	...	...	
V5038.........	11.0117	41.3040	65.0	20.69	20.37	21.28	0.25	0.23	0.19	
V7280.........	11.0851	41.3495	75.6	21.16	...	...	0.33	...	...	V8038 D31C
V4627.........	11.0012	41.3400	83.4	21.50	19.53	...	0.48	0.26	...	V1296 D31C
V7103.........	11.0823	41.1845	86.3	21.68	20.02	...	0.40	0.42	...	
V1840.........	10.9453	41.3217	87.2	21.46	19.96	...	0.47	0.27	...	RV Tauri
V6963.........	11.0737	41.2648	95.4	20.86	19.58	22.10	0.23	0.13	0.25	
V2797.........	10.9687	41.2493	101.4	22.03	...	...	0.61	...	...	
V2805.........	10.9676	41.2914	133.8	21.28	19.15	22.16	0.46	0.20	0.10	

NOTE.—Variables V7280 and V4627 were also found in Paper III.

TABLE 4

DIRECT MISCELLANEOUS VARIABLES IN M31D

Name (D31D)	α (J2000.0) (deg)	δ (J2000.0) (deg)	$\bar{V}$	$\bar{I}$	$\bar{B}$	σ_V	σ_I	σ_B	Comments
V7086......	11.0768	41.3285	17.27	17.16	17.31	0.05	0.04	0.06	LBV
V6157......	11.0451	41.2538	19.52	18.02	...	0.99	0.50	...	
V5592......	11.0274	41.2601	19.52	16.72	21.55	0.17	0.08	0.08	LP
V776	10.9279	41.2452	19.61	16.77	...	0.12	0.05	...	LP
V7855......	11.1324	41.3190	19.87	17.18	21.72	0.22	0.13	0.06	LP
V3712......	10.9878	41.1934	19.89	16.66	...	0.27	0.12	...	LP
V2136......	10.9546	41.2046	21.00	17.67	...	0.54	0.92	...	LP
V5309......	11.0175	41.3357	21.01	19.21	...	0.79	0.43	...	V2679 D31C
V6371......	11.0498	41.3000	21.19	19.71	...	0.82	0.68	...	RV Tauri
V7949......	11.1451	41.2299	21.21	19.05	...	0.83	0.25	...	RV Tauri
V7725......	11.1228	41.2280	21.47	19.85	...	0.84	0.42	...	RV Tauri
V5323......	11.0175	41.3497	21.47	...	...	0.56	...	...	V2724 D31C
V4599......	11.0041	41.2206	21.54	19.34	...	0.40	0.45	...	RV Tauri

NOTE.—Variables V5309 and V5323 were also found in Paper III.

calibrated *BVI* magnitudes and their standard errors. The *BV* databases for M31D field contain 8016 stars, with up to 91 measurements in *V* and up to five measurements in *B*, and the *I* database contains 35,576 stars with up to 45 measurements. Figure 1 shows the distributions of stars as a function of mean *B*, *V*, or *I* magnitude. As can be seen from the shape of the histograms, our completeness starts to drop rapidly at about $\bar{B} \sim 23$, $\bar{V} \sim 22$, and $\bar{I} \sim 20.5$. The primary reason for this difference in the depth of the photometry between *BV* and *I* is the level of the combined sky and background light, which is about 3 times higher in the *I* filter than in the *BV* filters.

The measurements flagged as "bad" (with unusually large DAOPHOT errors, compared with other stars) and measurements with errors exceeding the average error, for a given star, by more than 4 σ are removed. Usually zero to five points are removed, leaving the majority of stars with roughly $N_{\rm good} \sim 85$–90 *V* measurements. For further analysis we use only those stars that have at least $N_{\rm good} > N_{\rm max}/2$ (=45) measurements. There are 5813 such stars in the *V* database of the M31D field.

Our next goal is to select a sample of variable stars from the total sample defined above. There are many ways to proceed, and we largely follow the approach of Stetson (1996), also described in Paper I. In short, for each star we compute the Stetson's variability index J_S (eq. [7] in Paper I), and stars with values exceeding some minimum value $J_{S,\rm min}$ are considered candidate variables. The definition of J_S is rooted in the assumption that on each visit to the program field at least one pair of observations is obtained, and only when both observations have the residual from the mean of the same sign does the pair contribute positively to the variability index. The definition of Stetson's variability index includes the standard errors of individual observations. If, for some reason, these errors were overestimated or underestimated, we would either miss real variables or select spurious variables as real ones. Using the procedure described in Paper I, we scale the DAOPHOT errors to better represent the "true" photometric errors. We then select the candidate variable stars by computing the value of J_S for the stars in our *V* database. We used a cutoff of $J_{S,\rm min} = 0.75$ and additional cuts described in Paper I to select 178 candidate variable stars (about 3% of the total number of 5813). In Figure 2, we plot the variability index J_S versus apparent visual magnitude $\bar{V}$ for 5813 stars with $N_{\rm good} > 45$.

5. PERIOD DETERMINATION AND CLASSIFICATION OF VARIABLES

We based our candidate variables selection on the *V*-band data collected at the MDM and the FLWO telescopes. We also have the *B*- and *I*-band data for the field, up to 45 *I*-band epochs and up to five *B*-band epochs, although for a variety of reasons some of the candidate variable stars do not have a *B*- or *I*-band counterpart. We will therefore not use the *BI* data for the period determination and broad classification of the variables. We will however use the *BI* data for the "final" classification of some variables.

Next we searched for the periodicities for all 178 candidate variables, using a variant of the Lafler-Kinman (1965) string-length technique proposed by Stetson (1996). Starting with the minimum period of 0.25 days, successive trial periods are chosen so

$$P_{j+1}^{-1} = P_j^{-1} - \frac{0.02}{\Delta t}\,, \qquad (1)$$

where $\Delta t = t_N - t_1 = 398$ days is the time span of the series. The maximum period considered is 150 days. For each candidate variable 10 best trial periods are selected (Paper I) and then used in our classification scheme.

The variables we are most interested in are Cepheids and eclipsing binaries (EBs). We therefore searched our sample of variable stars for these two classes of variables. As mentioned above, for the broad classification of variables we restricted ourselves to the *V* band data. We will, however, present and use the *B*- and *I*-band data, when available, when discussing some of the individual variable stars.

For EBs, we used the search strategy described in Paper II. Within our assumption, the light curve of an EB is determined by nine parameters: the period, the zero point of the phase, the eccentricity, the longitude of periastron, the radii of the two stars relative to the binary separation, the inclination angle, the fraction of light coming from the bigger star, and the uneclipsed magnitude. A total of seven variables passed all of the criteria. We then went back to the CCD frames and tried to see by eye if the inferred variability is indeed there, especially in cases when

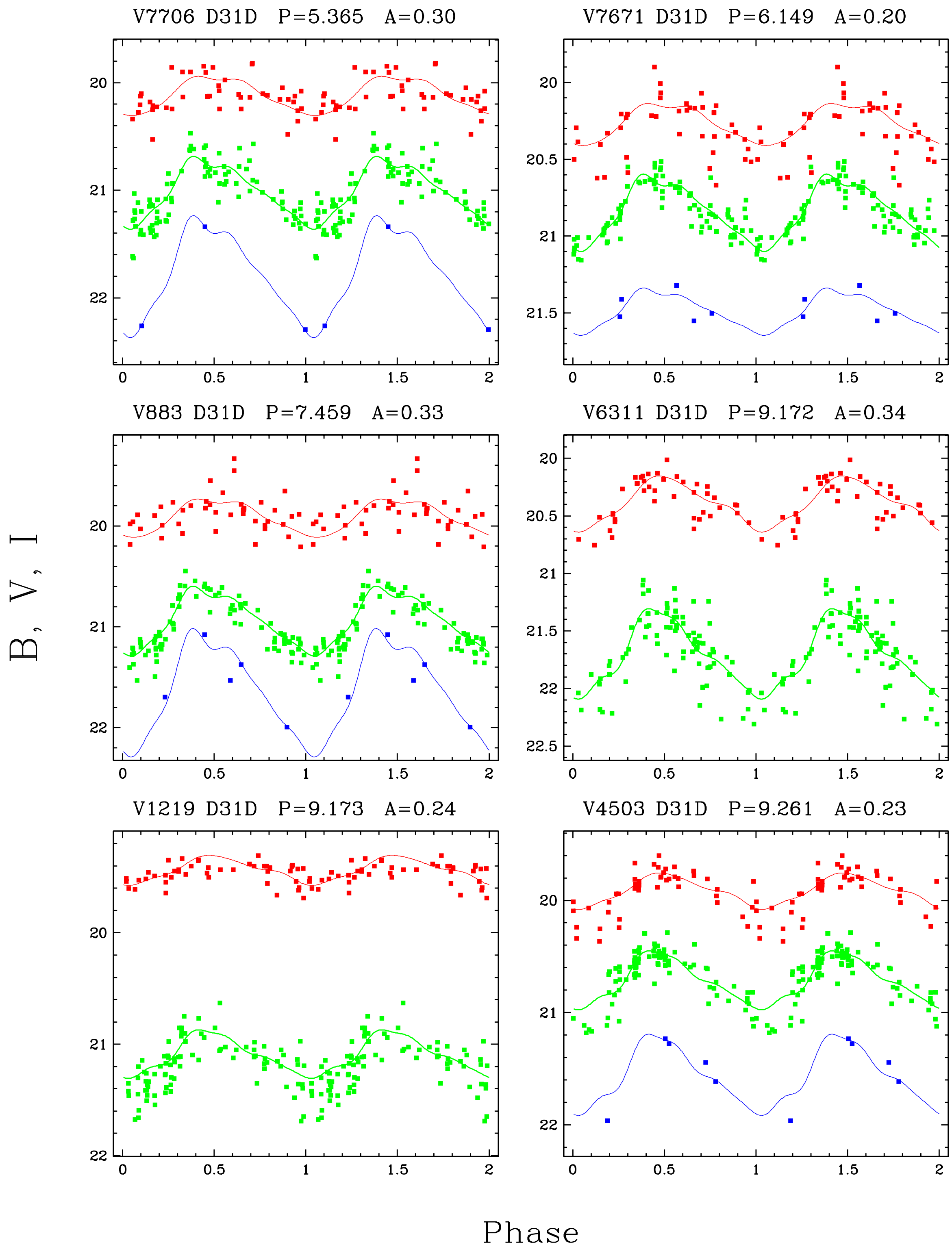

FIG. 4.—*BVI* light curves of Cepheid variables found in the field M31D. The thin solid line represents the best-fit Cepheid template for each star and photometric band. *B* (if present) is always the faintest, and *I* (if present) is always the brightest.

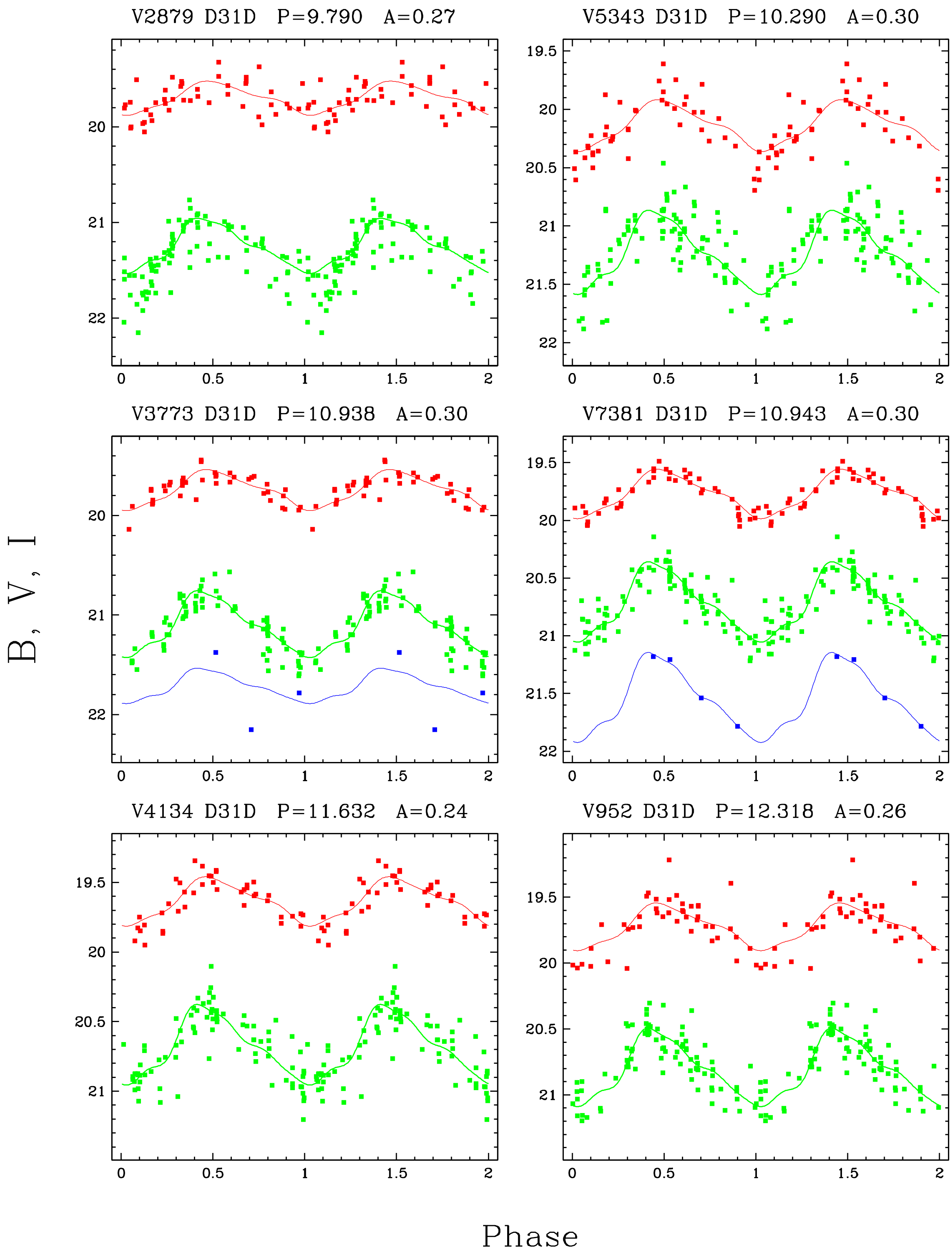

FIG. 4.—*Continued*

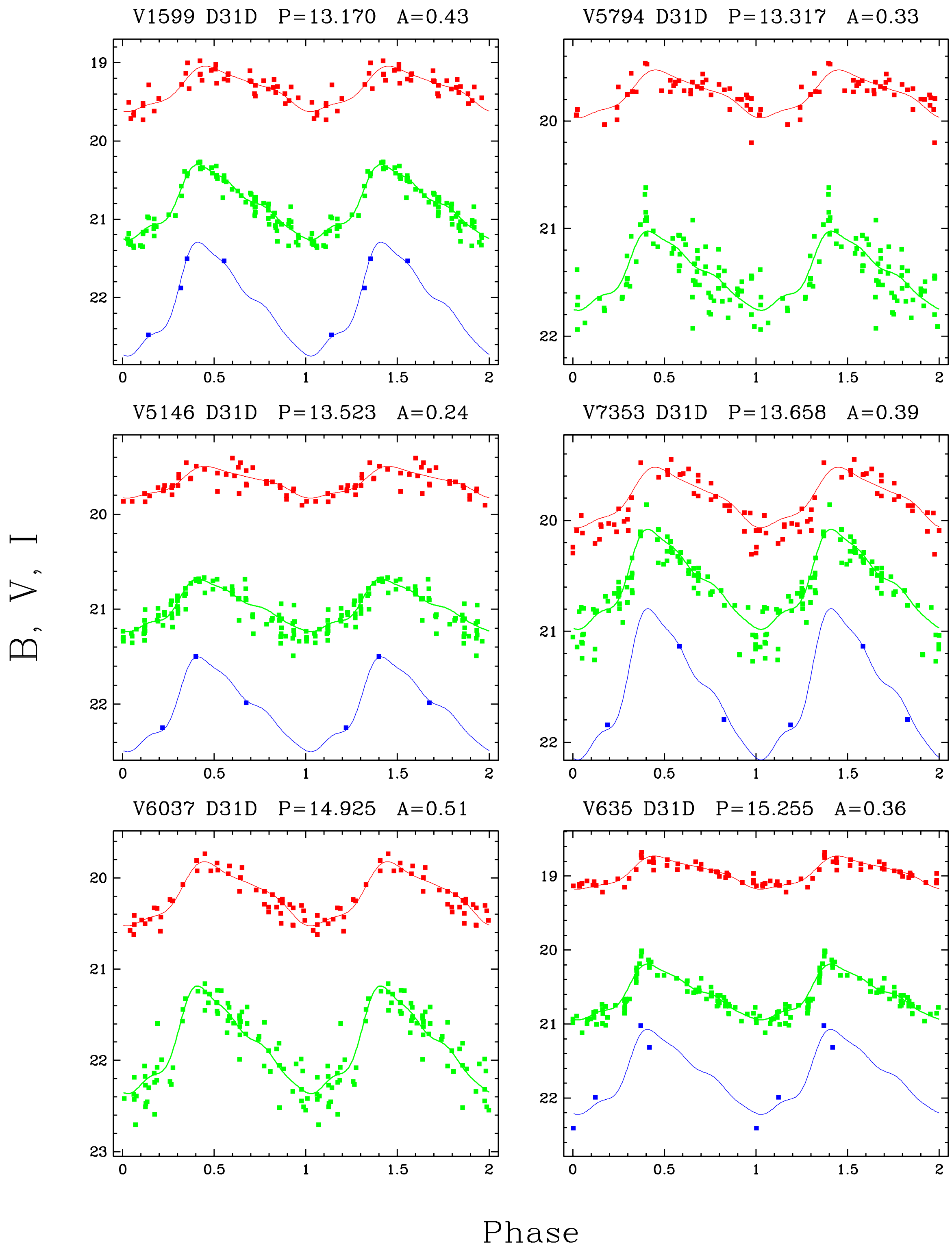

FIG. 4.—*Continued*

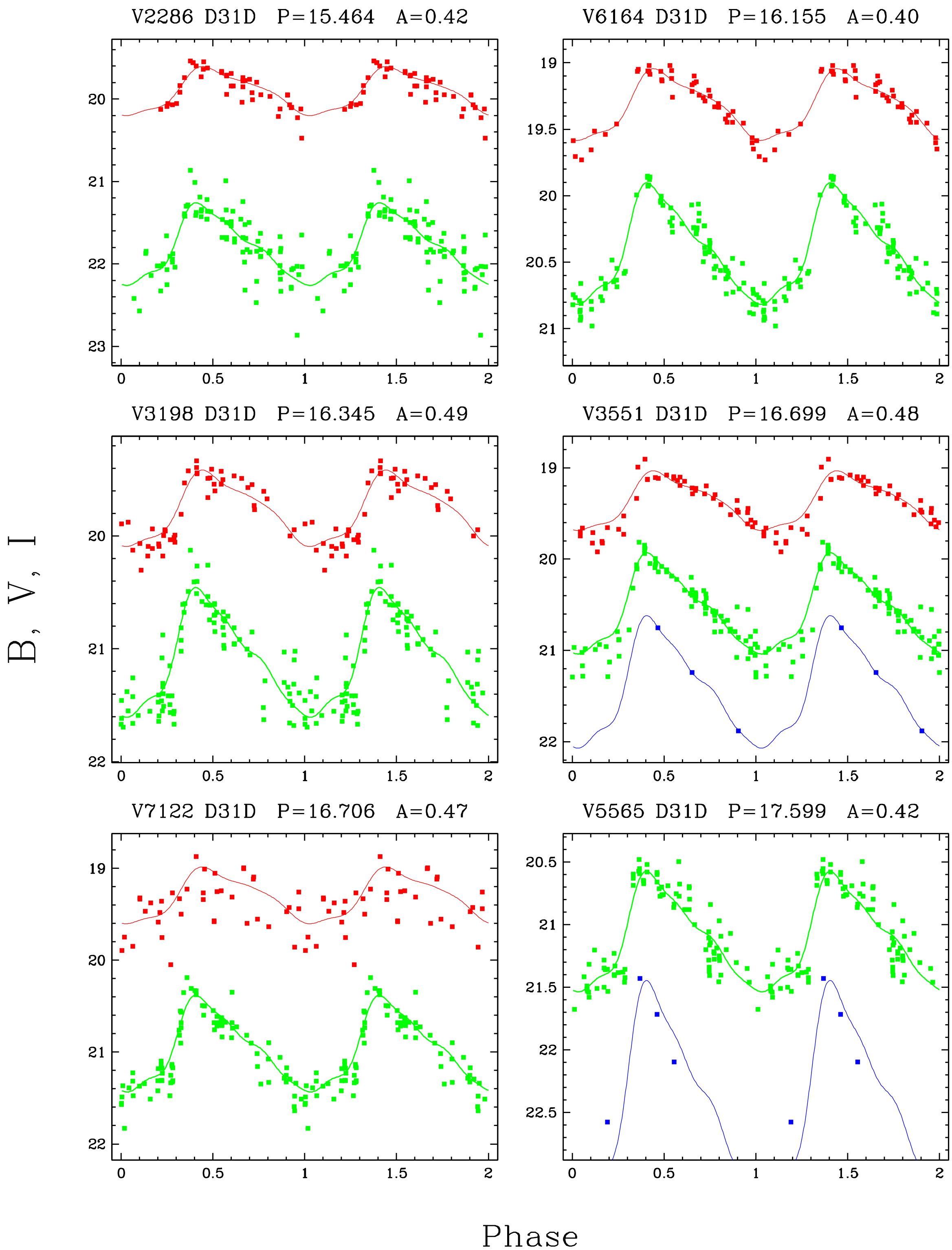

FIG. 4.—*Continued*

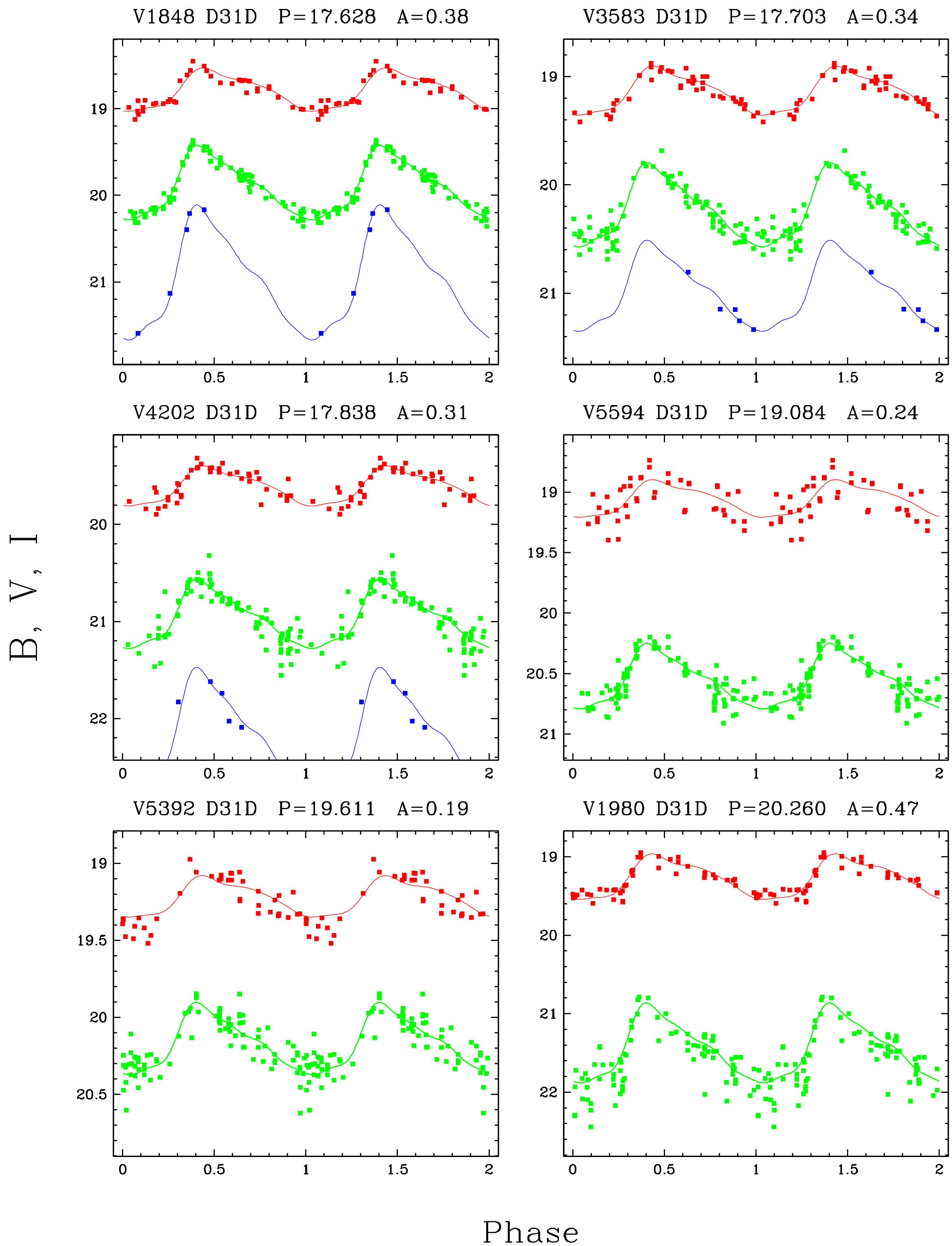

FIG. 4.—*Continued*

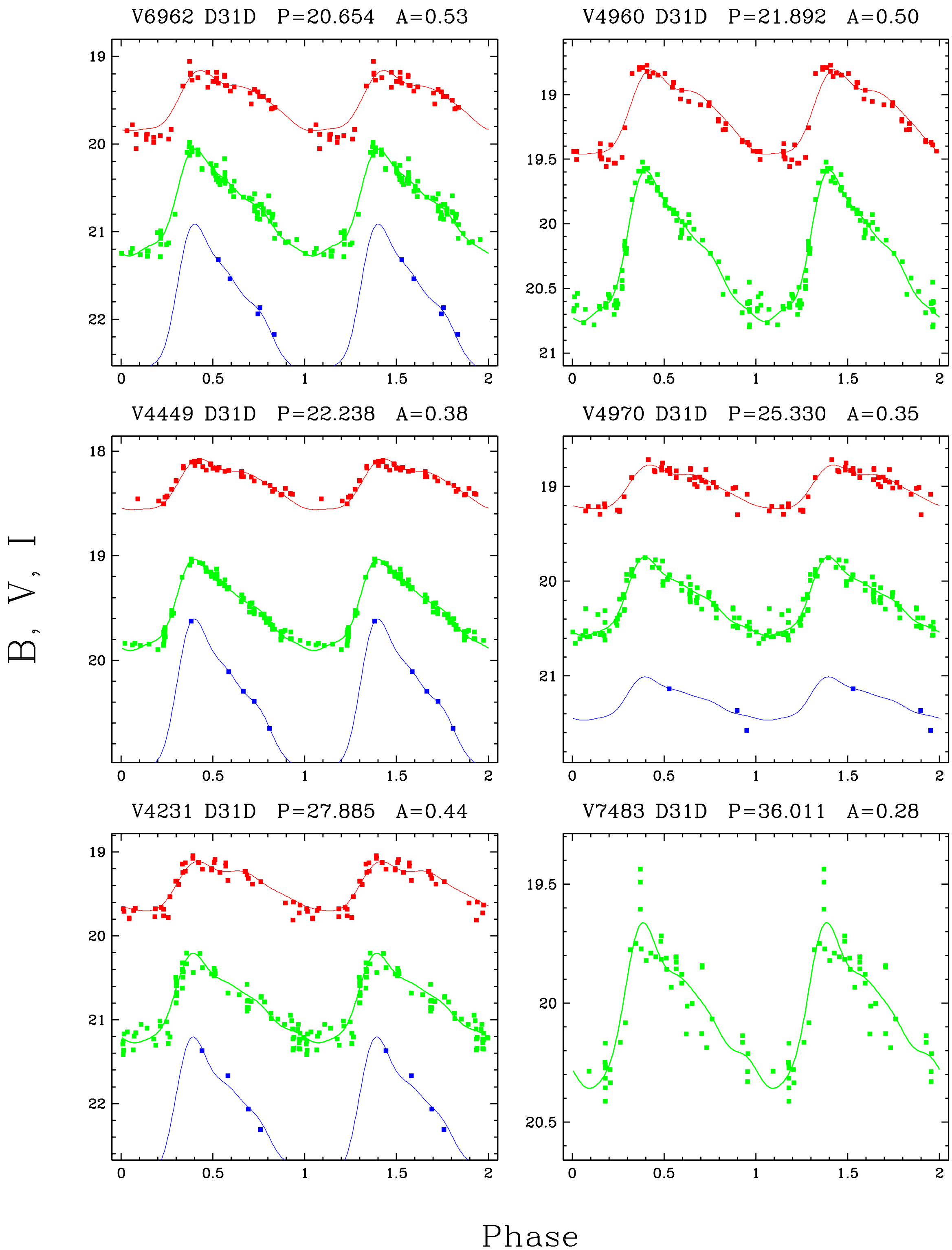

FIG. 4.—*Continued*

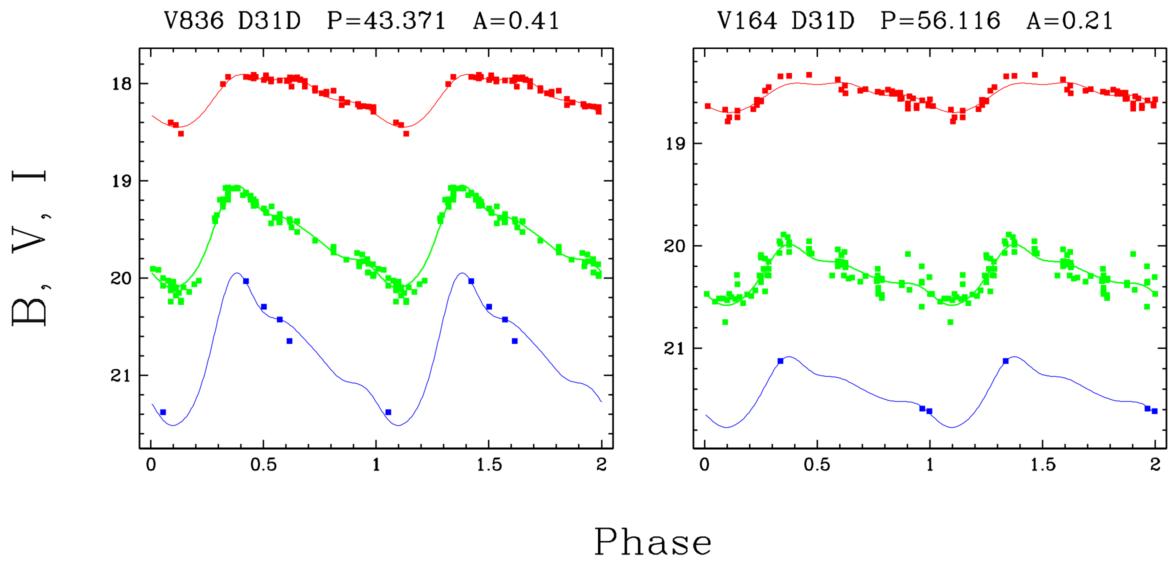

FIG. 4.—*Continued*

the light curve is very noisy/chaotic. We decided to remove two dubious eclipsing binaries. The remaining five EBs with their parameters and light curves are presented in § 6.1.

In the search for Cepheids we followed the approach by Stetson (1996) of fitting template light curves to the data. We used the parameterization of Cepheid light curves in the V band as given by Stetson (1996). There was a total of 65 variables passing all of the criteria (Papers I and II), but after investigating the CCD frames we removed 12 dubious "Cepheids," which leaves us with 53 probable Cepheids. Their parameters and light curves are presented in §§ 6.2 and 6.3.

After the preliminary selection of seven eclipsing binaries and 65 possible Cepheids, we were left with 106 "other" variable stars. After raising the threshold of the variability index to $J_{S,\min} = 1.2$ (Paper I), we are left with 25 variables. After investigating the CCD frames we removed 12 dubious variables from the sample, which leaves 13 variables, which we classify as miscellaneous. Their parameters and light curves are presented in § 6.4.

6. CATALOG OF VARIABLES

In this section we present light curves and some discussion of the 71 variable stars discovered by our survey in the field M31D.[5] The variable stars are named according to the following convention: letter "V" for "variable," the number of the star in the V database, then the letter "D" for our project, DIRECT, followed by the name of the field, in this case (M)31D, for example, V1599 D31D. Tables 1, 2, 3, and 4 list the variable stars sorted broadly by four categories: eclipsing binaries, Cepheids, other periodic variables, and "miscellaneous" variables, in our case meaning "variables with no clear periodicity." Some of the variables that were found independently by survey of Magnier et al. (1997, hereafter Ma97) are denoted in the "Comments" by "Ma97 ID," where the "ID" is the identification number assigned by Ma97. We also cross-identify several variables found by us in Paper III.

6.1. *Eclipsing Binaries*

In Table 1, we present the parameters of the five eclipsing binaries in the M31D field. The light curves of these variables are shown in Figure 3, along with the simple eclipsing binary models discussed in Papers I and II (see also Table 5). The variables are sorted in Table 1 by the increasing value of the period P. For each eclipsing binary we present its name, J2000.0 coordinates (in degrees), period P, magnitudes $V_{\max}$, $I_{\max}$, and $B_{\max}$ of the system outside of the eclipse, and the radii of the binary components R_1, R_2 in the units of the orbital separation. We also give the inclination angle of the binary orbit to the line of sight i and the eccentricity of the orbit e. The reader should bear in mind that the values of $V_{\max}$, $I_{\max}$, $B_{\max}$, R_1, R_2, i, and e are derived with a straightforward model of the eclipsing system, so they should be treated only as reasonable estimates of the "true" value.

6.2. *Cepheids*

In Table 2, we present the parameters of 38 Cepheids in the M31D field, sorted by the period P. For each Cepheid we present its name, J2000.0 coordinates, period P, flux-weighted mean magnitudes $\langle V \rangle$, the (when available) $\langle I \rangle$ and $\langle B \rangle$, and the V-band amplitude of the variation A. In Figure 4 we show the phased B, V, and I light curves of our Cepheids (see also Table 6). Also shown is the best-fit template light curve (Stetson 1996), which was fitted to the V data, and then for the I data only the zero-point offset was allowed. For the B-band data, lacking the template light-curve parameterization (Stetson 1996), we used the V-band template, allowing for different zero points and amplitudes. With our limited amounts of B-band data, this approach produces mostly satisfactory results, but extending the template-fitting approach of Stetson (1996) to the B band (and possibly other popular bands) would be most useful.

6.3. *Other Periodic Variables*

For many of the variables preliminarily classified as Cepheids we decided upon closer examination to classify them

[5] Complete V and (when available) BI photometry and 128 × 128 pixel (~40″ × 40″) V finding charts for all variables are available from the authors via the anonymous ftp from the Harvard-Smithsonian Center for Astrophysics and can also be accessed through the World Wide Web.

TABLE 5

LIGHT CURVES OF ECLIPSING BINARIES IN M31D

HJD − 2,450,000	Magnitude	σ_{mag}
V4520 D31D:		
B band:		
690.7929......	19.788	0.023
693.9048......	19.418	0.018
695.7549......	19.295	0.022
714.7865......	19.680	0.026
730.7500......	19.343	0.016
V4520 D31D:		
I band:		
341.8792......	19.624	0.104
348.7163......	19.623	0.115
349.7328......	19.488	0.086
349.7411......	19.513	0.098
350.8492......	19.634	0.102
350.8612......	19.691	0.118
351.7274......	19.601	0.113
351.7357......	19.836	0.144
353.6966......	19.761	0.175
353.6979......	19.596	0.272
354.9825......	19.744	0.156
355.8411......	19.587	0.109
355.8587......	19.694	0.160
358.7993......	19.682	0.100
358.8084......	19.731	0.104
359.9375......	19.432	0.092
364.9444......	19.618	0.109
644.9274......	19.553	0.107
645.8658......	19.633	0.113
647.8768......	19.511	0.111
647.8851......	19.529	0.109
651.8621......	19.564	0.267
652.8045......	19.693	0.275
653.8278......	19.725	0.122
660.8323......	19.448	0.078
665.8405......	19.437	0.115
672.8877......	19.518	0.113
673.8711......	19.707	0.104
674.8805......	19.526	0.094
679.7961......	19.645	0.115
682.9112......	19.586	0.122
683.8939......	19.744	0.144
688.8610......	19.506	0.111
690.8256......	19.896	0.304
693.8964......	19.557	0.100
695.8309......	19.533	0.104
708.9199......	19.728	0.122
708.9282......	19.705	0.169
709.9008......	19.557	0.142
710.8866......	19.586	0.105
711.8740......	19.800	0.162

NOTE.—Table 5 is presented in its entirety in the electronic edition of the Astronomical Journal. A portion is shown here for guidance regarding its form and content.

TABLE 6

LIGHT CURVES OF CEPHEIDS IN M31D

HJD − 2,450,000	Magnitude	σ_{mag}
V164 D31D:		
B band:		
693.9048......	21.590	0.121
695.7549......	21.614	0.140
714.7865......	21.124	0.085
V164 D31D:		
I band:		
341.8792......	18.483	0.039
348.7163......	18.475	0.048
349.7328......	18.489	0.044
349.7411......	18.512	0.044
350.8492......	18.506	0.046
350.8612......	18.517	0.046
351.7274......	18.566	0.048
351.7357......	18.504	0.042
353.6966......	18.608	0.050
353.6979......	18.658	0.070
354.9825......	18.558	0.053
355.8411......	18.656	0.053
355.8587......	18.629	0.059
358.7993......	18.628	0.046
358.8084......	18.612	0.046
359.9375......	18.634	0.046
364.9444......	18.784	0.046
644.9274......	18.669	0.046
645.8658......	18.747	0.059
647.8768......	18.681	0.063
647.8851......	18.742	0.057
651.8621......	18.666	0.079
652.8045......	18.625	0.072
653.8278......	18.587	0.057
660.8323......	18.341	0.031
665.8405......	18.332	0.059
672.8877......	18.374	0.046
673.8711......	18.476	0.035
674.8805......	18.510	0.046
679.7961......	18.471	0.046
682.9112......	18.496	0.059
683.8939......	18.505	0.048
688.8610......	18.558	0.053
690.8256......	18.538	0.070
693.8964......	18.579	0.042
695.8309......	18.571	0.050
708.9199......	18.574	0.061
708.9282......	18.573	0.061
709.9008......	18.580	0.066
710.8866......	18.483	0.048
711.8740......	18.449	0.046
714.8135......	18.344	0.039
730.7772......	18.435	0.037

NOTE.—Table 6 is presented in its entirety in the electronic edition of the Astronomical Journal. A portion is shown here for guidance regarding its form and content.

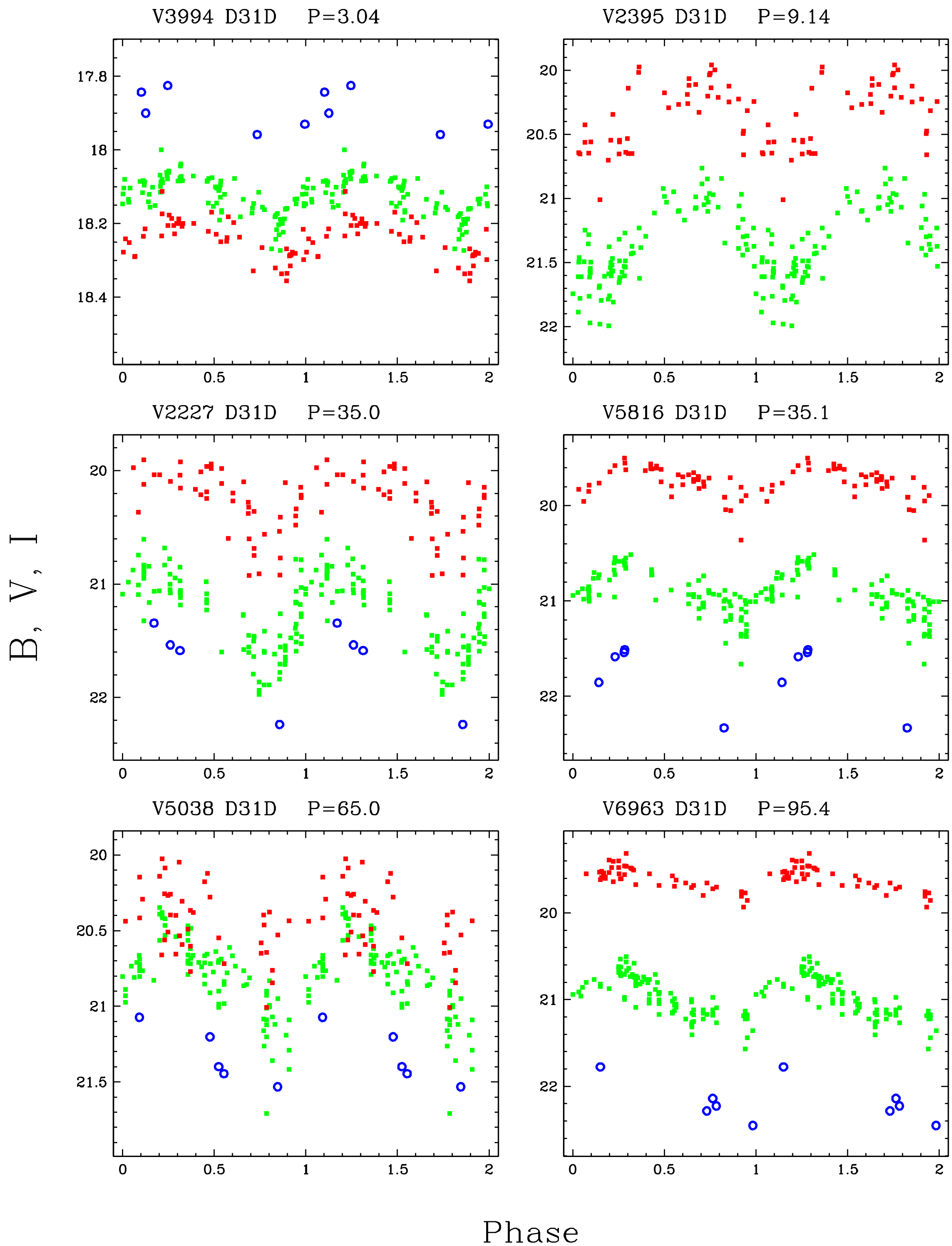

FIG. 5.—*BVI* light curves selected other periodic variables found in the field M31D. *B*-band data (*open circles*, if present) are usually the faintest, and *I*-band data (if present) are usually the brightest.

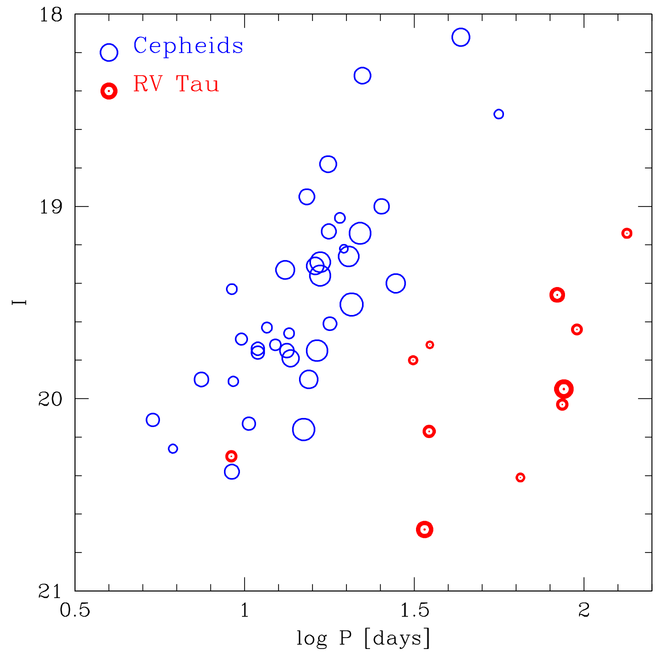

FIG. 6.—Diagram of log P vs. I for the Cepheids (*open circles*) and RV Tauri (*dotted circles*) variables. The sizes of the circles are proportional to the V amplitude of the variability.

as "other periodic variables." In Table 3, we present the parameters of 15 possible periodic variables, other than Cepheids and eclipsing binaries, in the M31D field, sorted by the increasing period P. In Figure 5 we show several phased BVI light curves selected from the sample of the other periodic variables (see also Table 7). For each variable we present its name, J2000.0 coordinates, period P, error-weighted mean magnitudes V, and (when available) I and B. To quantify the amplitude of the variability, we also give the standard deviations of the measurements in the BVI bands, σ_V, σ_I, and σ_B.

Note that in most cases the periods were derived by fitting the template Cepheids light curves so they should only be treated as the first approximation of the true period. Many of these periodic variables are Type II Cepheids (W Virginis and RV Tauri variables), based on their light curves and their location on the P-L diagram (Fig. 6). One of the variables, V3994 D31D, as its location in the color-magnitude diagram (CMD) suggests, is probably an eclipsing binary.

6.4. *Miscellaneous Variables*

In Table 4, we present the parameters of 13 miscellaneous variables in the M31D field, sorted by increasing value of the mean magnitude V. In Figure 7, we show several unphased VI light curves selected from the sample of the miscellaneous variables (see also Table 8). For each variable we present its name, J2000.0 coordinates and mean magnitudes V, I, and B. To quantify the amplitude of the variability, we also give the standard deviations of the measurements in BVI bands, σ_V, σ_I, and σ_B. In the "Comments" column we give a rather broad subclassification of the variability: LP, possible long-period variable; LBV; and RV Tauri.

Many of the miscellaneous variables seem to represent the LP type of variability. V7086 D31D is probably a luminous blue variable. However, inspection of the CMD (Fig. 8) reveals that some of the miscellaneous variables land in the CMD in the same area as the RV Tauri variables, which suggests that they are Type II Cepheids.

6.5. *Comparison with Other Catalogs*

The area of M31D field has not been observed frequently before, and the only overlapping variable star catalog is given by Ma97. Out of the nine variable stars in Ma97 that are in our M31D field, we cross-identified all nine, also classifying them as Cepheids (see Table 2 for cross-identifications).

There was also by design a slight overlap between the M31D and M31C fields (Fig. 9). There were three Cepheids from the M31D field in the overlap region, and they were all cross-identified in the M31C catalog with very similar properties of their light curves (see Table 2). Out of the remaining four Cepheids given in Paper III, one, V11190 D31C, failed to qualify as a variable candidate, with $J_S = 0.294$; the other three were found to be missing from the template. We also cross-identified two other periodic variables found in the overlap (see Table 3). Two miscellaneous variables in the M31D field were cross-identified with periodic variables in the M31C field (see Table 4). None of the five miscellaneous variables detected in the overlapping part of the M31C field were classified as variable stars in the M31D field. Four of them had $N_{\rm good} < 45$. One turned out to have $\sigma = 0.03$, thus very narrowly failing to qualify as a variable.

7. DISCUSSION

In Figure 8, we show V, $V-I$ and V, $B-V$ CMDs for the variable stars found in the field M31D. The eclipsing binaries and Cepheids (*left*) and the other periodic variables and miscellaneous variables (*right*). As expected, the eclipsing binaries occupy the blue upper main sequence of M31 stars. The Cepheid variables group near $B-V \sim 1.0$, with considerable scatter probably due to the differential reddening across the field. The other periodic variable stars have positions on the CMD similar to the Cepheids, with

TABLE 7

LIGHT CURVES OF OTHER PERIODIC VARIABLES IN M31D

HJD − 2,450,000	Magnitude	σ_{mag}
V1840 D31D:		
I band:		
341.8792……	19.926	0.117
348.7163……	19.810	0.172
349.7328……	20.413	0.321
349.7411……	20.517	0.215
350.8492……	20.395	0.187
350.8612……	20.184	0.142
351.7274……	19.971	0.174
351.7357……	20.063	0.142
353.6966……	20.251	0.358
353.6979……	20.185	0.337
354.9825……	20.109	0.204
355.8411……	20.119	0.177
355.8587……	19.963	0.142
358.7993……	20.330	0.198
358.8084……	20.426	0.185
359.9375……	20.344	0.194
364.9444……	20.215	0.189
644.9274……	19.764	0.103
645.8658……	19.778	0.121
647.8768……	19.749	0.134
647.8851……	19.826	0.121
648.8506……	19.741	0.329
648.8589……	19.708	0.366
651.8621……	19.664	0.183
652.8045……	20.072	0.219
653.8278……	19.719	0.130
660.8323……	19.760	0.117
665.8405……	19.806	0.187
672.8877……	19.806	0.168
673.8711……	19.764	0.114
674.8805……	19.787	0.112
679.7961……	19.740	0.128
682.9112……	20.079	0.191
683.8939……	20.013	0.170
688.8610……	19.801	0.141
690.8256……	19.786	0.215
693.8964……	20.085	0.138
695.8309……	19.963	0.141
708.9199……	20.426	0.376
708.9282……	20.468	0.402
709.9008……	20.313	0.316
710.8866……	20.343	0.215
711.8740……	20.487	0.373
714.8135……	20.521	0.217
730.7772……	20.292	0.185
V1840 D31D:		
V band:		
334.8022……	21.930	0.146

NOTE.—Table 7 is presented in its entirety in the electronic edition of the Astronomical Journal. A portion is shown here for guidance regarding its form and content.

TABLE 8

LIGHT CURVES OF MISCELLANEOUS VARIABLES IN M31D

HJD − 2,450,000	Magnitude	σ_{mag}
V776 D31D:		
I band:		
341.8792……	16.850	0.023
348.7163……	16.803	0.023
349.7328……	16.784	0.020
349.7411……	16.800	0.020
350.8492……	16.782	0.020
350.8612……	16.807	0.023
351.7274……	16.803	0.020
351.7357……	16.784	0.020
353.6966……	16.824	0.017
353.6979……	16.812	0.020
354.9825……	16.797	0.020
355.8411……	16.804	0.017
355.8587……	16.806	0.017
358.7993……	16.806	0.023
358.8084……	16.794	0.023
359.9375……	16.773	0.017
644.9274……	16.684	0.020
645.8658……	16.719	0.014
647.8768……	16.726	0.020
647.8851……	16.715	0.023
648.8506……	16.732	0.023
648.8589……	16.725	0.023
651.8621……	16.728	0.023
652.8045……	16.716	0.020
653.8278……	16.708	0.020
660.8323……	16.714	0.017
665.8405……	16.720	0.029
672.8877……	16.737	0.020
673.8711……	16.726	0.029
674.8805……	16.726	0.020
679.7961……	16.757	0.023
682.9112……	16.751	0.026
683.8939……	16.715	0.029
688.8610……	16.774	0.017
690.8256……	16.790	0.023
693.8964……	16.777	0.020
695.8309……	16.777	0.023
708.9199……	16.828	0.023
708.9282……	16.822	0.026
709.9008……	16.820	0.023
710.8866……	16.826	0.023
711.8740……	16.810	0.023
714.8135……	16.814	0.023
730.7772……	16.875	0.020
V776 D31D:		
V band:		
334.8022……	19.829	0.055
337.8149……	19.749	0.053

NOTE.—Table 8 is presented in its entirety in the electronic edition of the Astronomical Journal. A portion is shown here for guidance regarding its form and content.

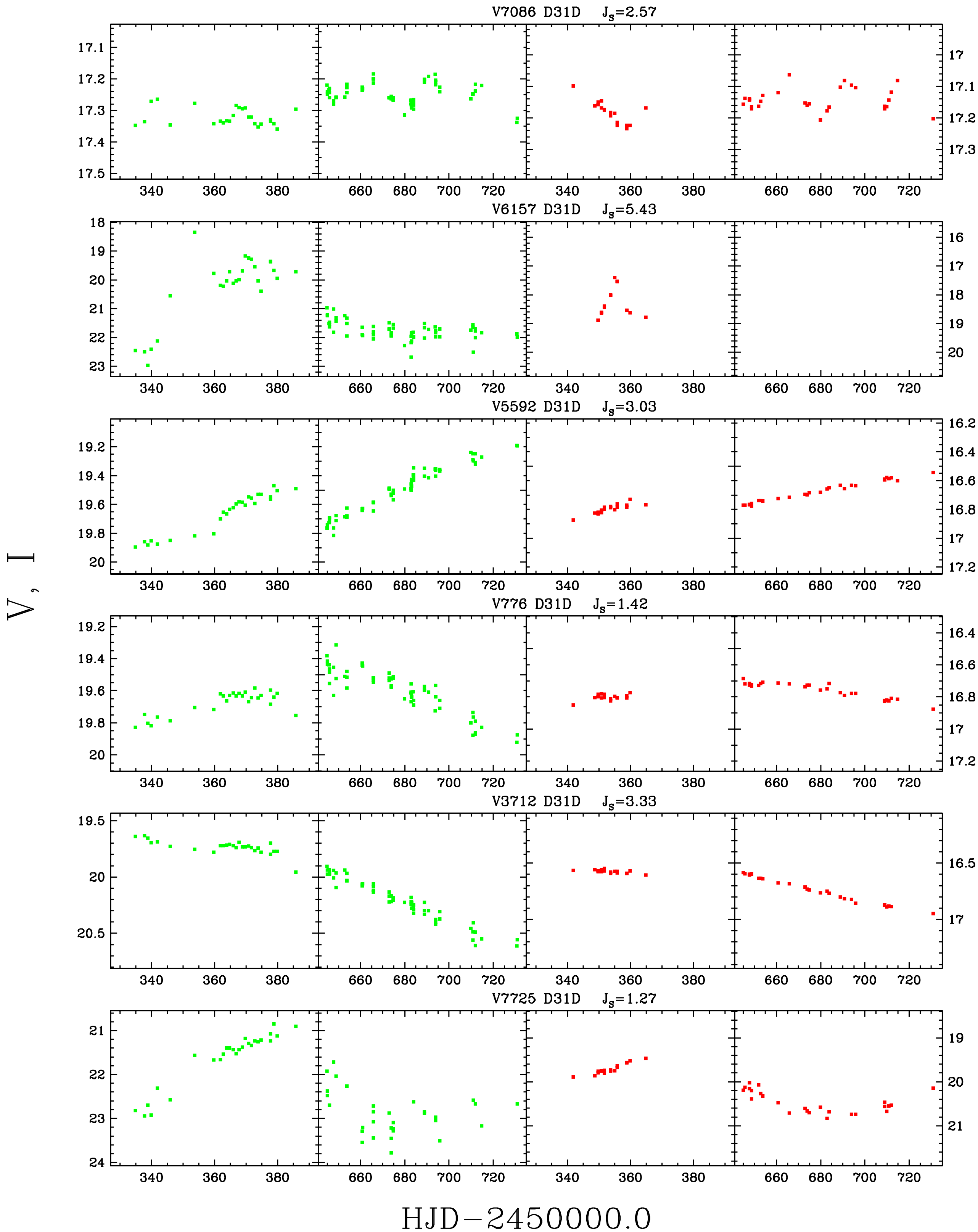

FIG. 7.—*VI* light curves of selected miscellaneous variables found in the field M31D. If present, *I* is plotted in the two right-hand panels. *B*-band data are not shown.

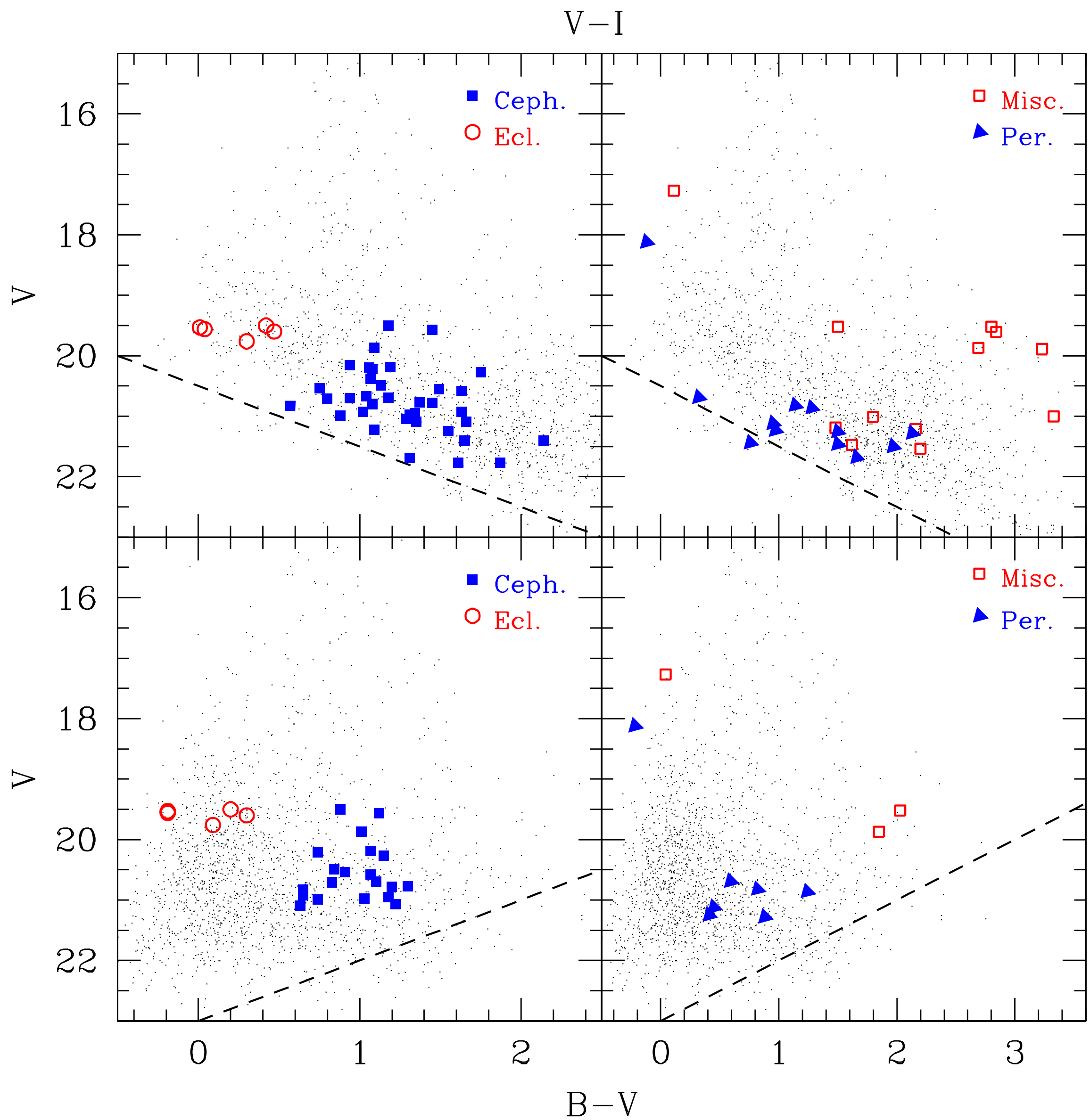

FIG. 8.—V, $V-I$ (*top*) and B, $B-V$ (*bottom*) CMDs for the variable stars found in the field M31D. The eclipsing binaries and Cepheids (*left*) and the other periodic variables and miscellaneous variables (*right*) are shown. The dashed lines correspond to the I detection limit of $I \sim 20.5$ mag (*top*) and the B detection limit of $B \sim 23$ mag (*bottom*).

the exception of V3994 D31D, which is probably an eclipsing binary. The miscellaneous variables are scattered throughout the CMDs and represent several classes of variability. Many of them are very red, with $V-I > 2.0$, and are probably Mira variables. The brightest miscellaneous variable is probably a foreground star belonging to our Galaxy.

In Figure 9, we plot the location of eclipsing binaries and Cepheids in the fields M31D and M31C, along with the blue stars ($B-V < 0.4$) selected from the photometric survey of M31 by Magnier et al. (1992) and Haiman et al. (1994). The sizes of the circles representing the Cepheids variables are proportional to the logarithm of their period. As could have been expected, both types of variables group along the spiral arms, as they represent relatively young populations of stars. We will explore various properties of our sample of Cepheids in a future paper (Sasselov et al. 1999).

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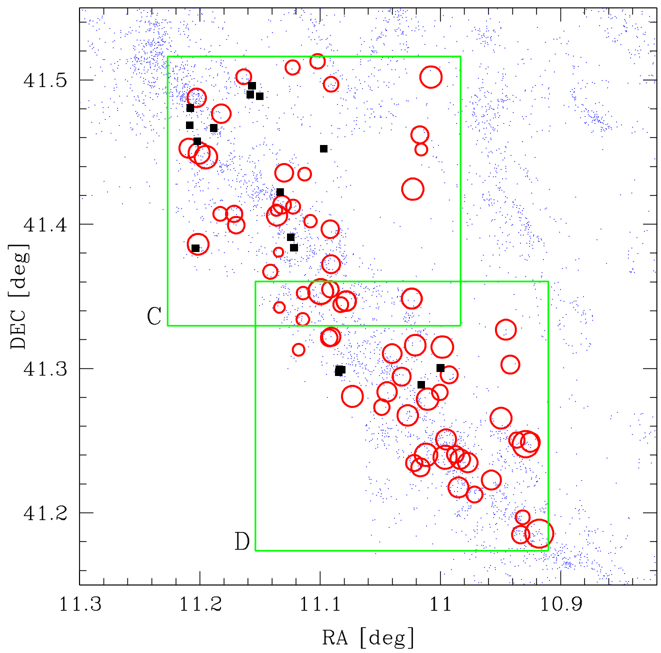

FIG. 9.—Location of eclipsing binaries (*filled squares*) and Cepheids (*open circles*) in the fields M31D and M31C, along with the blue stars ($B-V < 0.4$) selected from the photometric survey of M31 by Magnier et al. (1992) and Haiman et al. (1994). The sizes of the circles representing the Cepheids variables are proportional to the logarithm of their period.

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