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DIRECT DISTANCES TO NEARBY GALAXIES USING DETACHED ECLIPSING BINARIES AND CEPHEIDS. II. VARIABLES IN THE FIELD M31A[1]

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ABSTRACT

We have undertaken 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 January we obtained 36 full nights on the Michigan-Dartmouth-MIT Observatory 1.3 m telescope and 45 full/partial nights on the F. L. Whipple Observatory 1.2 m telescope to search for DEBs and new Cepheids in the M31 and M33 galaxies. In this paper, second in a series, we present the catalog of variable stars, most of them newly detected, found in the field M31A [$(\alpha, \delta) = (11.^\circ34, 41.^\circ73)$, J2000.0]. We have found 75 variable stars: 15 eclipsing binaries, 43 Cepheids, and 17 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 CCD frames are available upon request.

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

1. INTRODUCTION

The two nearby galaxies M31 and M33 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.

Detached eclipsing binaries (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 RR Lyrae and Cepheid distance indicators (see, e.g., Huterer, Sasselov, & Schechter 1995). 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 (see the papers from the recent "Debate on the Scale of the Universe": Tammann 1996; van den Bergh 1996).

The detached eclipsing binaries have yet to be used (Huterer et al. 1995; Hilditch 1996) as distance indicators to M31 and M33. According to Hilditch (1996), there are about 60 eclipsing binaries of all kinds known in M31 (Gaposchkin 1962; Baade & Swope 1963, 1965) and only *one* in M33 (Hubble 1929). 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). In the 1980s, Freedman & Madore (1990) and Freedman, Wilson, & Madore (1991) studied small samples of the earlier discovered Cepheids, to build period-luminosity (P-L) relations in M31 and M33, respectively. However, both the sparse photometry and the small samples do not provide a good basis for obtaining direct Baade-Wesselink distances (see, e.g., Krockenberger, Sas-

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selov, & Noyes 1997) to Cepheids—the need for new digital photometry has been long overdue. Recently, Magnier et al. (1997) surveyed large portions of M31, which 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), the first paper of the series, we presented a catalog of variable stars found in one of the fields in M31, called M31B. Here we present a catalog of variables from the neighboring field M31A. 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 discuss briefly 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.

2. FIELD 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. Some data for M31 were also obtained with the 1.2 m telescope at the F. L. Whipple Observatory (FLWO), where we used "AndyCam," with a thinned, back-side–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 Paper I, Fig. 1). We selected six 11′ × 11′ fields, M31A–M31F, with 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 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 occasionally observed at the FLWO 1.2 m telescope, whose main target was M33.

In this paper, we present the results for the M31A field. We obtained for this field useful data during 29 nights at the MDM Observatory, collecting a total of 109 × 900 s exposures in *V*, 27 × 600 s exposures in *I*, and 2 × 1200 s exposures in *B*. We also obtained for this field useful data during 15 nights at the FLWO, collecting a total of 8 × 900 s exposures in *V* and 18 × 600 s exposures in *I*.[3]

3. DATA REDUCTION, CALIBRATION, AND ASTROMETRY

The details of the reduction procedure are given in Paper I. Preliminary processing of the CCD frames was performed 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

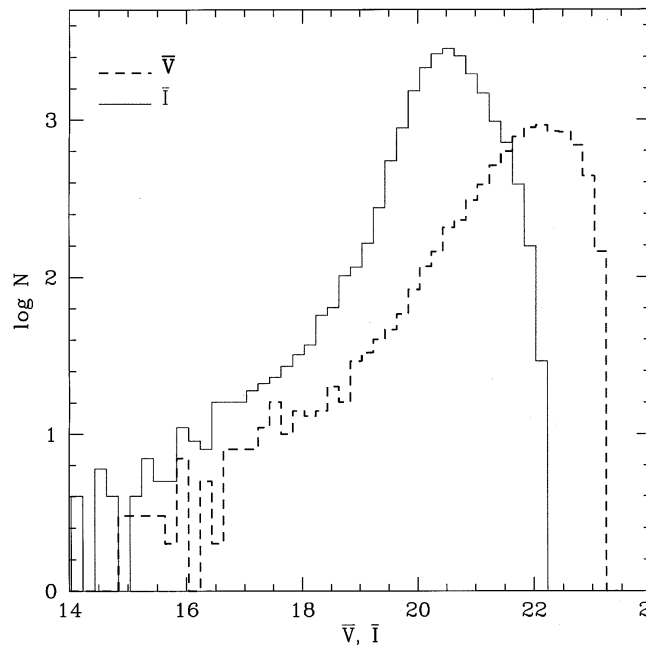

FIG. 1.—Distributions in *V* (*dashed line*) and *I* (*solid line*) of stars in the field M31A.

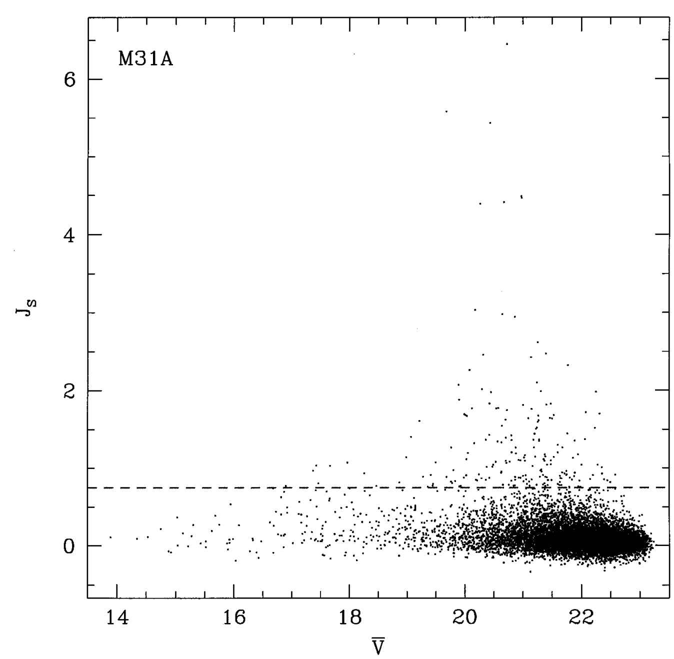

FIG. 2.—Variability index J_S vs. mean *V* magnitude for 8521 stars in the field M31A with $N_{good} > 58$. The dashed line at $J_S = 0.75$ defines the cutoff applied for variability.

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

TABLE 1

DIRECT ECLIPSING BINARIES IN M31A

Name (D31A)	α (J2000.0) (deg)	δ (J2000.0) (deg)	J_S	P (days)	V_{max}	I_{max}	R_1	R_2	i (deg)	e	Comments
V1555......	11.2717	41.6462	1.07	0.917	20.64	...	0.59	0.41	76	0.00	V6913 D31B
V9936......	11.4523	41.7306	0.77	0.930	21.33	...	0.65	0.34	61	0.06	
V4741......	11.3337	41.7511	1.43	1.604	20.35	20.16	0.51	0.40	73	0.03	
V8420......	11.4072	41.7188	1.21	1.931	20.71	20.58	0.42	0.37	74	0.04	DEB?
V6024......	11.3611	41.6841	0.83	2.083	20.93	...	0.38	0.37	69	0.00	DEB
V7393......	11.3851	41.7951	0.85	2.786	20.14	...	0.35	0.31	80	0.03	DEB
V6450......	11.3681	41.7400	1.39	3.076	20.60	20.63	0.56	0.44	67	0.04	
V6527......	11.3671	41.8256	0.84	4.180	20.77	...	0.31	0.31	76	0.01	
V5912......	11.3563	41.7510	0.88	5.006	19.92	...	0.67	0.33	61	0.01	
V9840......	11.4495	41.7034	0.78	5.215	21.51	...	0.63	0.36	75	0.03	
V8153......	11.4026	41.6701	0.87	5.794	21.49	20.36	0.56	0.44	83	0.14	Cepheid?
V5407......	11.3464	41.7504	1.02	7.061	20.33	19.51	0.51	0.44	57	0.02	
V538	11.2420	41.6695	0.85	7.171	21.07	20.44	0.59	0.40	66	0.00	
V4636......	11.3321	41.7514	0.80	8.181	19.44	19.43	0.14	0.14	83	0.18	DEB
V6423......	11.3671	41.7533	0.85	11.782	20.80	19.89	0.54	0.46	57	0.15	

NOTES.—V4636 D31A, with period $P = 8.181$ days, is a good detached eclipsing binary (DEB) candidate, with significant eccentricity. V1555 D31A was found as V6913 D31B in Paper I, with identical period, $V_{max} = 20.63$ and $I_{max} = 20.06$.

TABLE 2

DIRECT CEPHEIDS IN M31A

Name (D31A)	α (J2000.0) (deg)	δ (J2000.0) (deg)	J_S	P (days)	$\langle V \rangle$	$\langle I \rangle$	A	Comments
V3885......	11.3176	41.7868	1.13	3.801	21.84	21.62	0.34	
V4585......	11.3337	41.6685	1.18	3.953	22.01	21.69	0.44	
V8435......	11.4083	41.6933	1.05	4.097	22.01	21.35	0.43	
V3071......	11.3036	41.6866	1.05	4.557	21.48	...	0.23	
V8798......	11.4135	41.8081	1.36	4.861	22.06	...	0.38	
V9833......	11.4461	41.7914	1.60	4.867	21.20	20.19	0.29	
V9531......	11.4361	41.7111	1.69	4.869	21.52	20.54	0.36	
V7466......	11.3867	41.7830	1.15	5.007	21.40	20.70	0.29	
V3584......	11.3125	41.7674	0.80	5.020	21.09	20.12	0.14	
V6800......	11.3780	41.6476	0.91	5.077	21.79	...	0.35	
V5348......	11.3479	41.6677	1.65	5.346	21.57	20.74	0.41	
V8573......	11.4116	41.7128	1.35	5.476	21.37	20.49	0.32	Ma97 125
V8232......	11.4011	41.7727	1.37	5.681	21.15	19.87	0.27	Ma97 124
V589	11.2430	41.6840	2.42	6.192	21.21	20.24	0.40	
V3142......	11.3047	41.7006	1.83	6.244	21.49	21.08	0.38	
V2770......	11.2952	41.7592	1.62	6.413	21.23	20.45	0.29	
V6842......	11.3770	41.7058	1.20	6.482	21.63	20.78	0.30	
V9473......	11.4337	41.7366	1.76	6.582	21.14	20.21	0.32	Ma97 127
V5188......	11.3438	41.7022	1.52	6.776	21.30	20.38	0.23	Ma97 111
V1416......	11.2661	41.6983	2.98	6.925	20.62	19.56	0.28	
V3568......	11.3117	41.7760	2.10	7.165	21.28	20.72	0.35	
V5968......	11.3586	41.7275	1.64	8.519	21.11	20.04	0.24	Ma97 114
V2242......	11.2854	41.7508	1.12	8.680	21.45	20.50	0.26	
V7523......	11.3917	41.6581	1.82	8.709	21.04	20.42	0.24	Ma97 121
V2276......	11.2886	41.6656	1.42	9.803	20.85	19.70	0.17	V7553 D31B
V1791......	11.2763	41.6948	3.04	10.011	20.33	19.57	0.26	
V6363......	11.3683	41.6595	1.18	10.593	21.39	20.00	0.26	Ma97 117
V4733......	11.3324	41.7888	1.99	10.971	21.36	20.10	0.35	
V9029......	11.4211	41.7472	2.95	11.668	20.81	19.70	0.32	Ma97 126
V107	11.2255	41.7051	4.41	12.525	20.56	19.65	0.37	
V4104......	11.3261	41.6504	1.45	12.557	21.20	19.98	0.23	
V3407......	11.3085	41.7645	4.39	12.801	20.23	19.39	0.39	
V8530......	11.4076	41.8088	0.79	12.809	21.37	20.17	0.22	
V8882......	11.4152	41.8081	1.51	13.097	21.18	19.75	0.35	
V4407......	11.3308	41.6660	1.70	14.112	19.97	19.14	0.14	
V6759......	11.3772	41.6576	6.45	15.479	20.39	19.39	0.51	Ma97 118
V5760......	11.3544	41.7088	4.49	16.608	20.78	19.67	0.44	
V5614......	11.3509	41.7351	5.43	20.18	20.42	19.36	0.38	Ma97 113
V4452......	11.3319	41.6506	1.37	26.59	21.52	19.51	0.38	
V6165......	11.3632	41.6997	5.58	28.76	20.00	18.82	0.43	Ma97 116
V4711......	11.3361	41.6596	1.15	32.29	21.50	20.05	0.38	
V5415......	11.3483	41.6933	4.46	37.06	20.58	19.00	0.48	Ma97 112
V9679......	11.4405	41.7749	2.46	42.55	20.15	18.74	0.33	Ma97 129

NOTE.—Variable V2276 D31A (Ma97 108) was found as V7553 D31B in Paper I, with period $P = 9.482$ days, $\langle V \rangle = 20.93$, and $\langle I \rangle = 19.77$.

TABLE 3

DIRECT OTHER PERIODIC VARIABLES IN M31A

Name (D31A)	α (J2000.0) (deg)	δ (J2000.0) (deg)	J_S	P (days)	$\bar{V}$	$\bar{I}$	σ_V	σ_I	Comments
V1494......	11.2659	41.7755	1.30	23.15	21.56	...	0.33	...	
V410.......	11.2355	41.7199	1.10	28.62	20.92	...	0.13	...	
V1911......	11.2800	41.6786	1.68	36.74	19.99	19.25	0.12	0.14	RV Tau?
V3368......	11.3104	41.6779	2.62	46.18	21.14	20.34	0.36	0.23	RV Tau
V2977......	11.3018	41.6835	1.27	53.3	21.21	20.13	0.18	0.28	RV Tau
V9659......	11.4421	41.6874	1.75	56.6	20.77	19.96	0.40	0.27	RV Tau

using as an input the transformed object list from the template frames. For each frame, the list of instrumental photometry derived for a given frame was transformed to the common instrumental system of the appropriate "template" image. Photometry obtained for the V and I filters was combined into separate databases. Unlike for the M31B field, M31A images obtained at the FLWO were reduced using MDM "templates."

To obtain the photometric calibration, we observed four Landolt (1992) fields containing a total of 18 standard stars. These fields were observed through BVI filters at air masses ranging from 1.2 to 1.70. The transformation from the instrumental to the standard system was derived, and is described in Paper I. The derived transformation satisfactorily reproduces the V magnitudes and $V-I$ colors. The $B-V$ transformation reproduces the standard system poorly, and we decided to drop the B data from our analysis, especially since we took only two B frames.

To check the internal consistency of our photometry, we compared the photometry for 20 stars with $V < 20$ and 47 with $I < 20$ common to the overlap region between the fields M31A and M31B (Paper I, Fig. 1). There was an offset of 0.022 mag in V and 0.018 mag in I, i.e., well within our estimate of the 0.05 mag systematic error discussed in Paper I. 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 ~200 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 § 3 produces databases of calibrated V and I magnitudes and their standard errors. The V database for the M31A field contains 10,084 stars with up to 117 measurements, and the I database contains 21,341 stars with up to 45 measurements. Figure 1 shows the distributions of stars as a function of mean V or I magnitude. As can be seen from the shape of the histograms, our completeness starts to drop rapidly at about $\bar{V} \sim 22$ and $\bar{I} \sim 20.5$. The primary reason for this difference in the depth of the photometry between V 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 V filter.

The measurements flagged as "bad" and measurements with errors exceeding the average error by more than 4 σ are removed (Paper I). Usually zero to 10 points are removed, leaving the majority of stars with roughly $N_{good} \sim 105$–117 V measurements. For further analysis we use only those stars that have at least $N_{good} > N_{max}/2$ (=58) measurements. There are 8521 such stars in the V database of the M31A field.

Our next goal is to select objectively 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). The procedure is described in more detail in Paper I. In short, for each star we compute Stetson's variability index J_S (Paper I, eq. [8]), and stars with values exceeding some minimum value $J_{S,min}$ are considered candidate variables. The definition of Stetson's variability index includes the standard errors of individual observations. If, for some reason, these errors were over- 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

TABLE 4

DIRECT MISCELLANEOUS VARIABLES IN M31A

Name (D31A)	α (J2000.0) (deg)	δ (J2000.0) (deg)	J_S	$\bar{V}$	$\bar{I}$	σ_V	σ_I	Comments
V3222......	11.3081	41.6494	1.40	19.11	17.21	0.09	0.04	V8123 D31B
V3901......	11.3216	41.6633	1.61	19.25	16.72	0.10	0.05	LP
V2109......	11.2844	41.6975	1.67	20.07	19.13	0.11	0.07	RV Tau?
V7718......	11.3926	41.7313	2.02	20.23	19.59	0.15	0.10	RV Tau?
V8415......	11.4050	41.7867	1.98	20.37	19.65	0.17	0.12	RV Tau?
V5764......	11.3563	41.6507	1.36	20.75	20.20	0.14	0.12	RV Tau?
V2570......	11.2912	41.7629	1.82	21.42	19.60	0.53	0.20	LP
V541.......	11.2424	41.6594	2.47	21.51	19.20	0.54	0.13	V5897 D31B
V11........	11.2240	41.6504	1.27	21.72	19.31	0.47	0.12	V5075 D31B
V9459......	11.4322	41.7689	1.71	21.84	19.23	0.54	0.18	LP
V1032......	11.2565	41.6655	1.72	21.88	19.43	0.43	0.14	LP

NOTE.—Variables V3222, V541, and V11 were also found in Paper I.

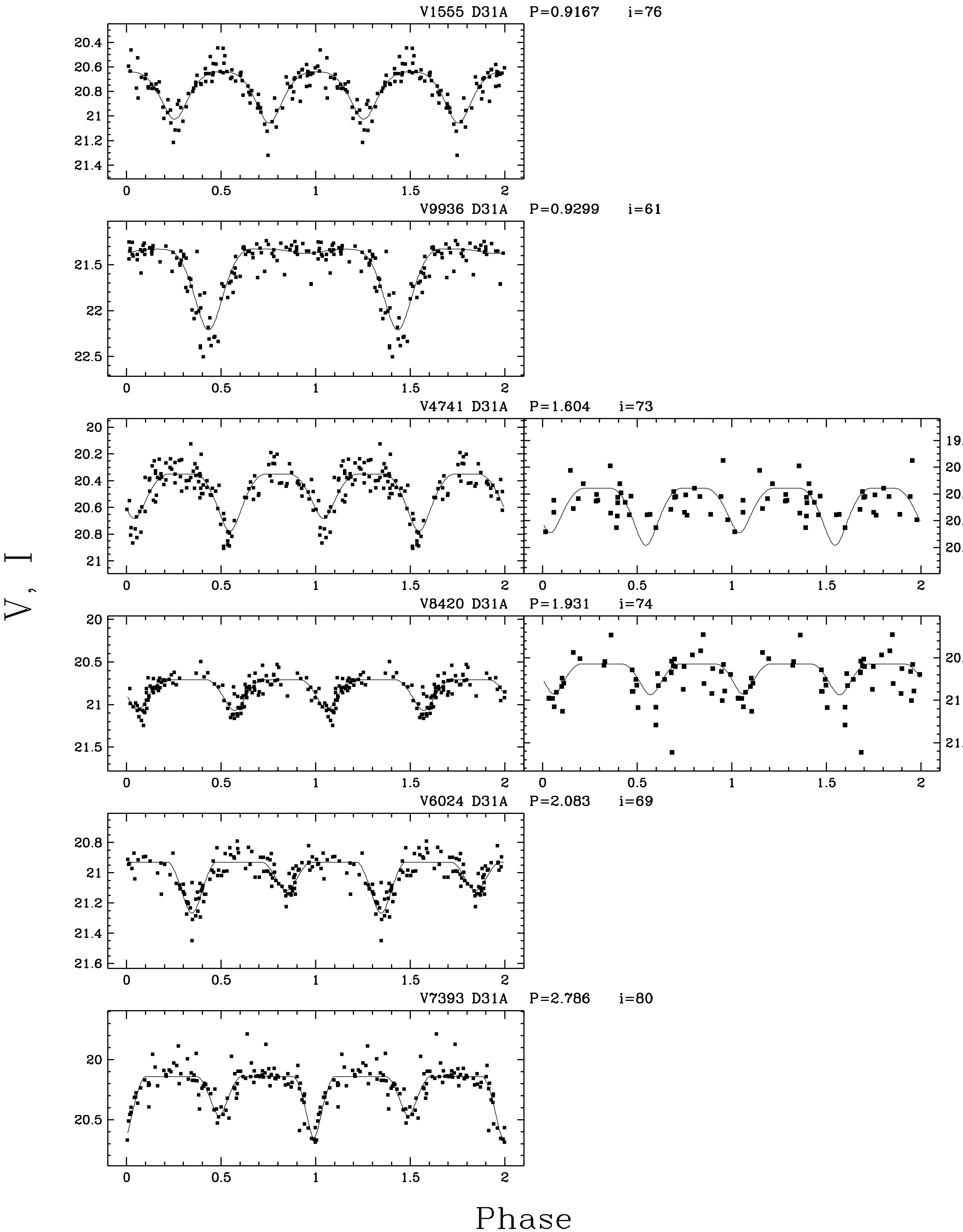

FIG. 3.—*VI* light curves of eclipsing binaries found in the field M31A. The solid line represents for each system the best-fit curve (fitted to the *V* data).

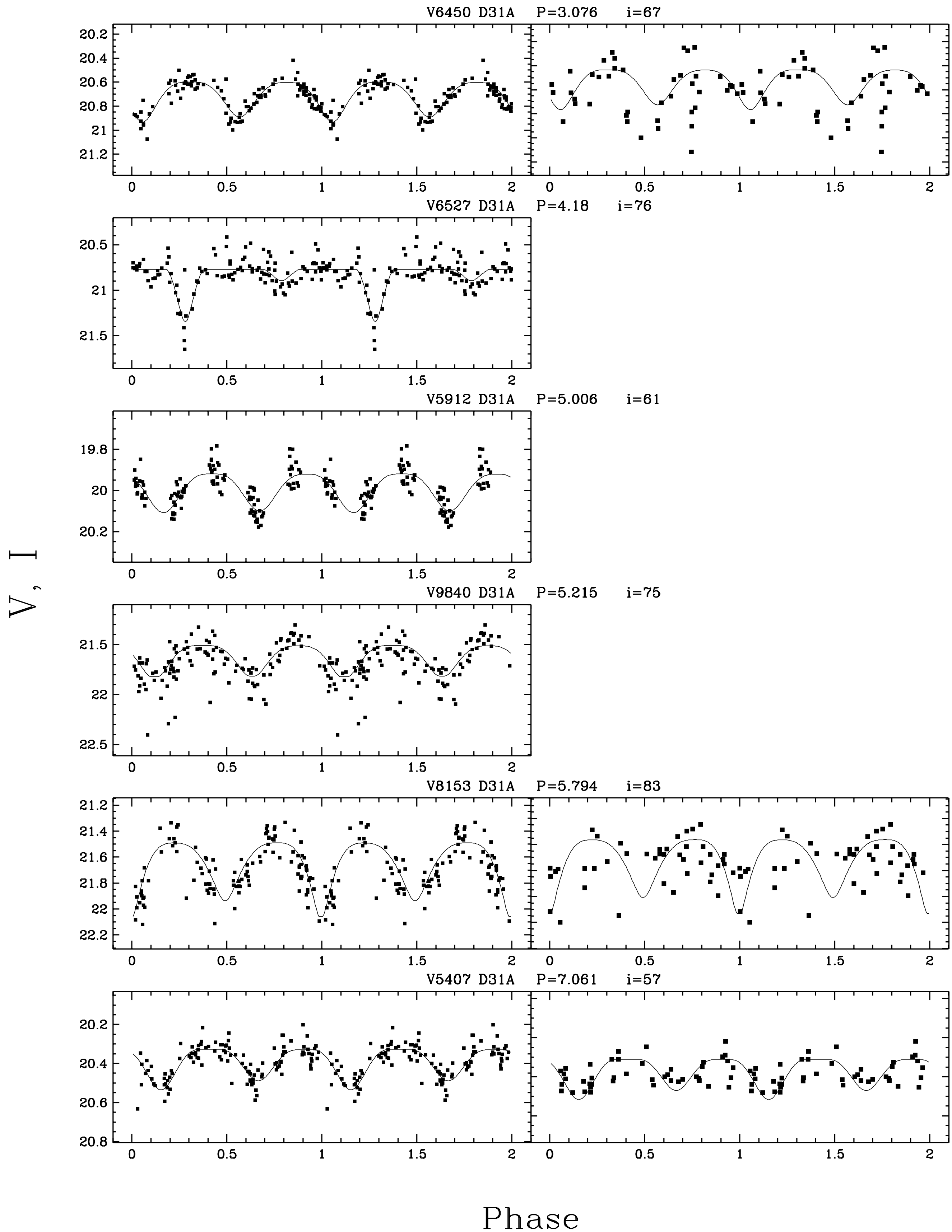

FIG. 3.—*Continued*

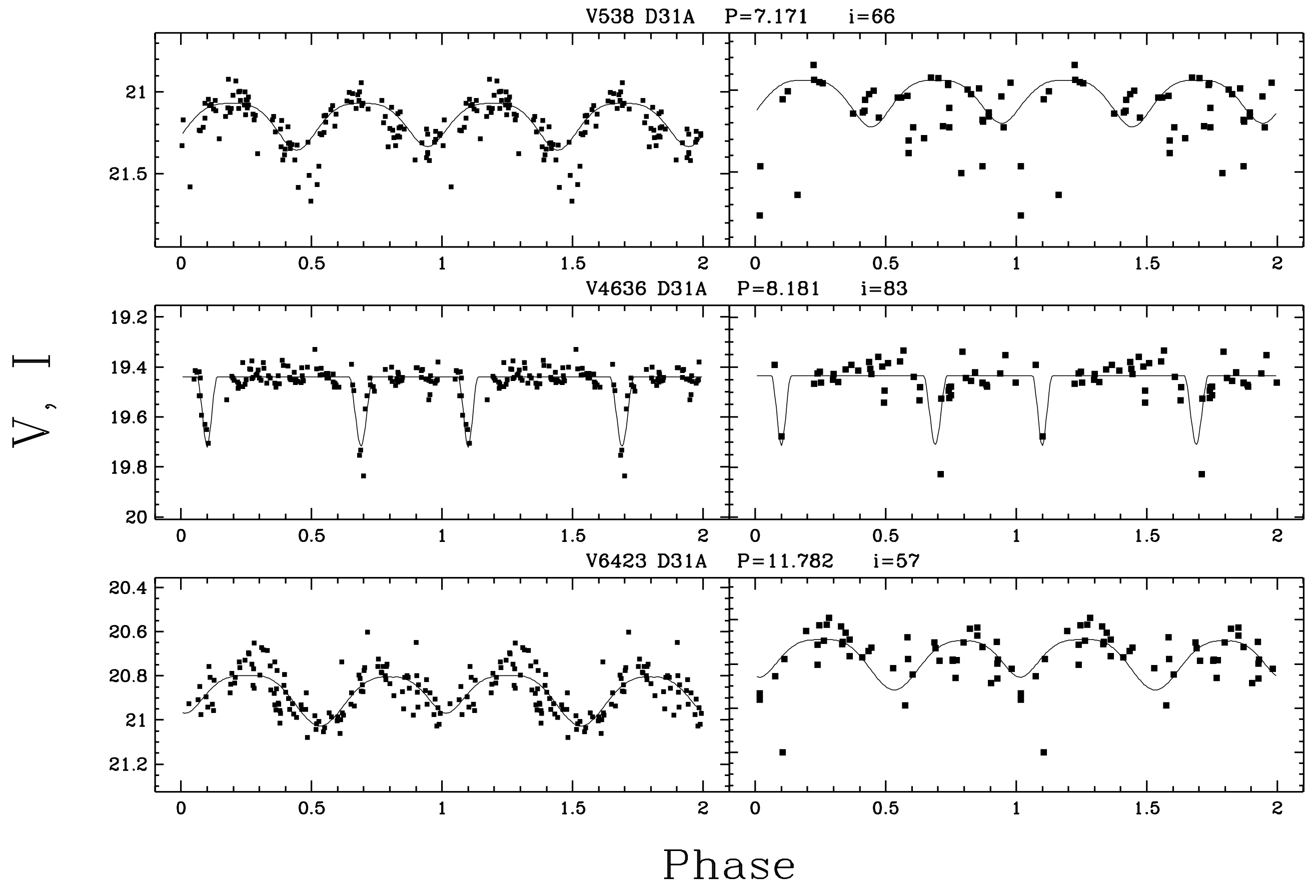

FIG. 3.—*Continued*

variable stars by computing the value of J_S for the stars in our V database. We used a cutoff of $J_{S,\min} = 0.75$ and additional cuts described in Paper I to select 183 candidate variable stars (about 2% of the total number of 8521). In Figure 2, we plot the variability index J_S versus apparent visual magnitude $\bar{V}$ for 8521 stars with $N_{good} > 58$.

5. PERIOD DETERMINATION AND CLASSIFICATION OF VARIABLES

We based our selection of candidate variables on the V-band data collected at the MDM and the FLWO telescopes. We also have the I-band data for the field, up to 27

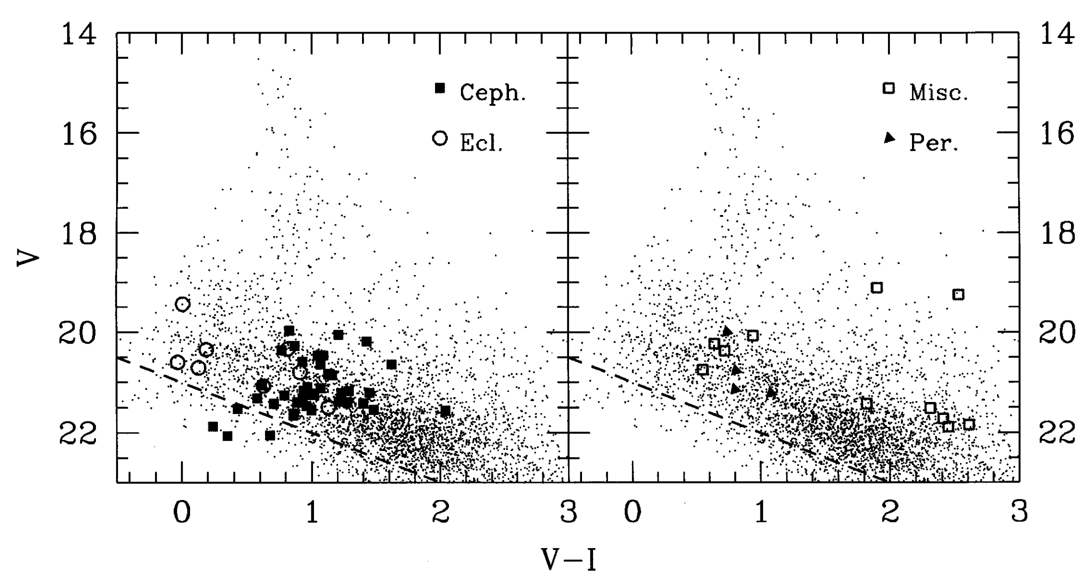

FIG. 4.—(V, $V-I$) color-magnitude diagrams for the variable stars found in the field M31A. The eclipsing binaries and Cepheids are plotted in the left panel, and the other periodic variables and miscellaneous variables are plotted in the right. The dashed lines correspond to the I detection limit of $I \sim 21$ mag.

TABLE 5

LIGHT CURVES OF ECLIPSING BINARIES IN M31A

HJD − 2,450,000	Magnitude	σ_{mag}
V538 D31A:		
I band:		
332.9998......	20.637	0.100
333.9569......	20.545	0.094
334.8714......	20.423	0.083
335.9755......	20.526	0.101
337.9797......	20.556	0.100
338.9734......	20.449	0.092
339.9079......	20.643	0.116
341.8612......	20.795	0.178
346.0009......	20.346	0.096
349.6847......	20.469	0.110
349.6930......	20.459	0.118
350.8054......	20.662	0.116
350.8137......	20.638	0.093
354.9567......	20.668	0.154
355.7721......	20.809	0.245
355.7804......	20.886	0.239
355.9033......	20.726	0.268
356.8894......	20.609	0.183
356.8976......	20.728	0.258
357.8002......	20.683	0.114
357.8095......	20.965	0.237
357.8214......	20.693	0.111
358.8562......	21.266	0.298
358.8658......	20.965	0.183
359.8995......	21.142	0.251
361.7532......	20.558	0.098
361.8675......	20.524	0.094
361.9817......	20.502	0.107
362.7419......	20.544	0.093
362.9221......	20.536	0.101
363.7636......	20.426	0.095
363.8993......	20.719	0.262
364.8796......	20.488	0.091
365.7479......	20.453	0.098
366.8004......	20.505	0.105
367.7522......	20.456	0.106
368.9146......	20.625	0.118
371.7358......	20.497	0.105
372.7346......	20.728	0.118
374.7000......	20.438	0.104
378.7421......	21.007	0.276
379.8454......	20.540	0.118
V band:		
332.9121......	21.349	0.154
333.7823......	21.568	0.186
333.9822......	21.146	0.072
334.7309......	21.061	0.070

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 M31A

HJD − 2,450,000	Magnitude	σ_{mag}
V107 D31A:		
I band:		
332.9998......	19.621	0.070
333.9569......	19.686	0.073
334.8714......	19.635	0.072
337.9797......	19.937	0.123
338.9734......	19.806	0.073
339.9079......	19.740	0.073
341.8612......	19.536	0.122
346.0009......	19.458	0.073
361.7532......	19.851	0.094
361.8675......	19.846	0.087
361.9817......	19.840	0.089
363.7636......	19.934	0.086
363.8993......	20.152	0.139
364.8796......	19.658	0.073
365.7479......	19.718	0.076
366.8004......	19.439	0.067
367.7522......	19.575	0.075
371.7358......	19.596	0.085
372.7346......	19.716	0.120
374.7000......	20.011	0.092
378.7421......	19.834	0.131
379.8454......	19.331	0.087
V band:		
332.9121......	20.609	0.075
333.7823......	20.340	0.130
333.9822......	20.518	0.042
334.7309......	20.721	0.075
334.7668......	20.724	0.063
334.8614......	20.710	0.064
334.9097......	20.662	0.057
334.9588......	20.761	0.057
335.0059......	20.825	0.089
335.8674......	20.818	0.085
335.9367......	20.950	0.111
335.9854......	20.876	0.085
337.7137......	21.178	0.136
337.7546......	20.978	0.089
337.8759......	21.004	0.074
337.9696......	20.989	0.078
338.7246......	20.825	0.083
338.7976......	20.814	0.058
338.8329......	20.793	0.089
338.9834......	20.778	0.057
339.7304......	20.759	0.114
339.7698......	20.728	0.072
339.8070......	20.654	0.042
339.9497......	20.764	0.054

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.

MDM epochs, and up to 18 FLWO epochs. As mentioned above, the *I* photometry is not as deep as the *V* photometry, so some of the candidate variable stars do not have an *I* counterpart. We will therefore not use the *I* data for the period determination and broad classification of the variables. We will, however, use the *I* data for the "final" classification of some variables.

Next we searched for the periodicities for all 183 candidate variables, using a variant of the Lafler-Kinman (1965) technique proposed by Stetson (1996). Starting with the minimum period of 0.25 days, successive trial periods are chosen so that

$$P_{j+1}^{-1} = P_j^{-1} - \frac{0.01}{\Delta t}, \quad (1)$$

where $\Delta t = t_N - t_1$ is the time span of the series. The maximum period considered is $\Delta t = 55.8$ 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 *I*-band data, when available, when discussing some of the individual variable stars.

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). Unlike for the M31B field, we classified the star as a Cepheid if the reduced $\chi^2/N_{\rm dof}$ of the fit was a factor of 3 smaller than the reduced $\chi^2/N_{\rm dof}$ of a straight-line fit, not a factor of 2 smaller. We also allowed for periods longer than 3 days, not longer than 4 days as in Paper I, which resulted in finding two possible Cepheids with periods of between 3 and 4 days. There were a total of 51 variables passing all of the criteria. Their parameters and light curves are presented in §§ 6.2 and 6.3.

For eclipsing binaries (EBs), we used a similar search strategy to that described in detail in Paper I, but we simplified the condition for the reduced $\chi^2/N_{\rm dof}$ of the fit to be at least 1.75 smaller than the reduced $\chi^2/N_{\rm dof}$ of a straight-line fit. Within our assumption of perfect spheres with uniform surface brightnesses, 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 larger star, and the uneclipsed magnitude. A total of 15 variables meeting all of the criteria and their parameters and light curves are discussed in § 6.1.

After we selected 15 eclipsing binaries and 51 possible Cepheids, we were left with 118 "other" variable stars. After raising the threshold of the variability index to $J_{S,\rm min} = 1.2$ (Paper I), we were left with 29 variables that we preliminarily classify as "miscellaneous." We then went back to the CCD frames to try to see by eye whether the inferred variability was indeed there, especially in cases in which the light curve was very noisy/chaotic. We decided to remove two dubious Cepheids and 18 dubious miscellaneous variables from the sample, which leaves 11 variables that 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 75 variable stars discovered in our survey.[5] The variable stars are named according to the following convention: letter "V" for "variable," the number of the star in the V-band database, then the letter "D" for our project, DIRECT, followed by the name of the field, in this case (M)31A, e.g., V3407 D31A. 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 the survey of Magnier et al. (1997) are denoted in the "Comments" columns by "Ma97 ID," where the "ID" is the identification number assigned by Magnier et al. (1997). We also identify several variables found in Paper I.

Note that this is a first step in a long-term project and that we are planning to collect additional data and information of various kinds for this and other fields. As a result, the current catalog might undergo changes, due to addition, deletion, or reclassification of some variables.

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

TABLE 7

LIGHT CURVES OF OTHER PERIODIC VARIABLES IN M31A

HJD − 2,450,000	Magnitude	$\sigma_{\rm mag}$
V410 D31A:		
V band:		
332.9121......	20.627	0.062
333.7823......	20.750	0.074
333.9822......	20.797	0.066
334.7309......	20.759	0.051
334.7668......	20.821	0.068
334.8614......	20.814	0.057
334.9097......	20.900	0.057
334.9588......	20.975	0.052
335.0059......	21.009	0.107
335.8674......	20.893	0.115
335.9367......	20.893	0.080
335.9854......	20.976	0.112
337.7137......	20.949	0.080
337.7546......	20.881	0.069
337.8759......	20.973	0.062
337.9696......	20.924	0.064
338.7246......	20.990	0.076
338.7976......	20.990	0.057
338.8329......	20.947	0.057
338.9834......	21.000	0.068
339.7304......	20.918	0.097
339.7698......	21.018	0.112
339.8070......	21.028	0.079
339.9497......	21.027	0.073
339.9867......	21.039	0.066
340.7112......	20.838	0.155
340.7467......	20.867	0.112
340.7823......	20.976	0.123
341.7767......	20.831	0.078
342.7451......	20.991	0.064
342.7804......	20.959	0.074
342.9126......	20.971	0.105
343.9589......	20.992	0.074
343.9945......	21.086	0.163
345.7002......	21.110	0.165
345.7385......	20.993	0.080
345.7768......	21.152	0.115
345.8148......	21.134	0.100
361.6888......	20.610	0.045
361.7242......	20.636	0.040
361.8575......	20.641	0.050
361.9188......	20.734	0.048
361.9541......	20.723	0.063
362.6650......	20.705	0.056
362.7063......	20.730	0.050
362.8577......	20.851	0.054

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.

6.1. *Eclipsing Binaries*

In Table 1, we present the parameters of the 15 eclipsing binaries in the M31A field. The light curves of these variables are shown in Figure 3, along with the simple eclipsing binary models discussed in Paper I (see also Table 5). The variables are presented in Table 1 by increasing value of the period P. For each eclipsing binary we present its name, J2000.0 coordinates (in degrees), value of the variability index J_S, period P, magnitudes $V_{\rm max}$ and $I_{\rm max}$ of the system outside of eclipse, and the radii of the binary components R_1 and R_2 in units of the orbital separation. We also give

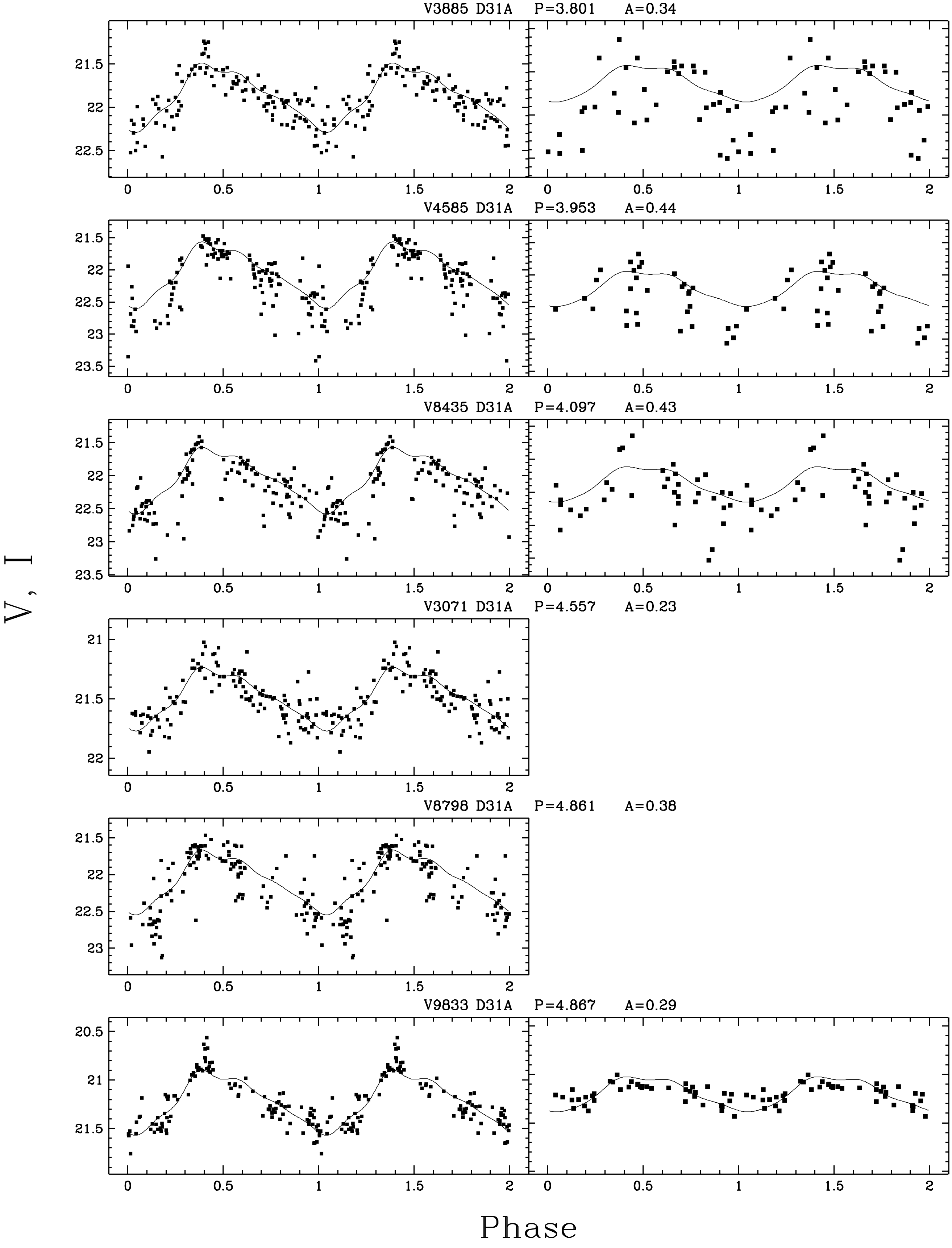

FIG. 5.—*VI* light curves of Cepheid variables found in the field M31A. The solid line represents for each star the best-fit Cepheid template (fitted to the *V* data).

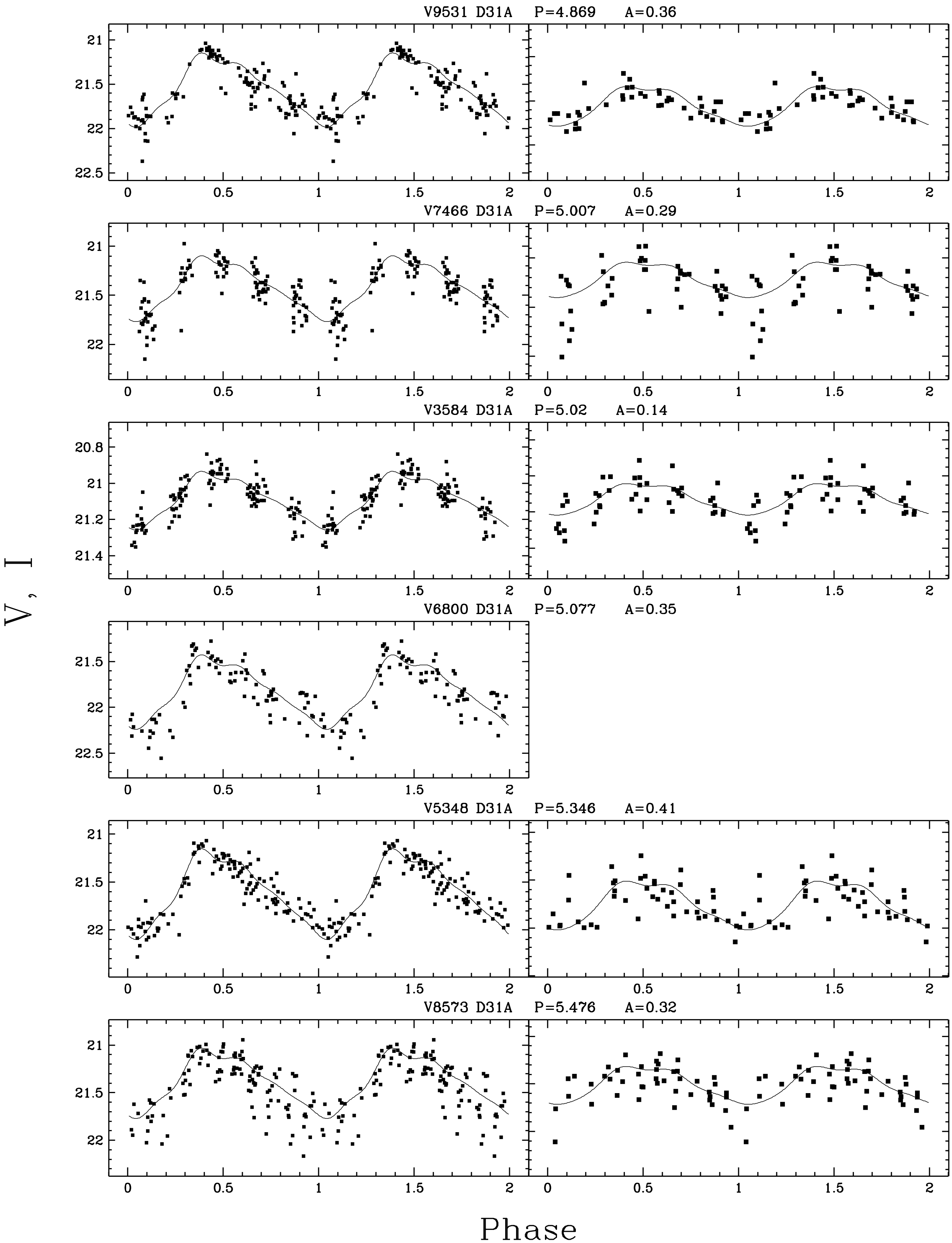

FIG. 5.—*Continued*

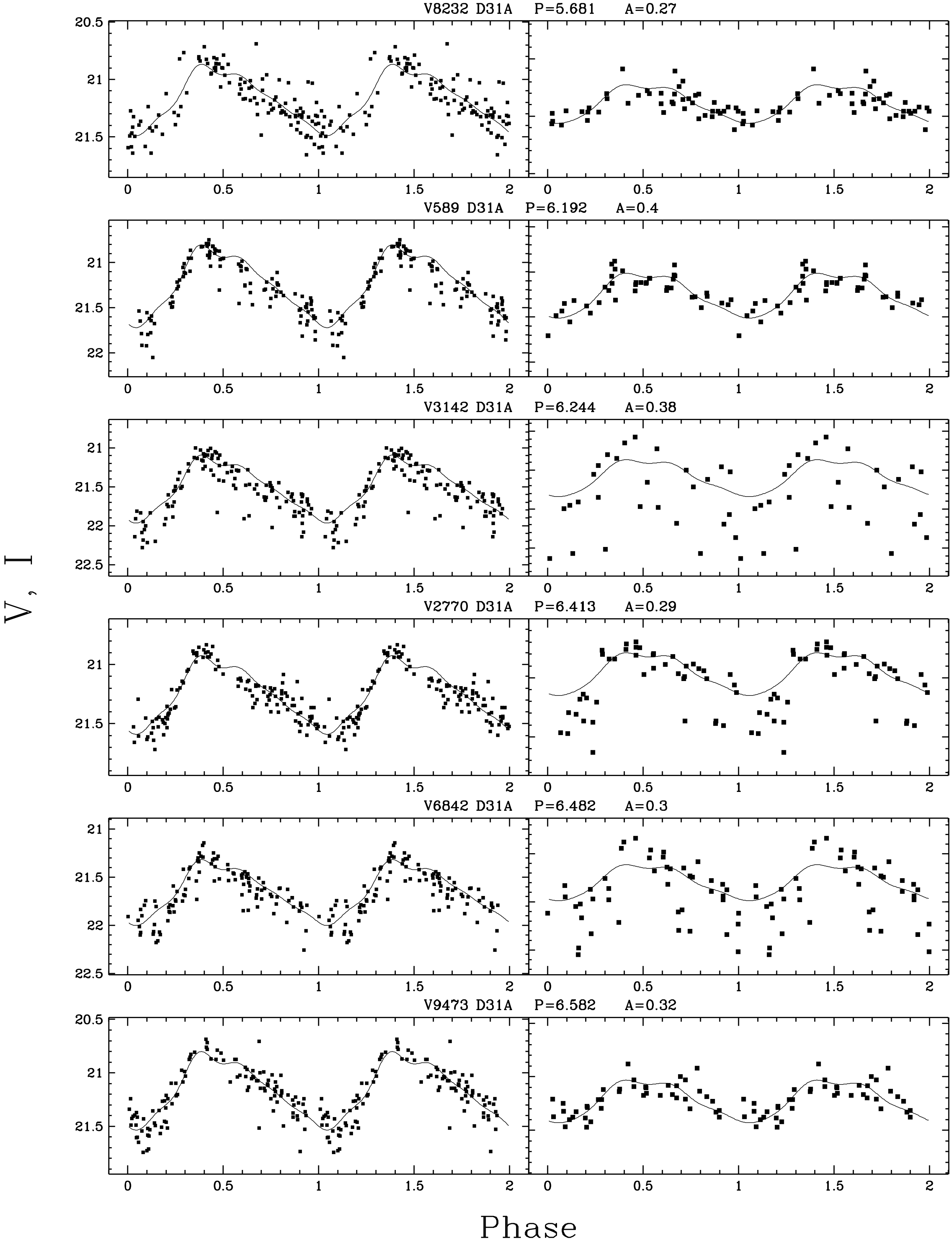

Fig. 5.—*Continued*

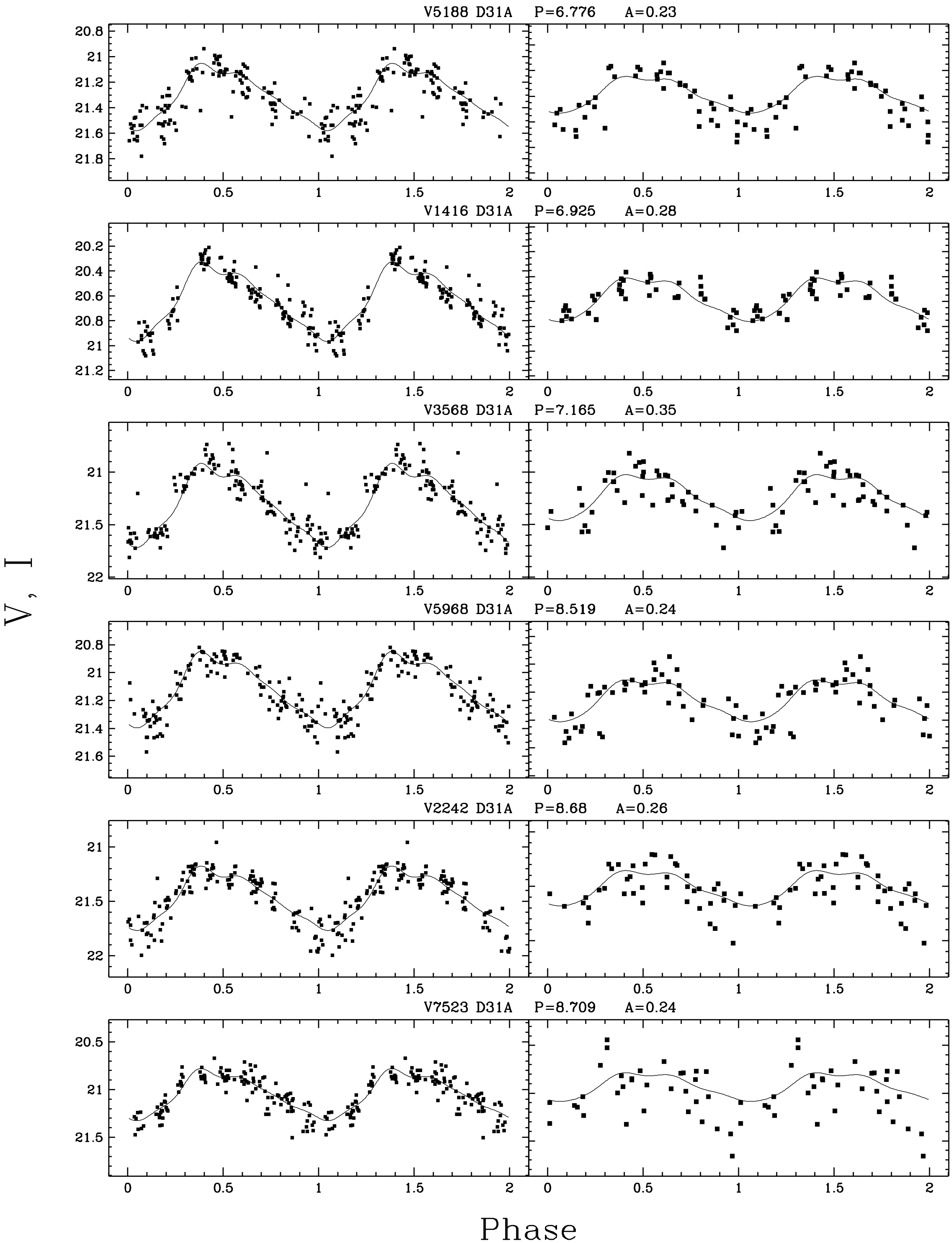

FIG. 5.—*Continued*

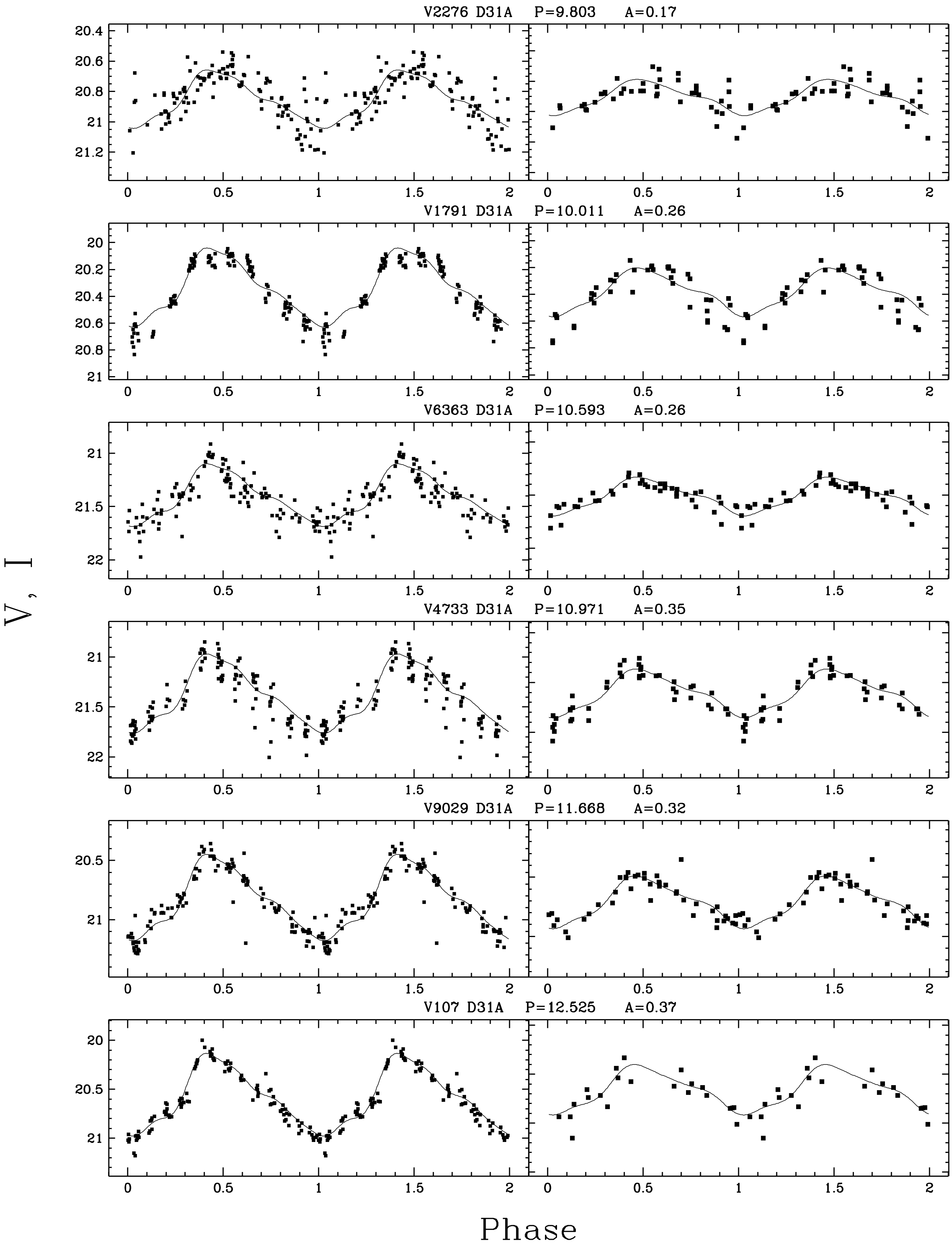

FIG. 5.—*Continued*

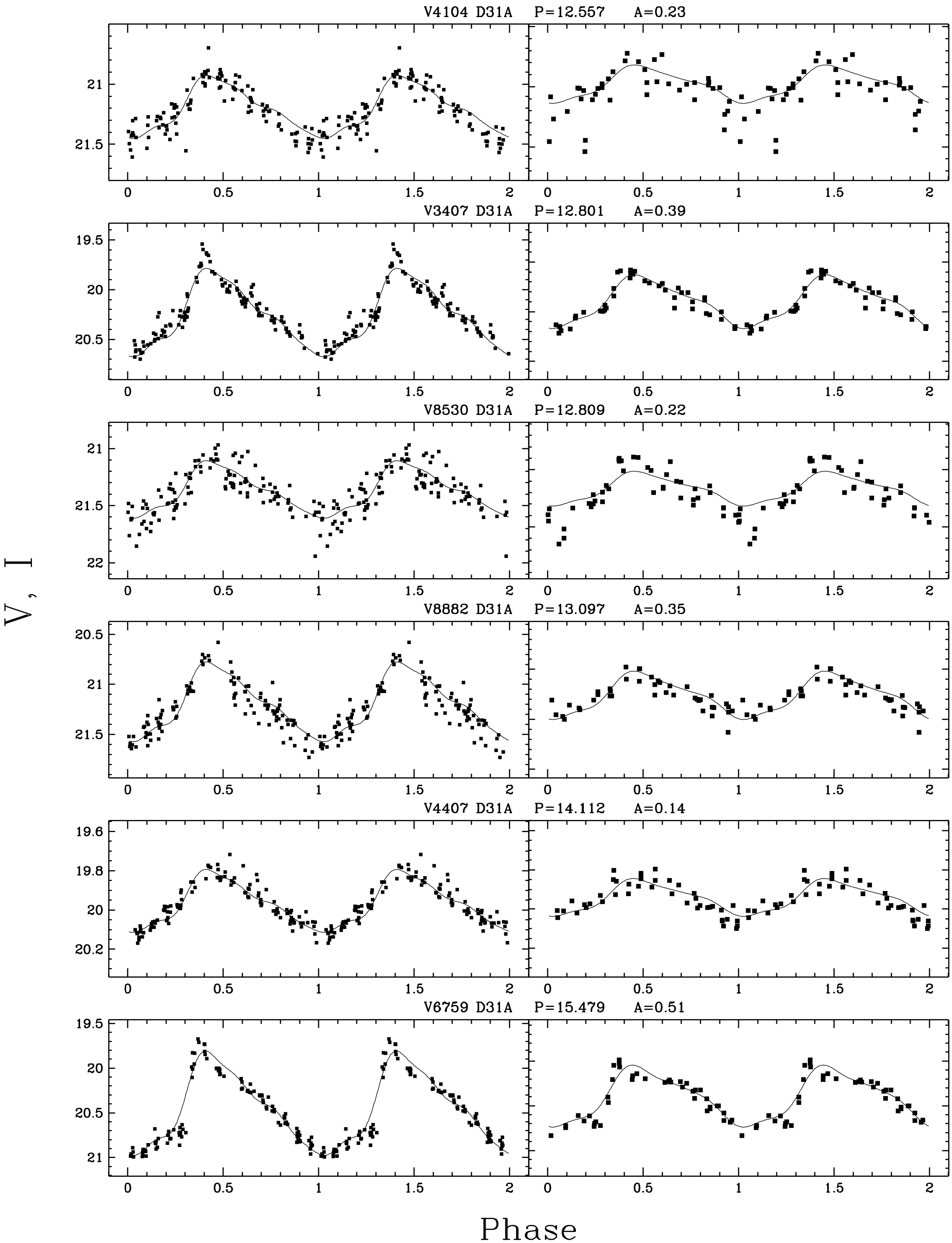

FIG. 5.—*Continued*

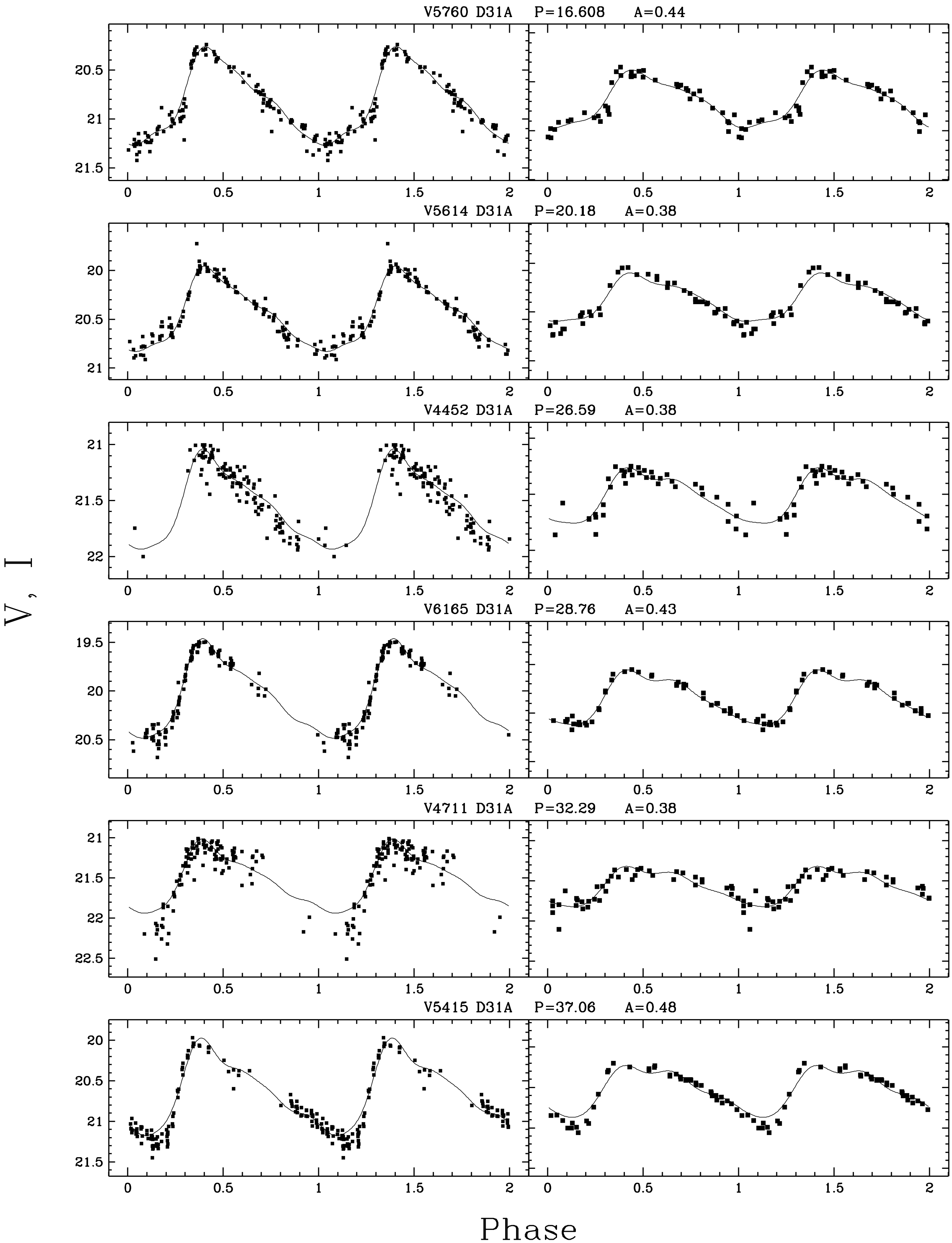

FIG. 5.—*Continued*

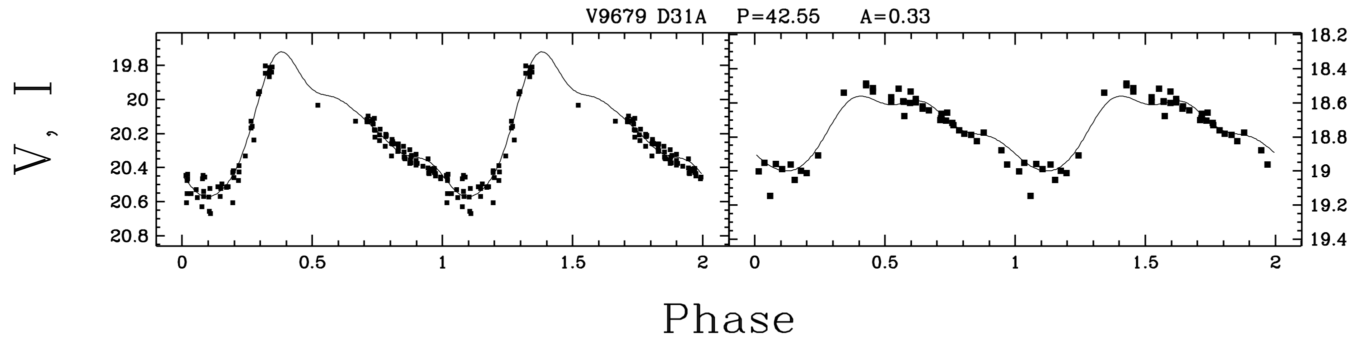

FIG. 5.—*Continued*

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}, 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.

One of the eclipsing binaries found, V4636 D31A, is a good DEB candidate, with reasonably deep eclipses and significant eccentricity, indicating that the system is young and unevolved. However, a much better light curve is necessary to accurately establish the properties of the system. Three other systems, V8420, V6024, and V7393 D31A, also seem to be detached, but they are significantly fainter than V4636 D31A and therefore less suitable for follow-up.

Inspection of the color-magnitude diagram (Fig. 4) reveals that four of the candidate eclipsing binaries land in the middle of the Cepheid portion of the CMD.[6] It turns out that three of these variables, V5407, V538, and V6423 D31A, are only marginally better fitted by an eclipsing binary light curve than by a Cepheid light curve with roughly half the period. The fourth variable, V8153, is marginally better fitted by a Cepheid light curve if we allow for Cepheid periods to be shorter than 3 days. Since all four have rather noisy light curves, we decided to keep them classified as eclipsing variables in order to avoid contamination of the Cepheid sample.

6.2. *Cepheids*

In Table 2, we present the parameters of 43 Cepheids in the M31A field, sorted by increasing period. For each Cepheid, we present its name, J2000.0 coordinates, value of the variability index J_S, period P, flux-weighted mean magnitudes $\langle V \rangle$and (when available) $\langle I \rangle$, and the V-band amplitude of the variation, A. In Figure 5, we show the phased VI 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.

6.3. *Other Periodic Variables*

For some of the variables preliminary classified as Cepheids (§ 5), we decided upon closer examination to classify them as "other periodic variables." In Table 3, we present the parameters of six possible periodic variables other than Cepheids and eclipsing binaries in the M31A field, sorted by increasing period. For each variable, we present its name, J2000.0 coordinates, value of the variability index J_S, period

[6] We thank the referee for pointing this out.

TABLE 8

LIGHT CURVES OF MISCELLANEOUS VARIABLES IN M31B

HJD − 2,450,000	Magnitude	σ_{mag}
V11 D31A:		
I band:		
332.9998......	19.502	0.054
333.9569......	19.529	0.049
334.8714......	19.447	0.054
335.9755......	19.466	0.052
337.9797......	19.431	0.045
338.9734......	19.393	0.048
339.9079......	19.388	0.047
341.8612......	19.436	0.063
346.0009......	19.358	0.049
361.7532......	19.373	0.042
361.8675......	19.343	0.047
361.9817......	19.320	0.052
362.7419......	19.340	0.052
362.9221......	19.276	0.045
363.7636......	19.325	0.045
363.8993......	19.327	0.063
364.8796......	19.216	0.045
365.7479......	19.312	0.044
366.8004......	19.266	0.042
368.9146......	19.163	0.048
371.7358......	19.099	0.042
372.7346......	19.272	0.045
374.7000......	19.201	0.048
378.7421......	19.161	0.049
379.8454......	19.101	0.051
V band:		
332.9121......	22.626	0.340
333.7823......	22.288	0.238
333.9822......	22.751	0.225
334.7309......	22.597	0.319
334.7668......	22.748	0.356
334.9097......	22.832	0.276
334.9588......	22.632	0.240
335.8674......	22.520	0.371
335.9367......	23.026	0.413
335.9854......	22.733	0.365
337.7137......	22.887	0.479
337.7546......	22.393	0.223
337.8759......	22.523	0.243
337.9696......	22.904	0.294
338.7246......	22.412	0.229
338.7976......	22.739	0.231
338.8329......	22.489	0.279
338.9834......	22.629	0.241
339.7304......	22.628	0.368
339.7698......	22.351	0.235
339.8070......	22.264	0.249

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.

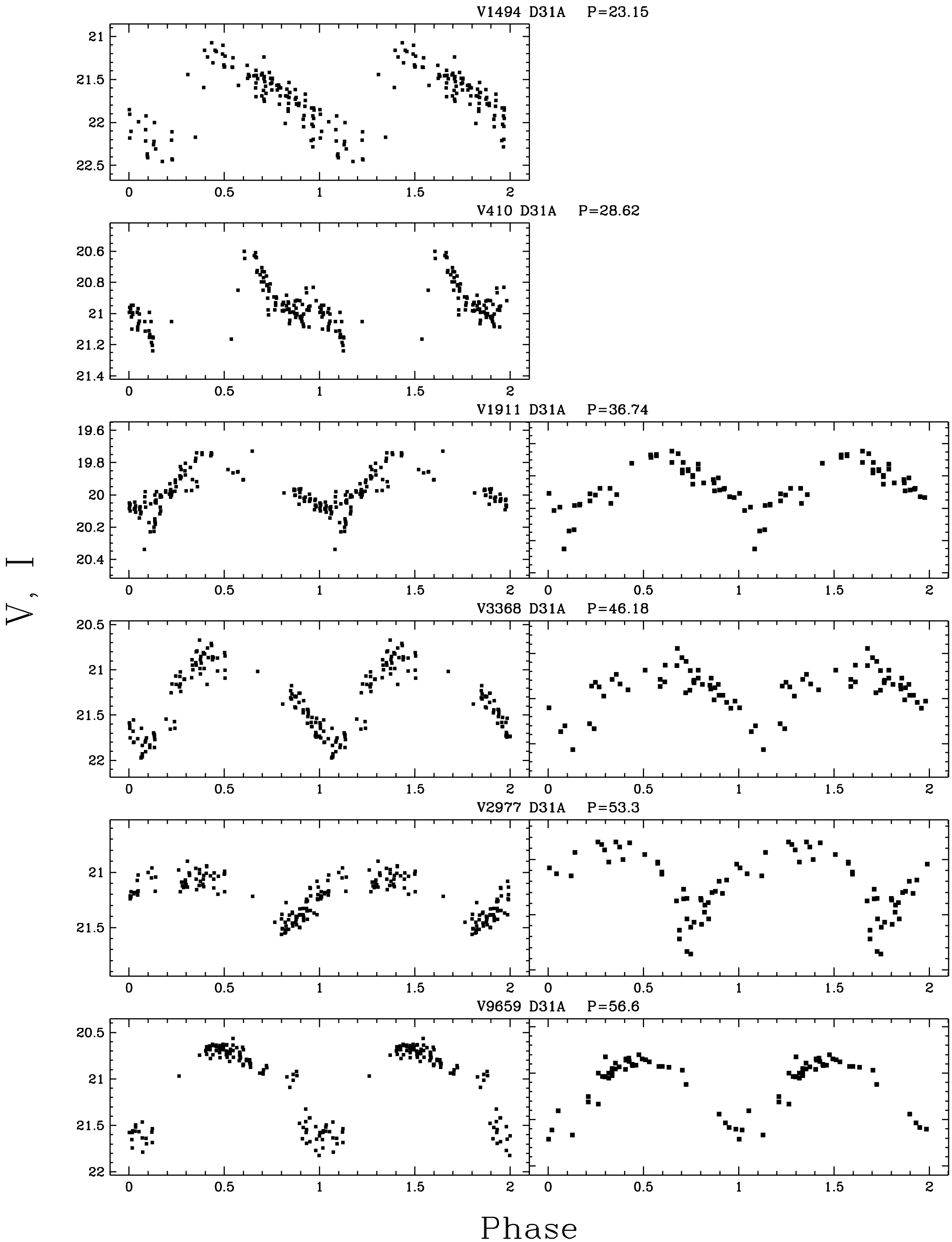

FIG. 6.—*VI* light curves of other periodic variables found in the field M31A

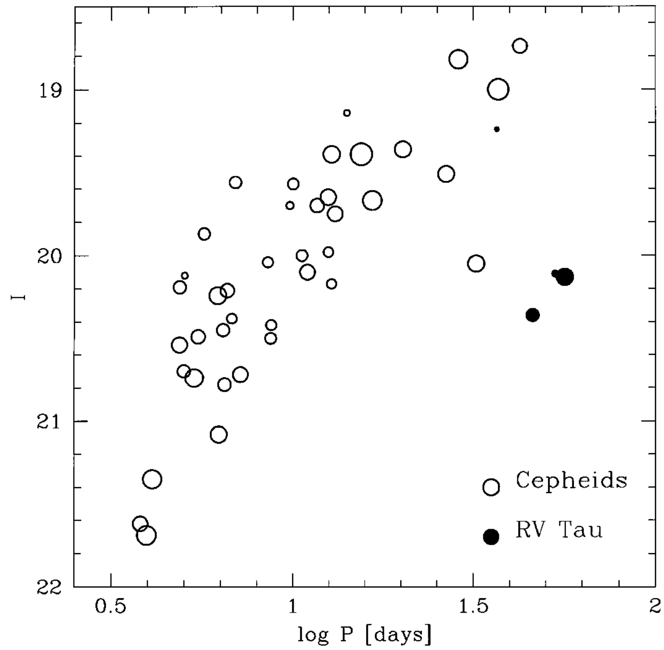

FIG. 7.—Diagram of log P vs. I for the Cepheid (*open circles*) and RV Tauri (*filled circles*) variables. The sizes of the circles are proportional to the V amplitude of the variability.

P, and error-weighted mean magnitudes $\bar{V}$ and (when available) $\bar{I}$. To quantify the amplitude of the variability, we also give the standard deviations of the measurements in the V and I bands, σ_V and σ_I. In Figure 6, we show the phased VI light curves of the other periodic variables (see also Table 7).

Four of the periodic variables were tentatively identified as RV Tauri variables based on their light curves, especially in the I band, and their location on the P-L diagram (Fig. 7). V1911 D31A was classified with RV Tau because, unlike for the Cepheid variables, its light curve has a larger amplitude in the I band than in the V band. If this star is a Cepheid, which is suggested by its location on the P-L diagram (Fig. 7), its larger I amplitude could be caused by a blue companion or a blue line-of-sight blend.

6.4. *Miscellaneous Variables*

In Table 4, we present the parameters of 11 miscellaneous variables in the M31A field, sorted by decreasing value of the mean magnitude $\bar{V}$. For each variable we present its name, J2000.0 coordinates, value of the variability index $J_S(>1.2)$, and mean magnitudes $\bar{V}$ and $\bar{I}$. To quantify the amplitude of the variability, we also give the standard deviations of the measurements in the V and I bands, σ_V and σ_I. In the "Comments" column we give a rather broad subclassification of the variability: LP, possible long-period variable ($P > 55$ days); Irr, irregular variable; "RV Tau," possible RV Tauri variable. In Figure 8, we show the unphased VI light curves of the miscellaneous variables (see also Table 8).

Most of the miscellaneous variables seem to represent the LP type of variability. However, inspection of the color-magnitude diagram (Fig. 4) reveals that four of the miscellaneous variables (V2109, V7718, V8415, and V5764 D31A) land in the CMD in the same area as the Cepheids and RV Tauri variables. A closer inspection of the light curves suggests that a maximum and a minimum are observed for all four stars, which allows a rough estimation of their periods as 80, 90, 80, and 60 days, respectively. Using these periods to place these stars on the P-L diagram suggests they might be RV Tauri type variables.[7]

6.5. *Comparison with Other Catalogs*

The M31A field has not been observed frequently before, and the only overlapping variable star catalog is given by Magnier et al. (1997, hereafter Ma97). Of 17 variable stars in Ma97 that are in our M31A field, we cross-identified 16. Of these 16 stars, one (Ma97 120) we did not classify as a variable ($J_S = 0.22$), and one (Ma97 123) was initially classified as a variable ($J_S = 1.1$) but then failed to classify as a Cepheid. The remaining 14 stars we classified as Cepheids (see Table 2 for cross-identifications).

There was also, by design, a slight overlap between the M31A and M31B fields (Fig. 9). Out of two eclipsing binaries found in the overlap from the M31A field, V1555 D31A was cross-identified as V6913 D31B, with very similar properties between the light curves (see Table 1). V538 D31A turned out to have $J_S = 0.749$ in the M31B database, i.e., it very narrowly escaped classification as a candidate variable star in this field. There was only one Cepheid from the M31A field in the overlap region, V2276 D31A (=Ma97 108), and it was cross-identified as V7553 D31B, again with very similar properties between the light curves (see Table 2). There was a second Cepheid in the overlap found in Paper I, V7845 D31B ($J_S = 0.88$), which failed to qualify as a Cepheid in the M31A field because of the more stringent requirements for the reduced $\chi^2/N_{\rm dof}$ of the fit (§ 5). We also cross-identified three miscellaneous variables (see Table 4), out of four detected in the M31A field and five detected in the M31B field, that fell into the overlap region.

7. DISCUSSION

In Figure 4, we show (V, $V-I$) color-magnitude diagrams for the variable stars found in the field M31A. The eclipsing binaries and Cepheids are plotted in the left panel and the other periodic variables and miscellaneous variables are plotted in the right panel. As expected, some of the eclipsing binaries occupy the blue upper main sequence of M31 stars, but there is a group of eclipsing binaries with $V-I \sim 1.0$ (see discussion in § 6.1). The Cepheid variables group near $V-I \sim 1.0$, with the exception of the possibly highly reddened system V4452 D31A. The other periodic variable stars have positions on the color-magnitude diagram similar to the Cepheids. The miscellaneous variables are scattered throughout the color-magnitude diagram and might represent the presence of several classes of variability (see discussion in § 6.4), but most of them are red, with $V-I = 1.8$–2.6, and are probably Mira variables.

In Figure 7, we plot the log ($P - I$) diagram for the Cepheids and RV Tauri variables. The sizes of the circles are proportional to the V amplitude of the variability. As discussed in § 6.3, three of the stars classified as RV Tau lie well below the P-L relation for Cepheids. On the other hand, one of the stars classified as a Cepheid, V4711 D31A, also lies below the P-L relation for the Cepheids, but its

[7] We thank the referee for pointing this out.

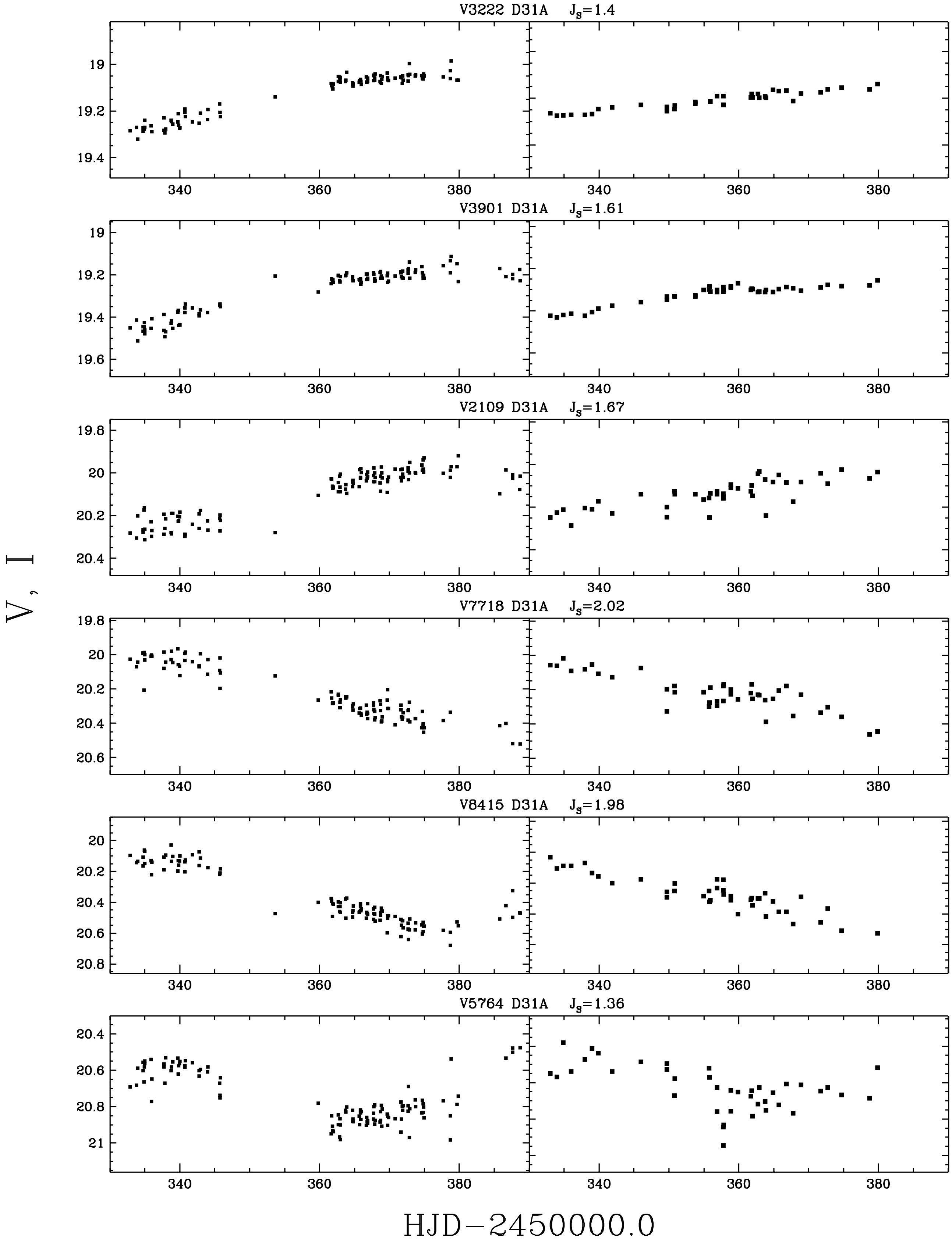

FIG. 8.—*VI* light curves of miscellaneous variables found in the field M31A

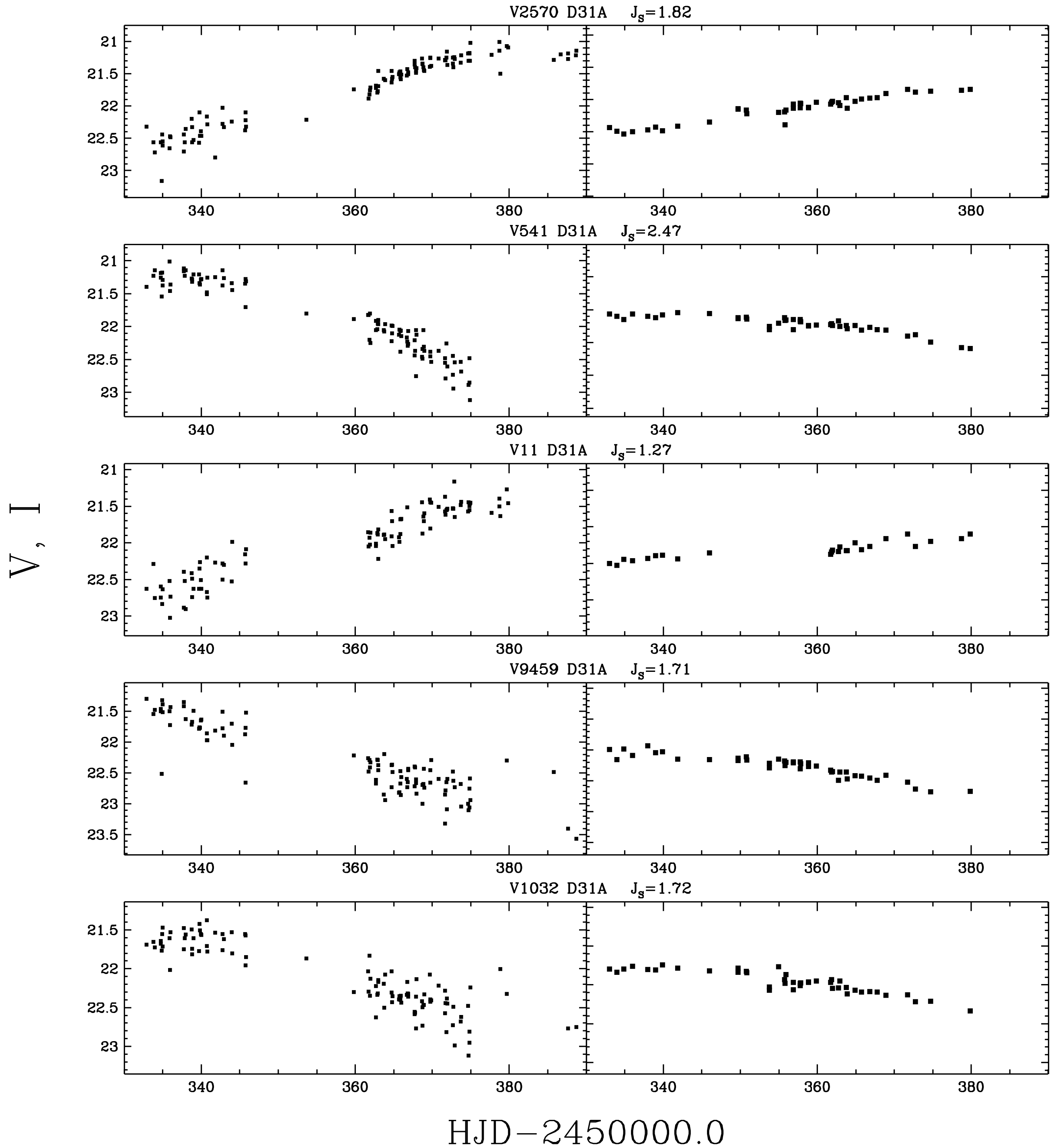

FIG. 8.—*Continued*

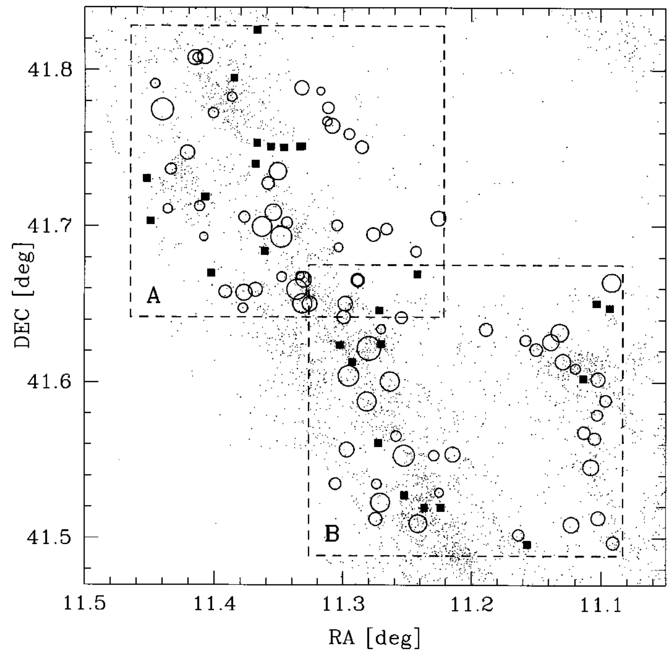

FIG. 9.—Location of eclipsing binaries (*squares*) and Cepheids (*circles*) in the fields M31A and M31B, along with the blue stars ($B-V < 0.4$) selected from the photometric survey of M31 by Magnier et al. (1992) and Haiman et al. (1994). The sizes of the circles representing the Cepheid variables are proportional to the logarithm of their period.

V- and I-band light curves both correspond well to the Cepheid template light curves (Fig. 5).

In Figure 9, we plot the location of eclipsing binaries and Cepheids in the fields M31A and M31B, 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 Cepheid 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. However, in the field M31A there is a group of Cepheids located outside the population of the blue stars [at $(\alpha, \delta) \sim (11^{\circ}.3, 41^{\circ}.76)$ and below]. These Cepheids, as well as those located in the inner spiral arm of M31 (field M31B at R.A. $\sim 11^{\circ}.1$), have, on average, shorter periods than the Cepheids located in the outer spiral arm. We will explore various properties of our sample of Cepheids in the future (Sasselov et al. 1998).

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