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DIRECT DISTANCES TO NEARBY GALAXIES USING DETACHED ECLIPSING BINARIES AND CEPHEIDS. III. VARIABLES IN THE FIELD M31C[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 third paper in the series, we present the catalog of variable stars, most of them newly detected, found in the field M31C [$(\alpha, \delta) = (11\overset{\circ}{.}10, 41\overset{\circ}{.}42)$, J2000.0]. We have found 115 variable stars: 12 eclipsing binaries, 35 Cepheids, and 68 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: close — 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 to the Large Magellanic Cloud.

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 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

[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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TABLE 1

DIRECT ECLIPSING BINARIES IN M31C

Name (D31C)	α (J2000.0) (deg)	δ (J2000.0) (deg)	P (days)	V_{max}	I_{max}	B_{max}	R_1	R_2	i (deg)	e	Comments
V12262	11.1503	41.4888	2.0489	20.02	20.19	19.85	0.50	0.32	71	0.00	
V12594	11.1568	41.4962	2.3013	20.49	20.68	20.37	0.59	0.41	72	0.01	V2763 D31B
V10732	11.1246	41.3909	2.3048	20.65	...	20.34	0.42	0.34	84	0.00	DEB
V14662	11.2087	41.4686	2.8606	20.28	19.81	20.19	0.46	0.35	83	0.01	DEB
V10550	11.1219	41.3837	3.1687	19.35	19.26	19.18	0.50	0.49	90	0.00	
V12650	11.1582	41.4899	3.5500	19.19	18.96	19.13	0.50	0.49	89	0.02	
V14653	11.2081	41.4807	3.8839	20.60	...	20.36	0.50	0.49	90	0.02	
V14396	11.2035	41.3833	5.4260	21.32	...	21.80	0.63	0.37	90	0.00	
V9037	11.0969	41.4523	5.7735	19.22	19.13	19.24	0.31	0.26	76	0.14	DEB
V11295	11.1333	41.4223	7.6907	17.31	16.16	18.20	0.52	0.39	49	0.00	W UMa
V14439	11.2024	41.4577	9.1370	21.12	20.96	21.06	0.33	0.33	72	0.17	DEB?
V13944	11.1886	41.4667	11.5385	18.68	18.55	18.71	0.68	0.32	69	0.00	Ma97 92

NOTE.—V9037 D31C with period $P = 5.7735$ days is a good detached eclipsing binary (DEB) candidate, with significant eccentricity. V12594 D31C was found in Paper I as V2763 D31B, with $P = 2.302$ days, $V_{max} = 20.51$, and $I_{max} = 20.84$.

TABLE 2

DIRECT CEPHEIDS IN M31C

Name (D31C)	α (J2000.0) (deg)	δ (J2000.0) (deg)	P (days)	⟨V⟩	⟨I⟩	⟨B⟩	A	Comments
V11298	11.1346	41.3806	3.743	21.67	20.73	22.48	0.19	
V11190	11.1339	41.3424	4.651	21.56	...	22.22	0.22	
V11426	11.1363	41.4097	5.136	21.03	19.86	21.64	0.16	Ma97 85
V2837	11.0159	41.4518	5.607	21.34	19.63	22.25	0.25	
V9709	11.1081	41.4021	5.979	21.11	...	21.93	0.19	
V9987	11.1141	41.3523	6.170	21.62	...	23.28	0.25	
V10063	11.1129	41.4347	6.258	21.04	...	21.74	0.24	
V13640	11.1831	41.4072	7.253	21.23	20.42	21.92	0.22	
V10632	11.1225	41.4122	7.485	20.88	20.08	21.54	0.31	Ma97 83
V10846	11.1229	41.5087	7.736	21.12	20.38	...	0.21	V1562 D31B
V11633	11.1414	41.3671	7.773	21.67	20.64	22.16	0.28	
V9544	11.1021	41.5129	8.151	20.25	19.54	...	0.18	V643 D31B
V8771	11.0909	41.4971	8.243	20.68	19.44	21.35	0.25	V129 D31B
V12902	11.1635	41.5022	8.509	21.93	20.41	23.28	0.41	V2977 D31B
V7871	11.0829	41.3443	8.598	20.84	19.70	21.67	0.14	
V8515	11.0915	41.3549	10.308	21.16	20.24	22.02	0.29	
V13153	11.1715	41.4072	10.350	21.14	19.66	22.46	0.29	Ma97 90
V13042	11.1698	41.3994	10.847	21.10	19.73	22.01	0.24	
V3003	11.0171	41.4620	11.695	20.68	19.60	21.61	0.44	
V8610	11.0916	41.3966	12.566	20.85	19.90	21.61	0.36	Ma97 77
V11179	11.1317	41.4136	12.783	20.64	19.17	21.53	0.51	
V11126	11.1299	41.4356	12.965	21.85	20.40	22.30	0.24	
V8509	11.0909	41.3723	13.151	20.85	19.65	21.72	0.42	Ma97 76
V14487	11.2027	41.4876	14.136	19.95	18.95	20.75	0.22	Ma97 95
V13705	11.1822	41.4766	14.662	21.50	19.98	22.83	0.48	
V14661	11.2092	41.4527	15.503	21.39	19.70	22.76	0.29	
V7557	11.0783	41.3467	16.726	20.85	19.14	21.98	0.45	Ma97 75
V3277	11.0238	41.3485	17.599	21.02	19.60	22.29	0.40	
V11401	11.1358	41.4061	18.751	21.77	20.04	22.59	0.39	
V14312	11.2015	41.3861	20.058	21.57	...	22.57	0.27	
V14361	11.2006	41.4493	21.210	21.21	19.32	22.36	0.48	Ma97 94
V3392	11.0229	41.4243	21.771	19.85	18.82	20.91	0.45	
V2294	11.0078	41.5020	22.216	20.01	19.02	21.15	0.47	
V14145	11.1950	41.4465	25.704	21.64	19.73	23.22	0.33	
V9029	11.0996	41.3533	35.861	20.31	18.62	21.39	0.32	

NOTE.—V10846 D31C was found in Paper I as V1562 D31B, with $P = 7.784$ days, $\langle V \rangle = 21.20$, and $\langle I \rangle = 20.43$. V9544 D31C was found as V643 D31B, with $P = 7.889$ days, $\langle V \rangle = 20.39$, and $\langle I \rangle = 19.52$. V8771 D31C was found as V129 D31B, with $P = 8.242$ days, $\langle V \rangle = 20.74$, and $\langle I \rangle = 19.58$. V12902 D31C was found as V2977 D31B, with $P = 8.518$ days, $\langle V \rangle = 21.80$, and $\langle I \rangle = 20.40$.

TABLE 3

DIRECT OTHER PERIODIC VARIABLES IN M31C

Name (D31C)	α (J2000.0) (deg)	δ (J2000.0) (deg)	P (days)	$\overline{V}$	$\overline{I}$	$\overline{B}$	σ_V	σ_I	σ_B	Comments
V156..........	10.9877	41.3845	27.8	21.18	20.00	22.45	0.49	0.22	0.76	RV Tau
V11327.......	11.1349	41.3930	33.5	20.97	19.71	21.43	0.15	0.09	0.24	
V5037........	11.0424	41.4547	37.2	21.72	...	23.36	0.30	...	0.29	
V5494........	11.0515	41.3655	40.9	20.81	20.17	21.06	0.15	0.18	0.09	
V8130........	11.0829	41.4698	41.8	21.31	19.94	22.06	0.22	0.15	0.16	
V1296........	11.0011	41.3400	50.4	21.36	19.46	23.15	0.37	0.13	0.48	
V14350.......	11.2033	41.3398	56.3	21.36	19.71	...	0.55	0.21	...	
V3830........	11.0256	41.5107	56.4	20.72	19.96	...	0.14	0.13	...	
V1213........	10.9989	41.3831	58.6	21.73	19.66	23.24	0.33	0.17	0.30	
V5583........	11.0529	41.3526	59.9	21.37	19.75	23.04	0.24	0.22	0.39	
V11667.......	11.1391	41.4679	63.6	20.63	19.42	21.41	0.27	0.18	0.11	RV Tau
V8416........	11.0869	41.4684	72.0	21.62	20.09	...	0.62	0.37	...	
V13328.......	11.1725	41.4973	73.3	21.67	19.97	22.73	0.33	0.15	0.10	
V8612........	11.0922	41.3798	83.5	20.24	19.70	20.89	0.29	0.31	0.27	RV Tau
V5340........	11.0475	41.4341	85.3	21.21	...	22.33	0.25	...	0.54	
V13821.......	11.1879	41.3777	86.6	21.62	19.23	22.71	0.25	0.09	0.18	
V1485........	11.0030	41.3578	86.8	20.61	19.96	21.46	0.25	0.22	0.10	
V5776........	11.0518	41.4741	87.0	21.38	19.48	23.07	0.32	0.15	0.15	
V10998.......	11.1257	41.4913	88.0	20.56	19.93	21.33	0.15	0.12	0.18	
V5633........	11.0524	41.3904	92.3	21.75	20.45	23.10	0.28	0.30	0.28	
V13725.......	11.1842	41.4296	92.4	20.93	17.97	22.98	0.17	0.05	0.28	LP
V9904........	11.1114	41.3963	93.4	21.55	19.45	...	0.48	0.15	...	
V5433........	11.0498	41.3979	93.8	22.10	...	...	0.51	...	...	
V7386........	11.0716	41.4897	94.4	21.33	19.49	23.38	0.69	0.17	0.16	
V12847.......	11.1635	41.4683	95.1	21.18	19.55	22.80	0.45	0.21	0.23	
V11256.......	11.1332	41.4051	95.2	21.57	19.91	23.20	0.32	0.17	0.35	
V2589........	11.0152	41.3759	96.2	21.84	20.81	23.27	0.39	0.45	0.35	
V2724........	11.0175	41.3498	97.0	21.19	19.55	23.44	0.44	0.26	0.29	
V9404........	11.1038	41.3895	97.4	20.08	16.75	21.93	0.11	0.08	0.08	LP
V14366.......	11.2033	41.3553	98.0	21.21	19.69	22.82	0.36	0.26	0.21	
V3851........	11.0285	41.4277	98.3	20.91	18.99	22.73	0.30	0.20	0.21	
V1938........	11.0045	41.4926	98.6	20.95	19.32	22.61	0.28	0.15	0.27	
V3805........	11.0294	41.3836	99.1	21.20	19.68	22.53	0.18	0.10	0.13	
V2679........	11.0174	41.3357	99.3	20.92	18.97	22.54	0.32	0.27	0.21	
V2136........	11.0081	41.4458	100.2	20.35	19.34	21.09	0.15	0.11	0.27	
V7892........	11.0818	41.3915	104.8	21.22	19.56	22.09	0.44	0.28	0.16	
V8038........	11.0851	41.3495	121.6	21.18	19.85	22.25	0.19	0.16	0.33	

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, respectively. However, both the sparse photometry and the small samples (11 Cepheids in M33 and 38 Cepheids in M31) do not 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, 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) and Stanek et al. (1998, hereafter Paper II), the first two papers of this series, we presented the catalogs of variable stars found in two fields in M31, called M31B and M31A. Here we present the catalog of variables from the next field, M31C. 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, 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 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-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.

TABLE 4

DIRECT MISCELLANEOUS VARIABLES IN M31C

Name (D31C)	α (J2000.0) (deg)	δ (J2000.0) (deg)	$\overline{V}$	$\overline{I}$	$\overline{B}$	σ_V	σ_I	σ_B	Comments
V5497	11.0489	41.4535	16.25	15.33	17.62	0.07	0.05	0.02	
V9306	11.1039	41.3451	16.60	15.98	16.97	0.04	0.03	0.02	
V11839	11.1443	41.4177	16.74	16.61	16.65	0.04	0.03	0.01	
V9102	11.1007	41.3543	16.74	15.64	17.49	0.04	0.03	0.04	
V12381	11.1542	41.4424	17.12	16.52	17.54	0.04	0.02	0.03	
V13814	11.1854	41.4551	18.07	17.65	18.34	0.05	0.03	0.03	
V13102	11.1691	41.4512	18.16	16.77	19.52	0.07	0.03	0.04	
V13833	11.1854	41.4678	18.25	16.67	19.09	0.05	0.04	0.03	
V9360	11.1033	41.3911	18.84	16.72	20.50	0.04	0.04	0.05	
V10916	11.1269	41.4099	19.13	16.78	22.44	0.12	0.19	0.15	
V11413	11.1367	41.3870	19.39	18.54	19.98	0.07	0.07	0.08	
V8969	11.0983	41.3713	19.63	17.13	22.20	0.07	0.02	0.10	
V14370	11.1986	41.5138	19.72	16.69	...	0.12	0.06	...	V4062 D31B
V13441	11.1767	41.4471	19.94	16.53	21.00	0.23	0.20	0.06	
V5768	11.0547	41.3761	20.03	19.40	20.39	0.09	0.08	0.04	
V6175	11.0605	41.3568	20.14	17.32	22.67	0.12	0.04	0.14	
V9115	11.1004	41.3696	20.23	17.77	22.05	0.10	0.03	0.11	
V5588	11.0488	41.4869	20.95	19.66	21.64	0.19	0.11	0.32	
V5283	11.0471	41.4166	21.02	19.01	22.30	0.41	0.11	0.17	
V433	10.9907	41.3868	21.07	19.06	22.56	0.24	0.26	0.13	
V9205	11.0987	41.4678	21.15	19.30	23.42	0.74	0.48	0.36	
V499	10.9906	41.4050	21.16	19.53	22.33	0.24	0.17	0.11	
V14148	11.1968	41.3900	21.16	17.93	...	0.37	0.40	...	
V7581	11.0783	41.3585	21.26	...	22.24	0.45	...	0.41	
V3225	11.0230	41.3558	21.30	19.27	23.49	0.32	0.17	0.17	
V4241	11.0321	41.4616	21.66	18.41	...	0.34	0.09	...	
V8170	11.0830	41.4826	21.71	...	23.18	0.34	...	0.39	
V11642	11.1412	41.3844	21.74	19.89	23.04	0.31	0.12	0.35	
V4674	11.0385	41.4262	21.83	19.29	23.39	0.45	0.21	0.39	
V2346	11.0116	41.4046	21.87	19.86	23.38	0.46	0.39	0.25	
V8443	11.0880	41.4442	21.95	20.38	...	0.35	0.27	...	

NOTE.—Variable V14370 D31C was also found in Paper I.

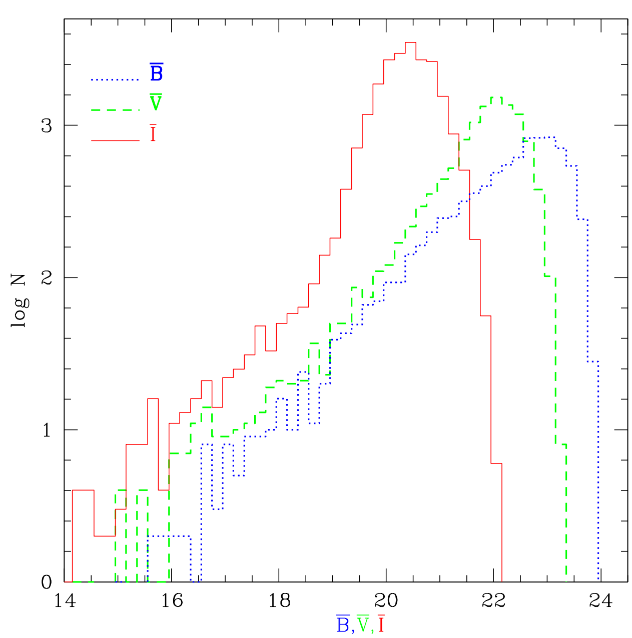

FIG. 1.—Distributions in $\overline{B}$ (*dotted line*), $\overline{V}$ (*dashed line*), and $\overline{I}$ (*solid line*) of stars in the field M31C.

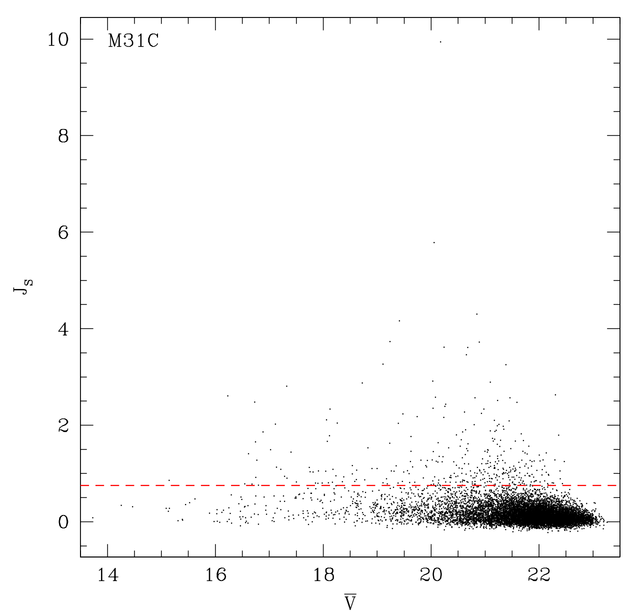

FIG. 2.—Variability index J_S vs. mean V magnitude for 11,262 stars in the field M31C with $N_{good} > 80$. Dashed line at $J_S = 0.75$ defines the cutoff applied for variability.

TABLE 5

LIGHT CURVES OF ECLIPSING BINARIES IN M31C

HJD − 2,450,000	Magnitude	σ_{mag}
V9037 D31C:		
B band:		
687.9796......	19.337	0.012
690.7614......	19.210	0.011
691.9609......	19.261	0.014
694.7742......	19.210	0.013
694.8080......	19.228	0.013
695.7386......	19.204	0.012
696.7953......	19.209	0.011
696.8315......	19.203	0.011
714.8218......	19.367	0.015
730.8074......	19.199	0.010
V9037 D31C:		
I band:		
333.0075......	19.134	0.050
333.9487......	19.136	0.047
334.8880......	19.368	0.055
335.9670......	19.118	0.046
337.9142......	19.177	0.050
338.9630......	19.111	0.052
339.8997......	19.119	0.048
341.8702......	19.040	0.048
345.9926......	19.144	0.049
348.7098......	19.397	0.067
349.7247......	19.114	0.050
349.7330......	19.090	0.047
350.8342......	19.142	0.050
350.8430......	19.138	0.045
351.7529......	19.207	0.060
351.7612......	19.160	0.052
353.8649......	19.043	0.072
354.9803......	19.156	0.055
355.8160......	19.143	0.049
355.8243......	19.146	0.052
357.8781......	19.450	0.050
357.8880......	19.401	0.052
358.8218......	19.140	0.052
358.8312......	19.088	0.050
359.9288......	19.103	0.048
361.7438......	19.132	0.052
361.8853......	19.160	0.050
361.9725......	19.053	0.047
362.7310......	19.144	0.049
362.9138......	19.122	0.049
363.7551......	19.350	0.048
363.8905......	19.320	0.060
364.9251......	19.135	0.048
365.7657......	19.137	0.048
366.7666......	19.145	0.050
367.7434......	19.108	0.067

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 M31C

HJD − 2,450,000	Magnitude	σ_{mag}
V2294 D31C:		
B band:		
687.9796......	20.402	0.026
690.7614......	20.366	0.028
691.9609......	20.696	0.036
694.7742......	20.970	0.055
694.8080......	21.044	0.054
695.7386......	21.278	0.049
696.7953......	21.408	0.066
696.8315......	21.335	0.046
714.8218......	20.741	0.040
730.8074......	21.975	0.078
V2294 D31C:		
I band:		
333.0075......	18.739	0.045
333.9487......	18.686	0.036
334.8880......	18.724	0.041
335.9670......	18.767	0.042
337.9142......	18.824	0.041
338.9630......	18.832	0.038
339.8997......	18.882	0.041
341.8702......	18.994	0.046
345.9926......	19.239	0.081
348.7098......	19.535	0.112
349.7247......	19.444	0.098
349.7330......	19.488	0.113
350.8342......	19.537	0.136
350.8430......	19.405	0.102
351.7529......	19.585	0.144
354.9803......	18.722	0.049
355.8160......	18.680	0.041
355.8243......	18.816	0.055
357.8781......	18.763	0.046
357.8880......	18.710	0.045
358.8218......	18.755	0.043
358.8312......	18.766	0.038
359.9288......	18.849	0.050
361.7438......	18.865	0.038
361.8853......	18.857	0.038
361.9725......	18.895	0.044
362.7310......	18.884	0.040
362.9138......	18.964	0.045
363.7551......	18.956	0.043
363.8905......	19.035	0.052
364.9251......	19.059	0.048
365.7657......	19.084	0.046
366.7666......	19.153	0.050
367.7434......	19.288	0.087
368.8863......	19.283	0.078

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.

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 5–8 times per night in the *V* band,

TABLE 7

LIGHT CURVES OF OTHER PERIODIC VARIABLES IN M31C

HJD − 2,450,000	Magnitude	σ_{mag}
V156 D31C:		
B band:		
687.9796......	23.854	0.507
690.7614......	23.841	0.508
696.7953......	23.563	0.388
730.8074......	22.266	0.101
V156 D31C:		
I band:		
333.0075......	20.081	0.118
333.9487......	20.105	0.114
334.8880......	20.060	0.102
335.9670......	20.102	0.098
337.9142......	19.960	0.089
338.9630......	19.905	0.083
339.8997......	19.836	0.091
341.8702......	19.881	0.100
345.9926......	19.999	0.092
348.7098......	20.020	0.107
349.7247......	20.015	0.107
349.7330......	20.044	0.107
350.8342......	19.836	0.086
350.8430......	19.874	0.098
351.7529......	19.905	0.094
351.7612......	19.905	0.113
353.8649......	19.815	0.139
354.9803......	19.954	0.115
355.8160......	20.032	0.115
355.8243......	19.975	0.101
358.8218......	20.314	0.114
358.8312......	20.468	0.139
359.9288......	20.282	0.115
361.7438......	20.248	0.104
361.8853......	20.399	0.158
361.9725......	20.404	0.150
362.7310......	20.241	0.111
362.9138......	20.282	0.118
363.7551......	20.086	0.111
363.8905......	20.175	0.117
364.9251......	19.999	0.098
365.7657......	19.883	0.070
366.7666......	19.785	0.085
367.7434......	19.779	0.101
368.8863......	19.751	0.091
370.8412......	19.794	0.094
371.7275......	19.807	0.095
372.7778......	19.762	0.078
373.9355......	20.034	0.139
374.6907......	19.902	0.095
377.7541......	19.954	0.108

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 M31C

HJD − 2,450,000	Magnitude	σ_{mag}
V433 D31C:		
B band:		
687.9796......	22.653	0.156
690.7614......	22.644	0.143
691.9609......	22.550	0.173
694.7742......	22.378	0.156
694.8080......	22.525	0.179
695.7386......	22.804	0.181
696.7953......	22.685	0.167
696.8315......	22.396	0.118
714.8218......	22.602	0.153
730.8074......	22.551	0.114
V433 D31C:		
I band:		
333.0075......	18.834	0.049
333.9487......	19.194	0.082
334.8880......	19.181	0.055
335.9670......	19.073	0.058
337.9142......	19.219	0.060
338.9630......	19.211	0.052
339.8997......	19.159	0.057
341.8702......	19.336	0.069
345.9926......	19.104	0.102
348.7098......	18.776	0.051
349.7247......	18.673	0.069
349.7330......	18.658	0.072
350.8342......	18.879	0.121
350.8430......	18.618	0.069
351.7529......	18.844	0.055
351.7612......	18.758	0.050
353.7496......	18.912	0.113
353.8649......	18.839	0.095
354.9803......	18.708	0.095
355.8160......	18.870	0.058
355.8243......	18.924	0.058
358.8218......	18.776	0.050
358.8312......	18.790	0.050
359.9288......	18.725	0.050
361.7438......	19.193	0.072
361.9725......	19.247	0.082
362.7310......	19.247	0.095
362.9138......	19.354	0.082
363.7551......	19.284	0.110
363.8905......	19.300	0.075
364.9251......	19.247	0.080
365.7657......	19.269	0.111
366.7666......	19.210	0.075
367.7434......	19.368	0.079
368.8863......	19.275	0.122

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.

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 observed, in 1996 and 1997, at the FLWO 1.2 m telescope, whose main target was M33.

In this paper we present the results for the M31C field. We obtained for this field useful data during 29 nights at the MDM, collecting a total of 141 × 900 s exposures in *V* and 30 × 600 s exposures in *I*. We also obtained for this field useful data during 24 nights at the FLWO, in 1996 and

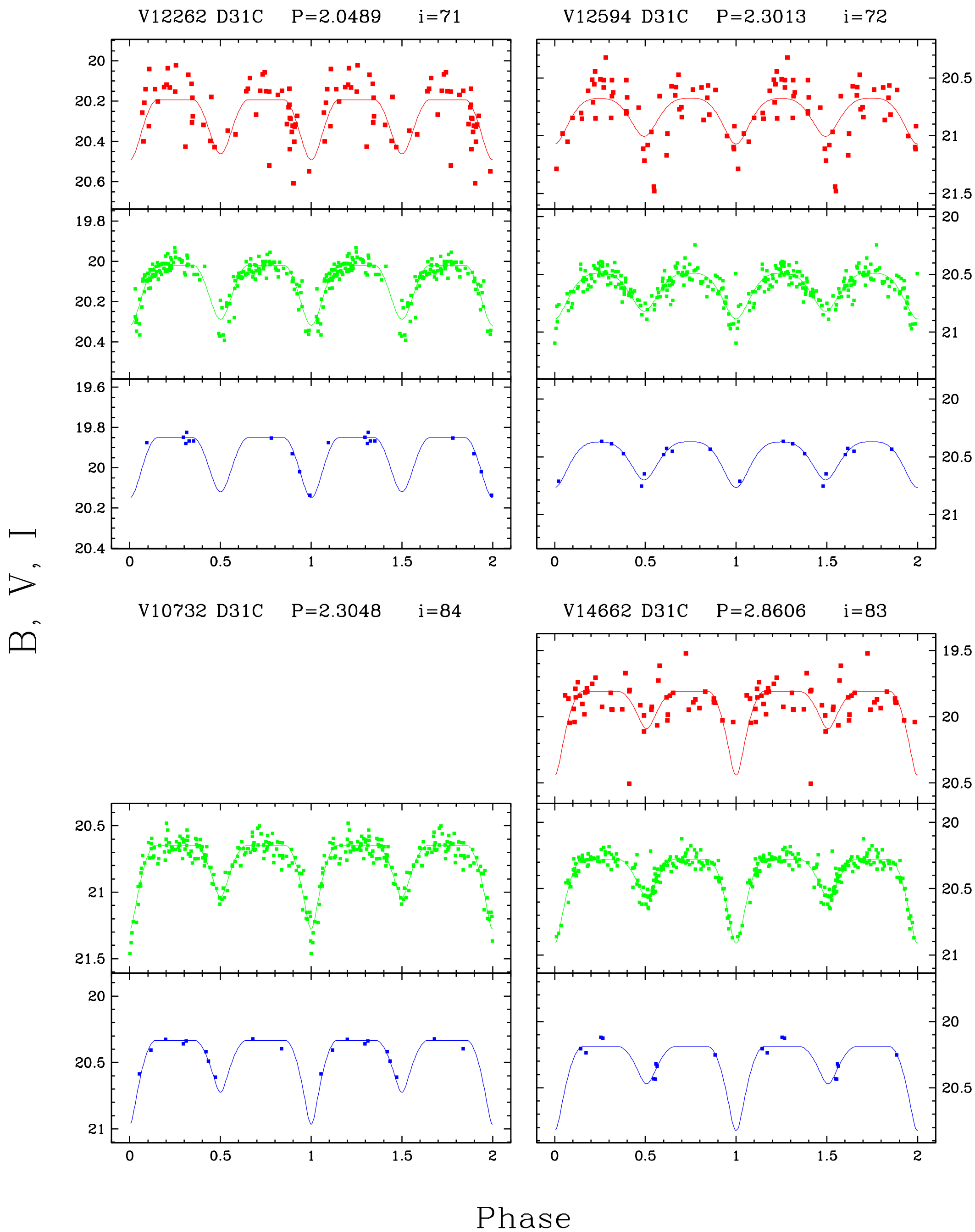

FIG. 3.—*BVI* light curves of eclipsing binaries found in the field M31C. The thin solid line represents the best-fit model for each star and photometric band. The *B*-band light curve is shown in the bottom panels and *I*-band light curve (when present) is shown in the top panels.

1997, collecting a total of 20 × 900 s exposures in *V*, 25 × 600 s exposures in *I*, and 10 × 1200 s exposures of *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 a given frame was transformed to the

[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 Associations of Universities for Research in Astronomy, Inc., under cooperative agreement with the NSF.

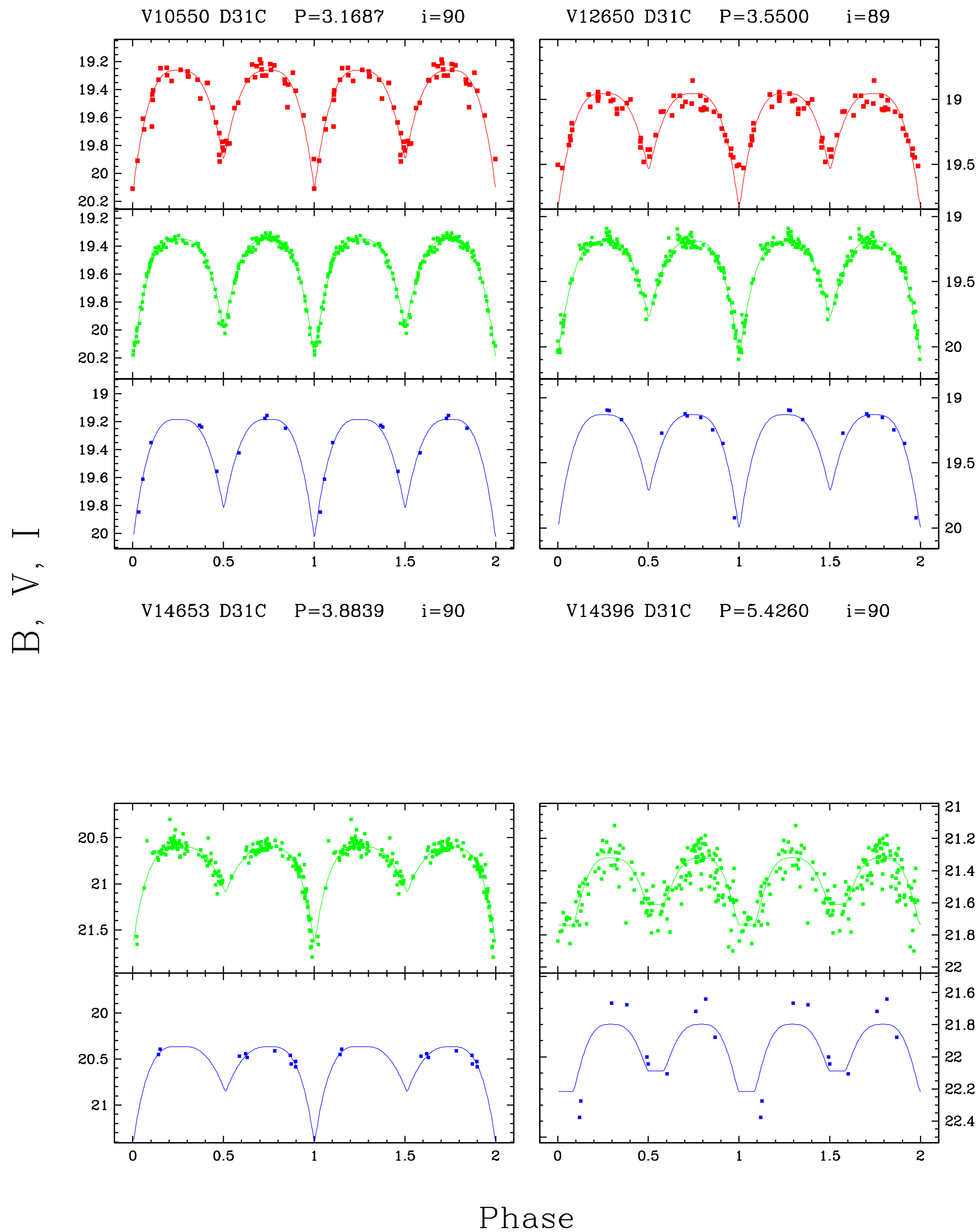

FIG. 3.—*Continued*

common instrumental system of the appropriate "template" image. Photometry obtained for the *B*, *V*, and *I* filters was combined into separate data bases. M31C images obtained at the FLWO were reduced using MDM "templates." In case of *B*-band images obtained at FLWO 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 M31C 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 0.012 mag in *V* and 0.024 mag in $V-I$ between the FLWO and the MDM calibration, that is, well 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 31 $V < 20$ and 55 $I < 20$ common stars (there were no *B*-band data taken for the M31B field) in the overlap region between the fields M31B and M31C. There was an offset of 0.034 mag in *V* and 0.024 mag in *I*. We also derived equatorial coordinates for all objects included in the data bases for the *V* filter. The transformation from rectangular coordinates to equatorial coordinates was derived using $\sim$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

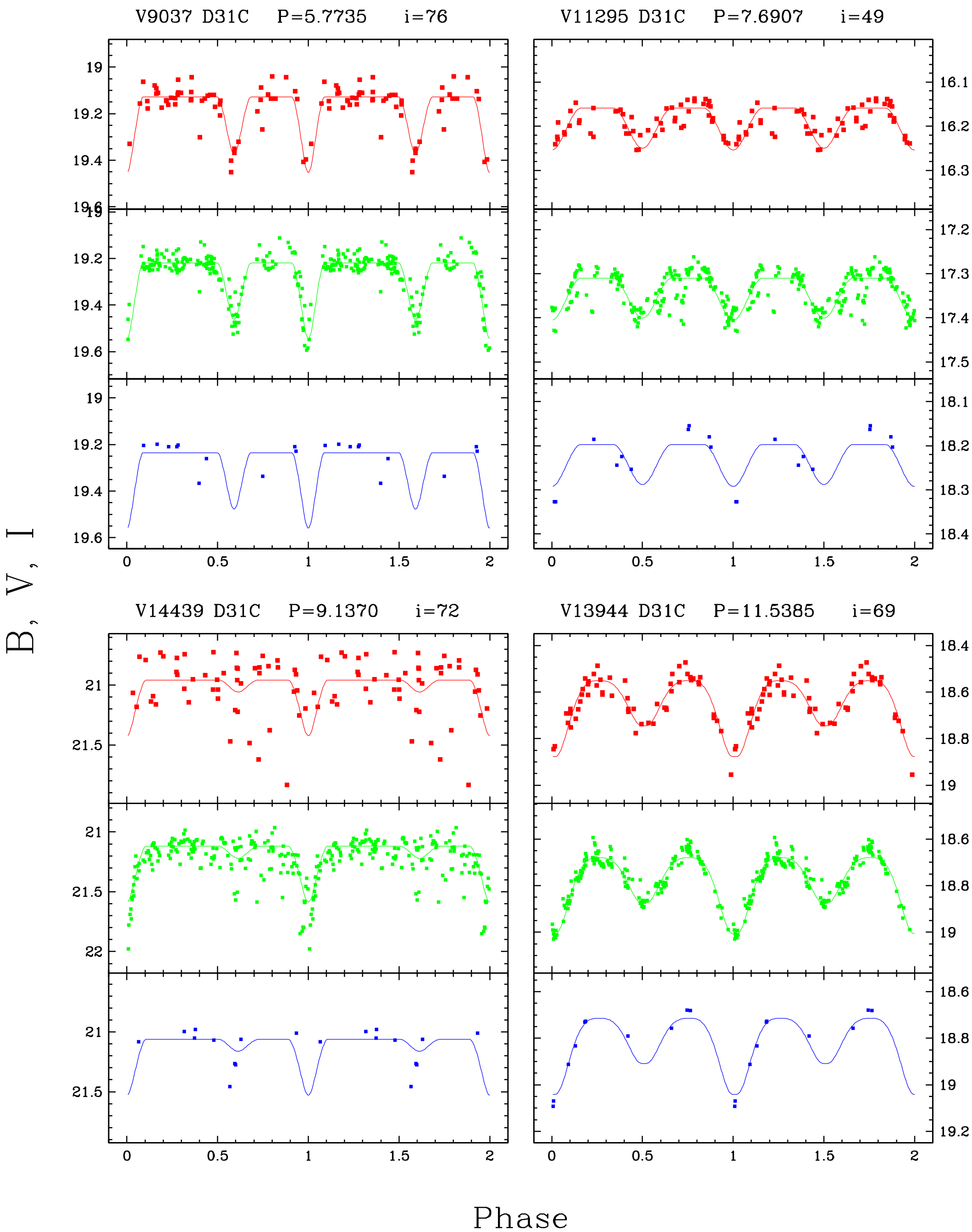

FIG. 3.—*Continued*

described in the previous section produces data bases of calibrated *BVI* magnitudes and their standard errors. The *BV* data bases for M31C field contain 15120 stars, with up to 161 measurements in *V* and up to 10 measurements in *B*, and the *I* data base contains 28,441 stars with up to 55 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 0–10 points are removed, leaving the majority of stars with roughly $N_{\rm good} \sim 150$–160 *V* measurements. For further analysis, we use only those stars that have at least $N_{\rm good} > N_{\rm max}/2 (=80)$ measurements. There are 11,263 such stars in the *V* data base of the M31C 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

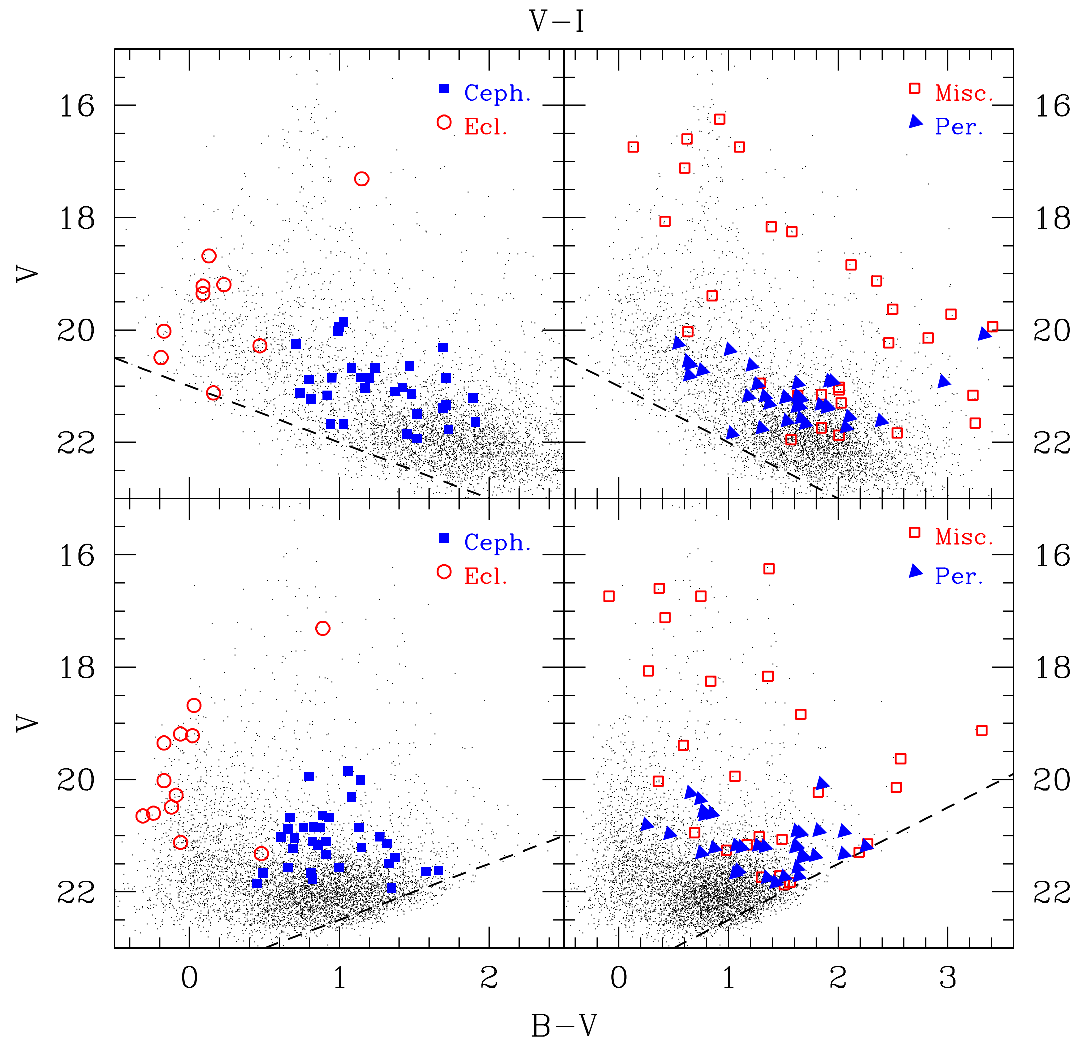

FIG. 4.—V, $V-I$ (*top*) and B, $B-V$ (*bottom*) CMDs for the variable stars found in the field M31C. The eclipsing binaries and Cepheids are plotted in the left panels, and the other periodic variables and miscellaneous variables are plotted in the right panels. The dashed lines correspond to the I detection limit of $I \sim 21$ mag (*top*) and the B detection limit of $B \sim 23.5$ mag (*bottom*).

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 data base. We used a cutoff of $J_{S,\mathrm{min}} = 0.75$ and additional cuts described in Paper I to select 313 candidate variable stars (about 3% of the total number of 11,263). In Figure 2 we plot the variability index J_S versus apparent visual magnitude $\bar{V}$ for 11,262 stars with $N_{\mathrm{good}} > 80$.

5. PERIOD DETERMINATION, 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 55 I-band epochs and up to 10 B-band epochs, although for a variety of reasons some of the candidate variable stars do not have an B-band 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 313 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

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

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 before, for the broad classification of variables we

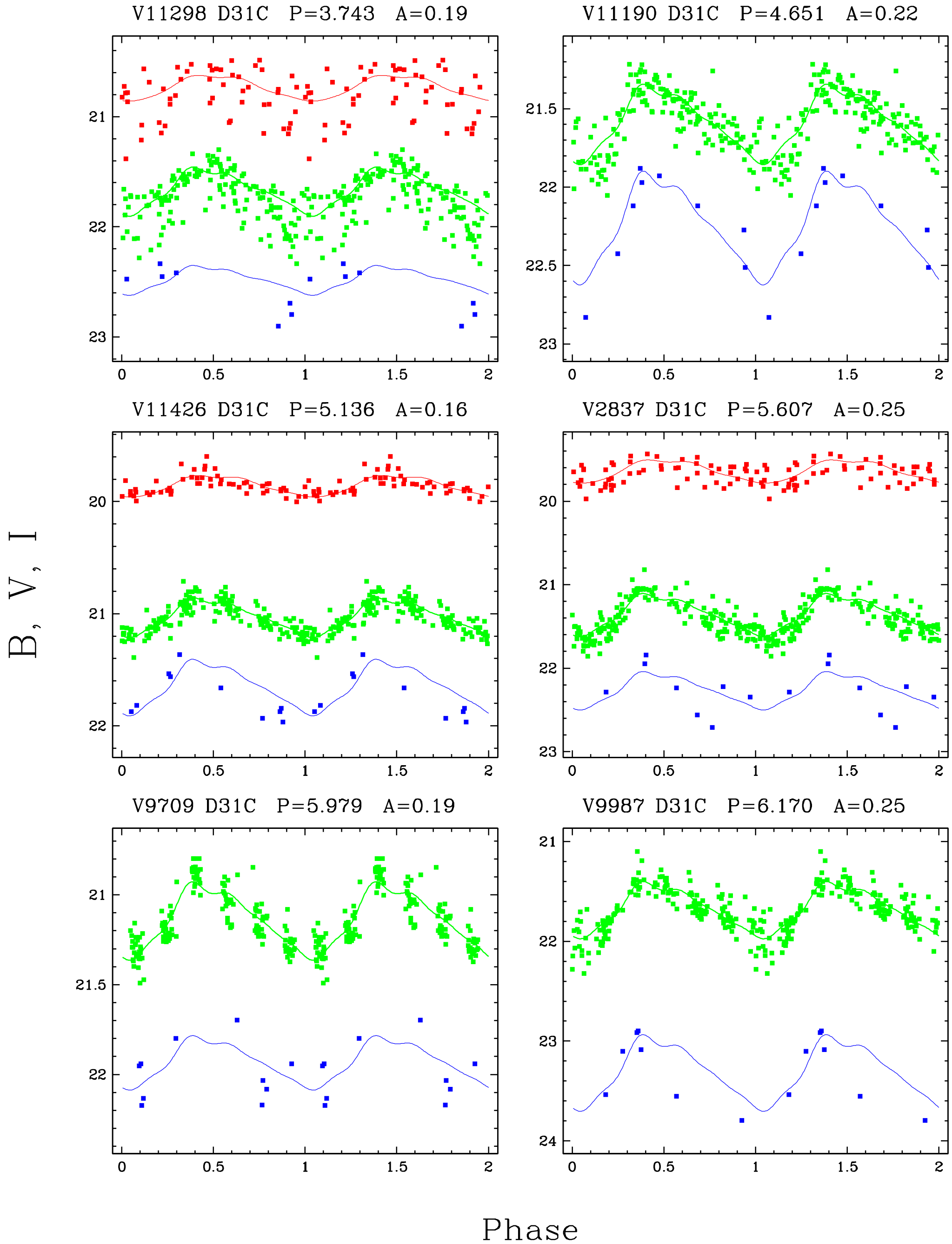

FIG. 5.—*BVI* light curves of Cepheid variables found in the field M31C. The thin solid line represents the best-fit Cepheid template for each star and photometric band. *B* (if present) is always the faintest, and *I* (if present) is always the brightest.

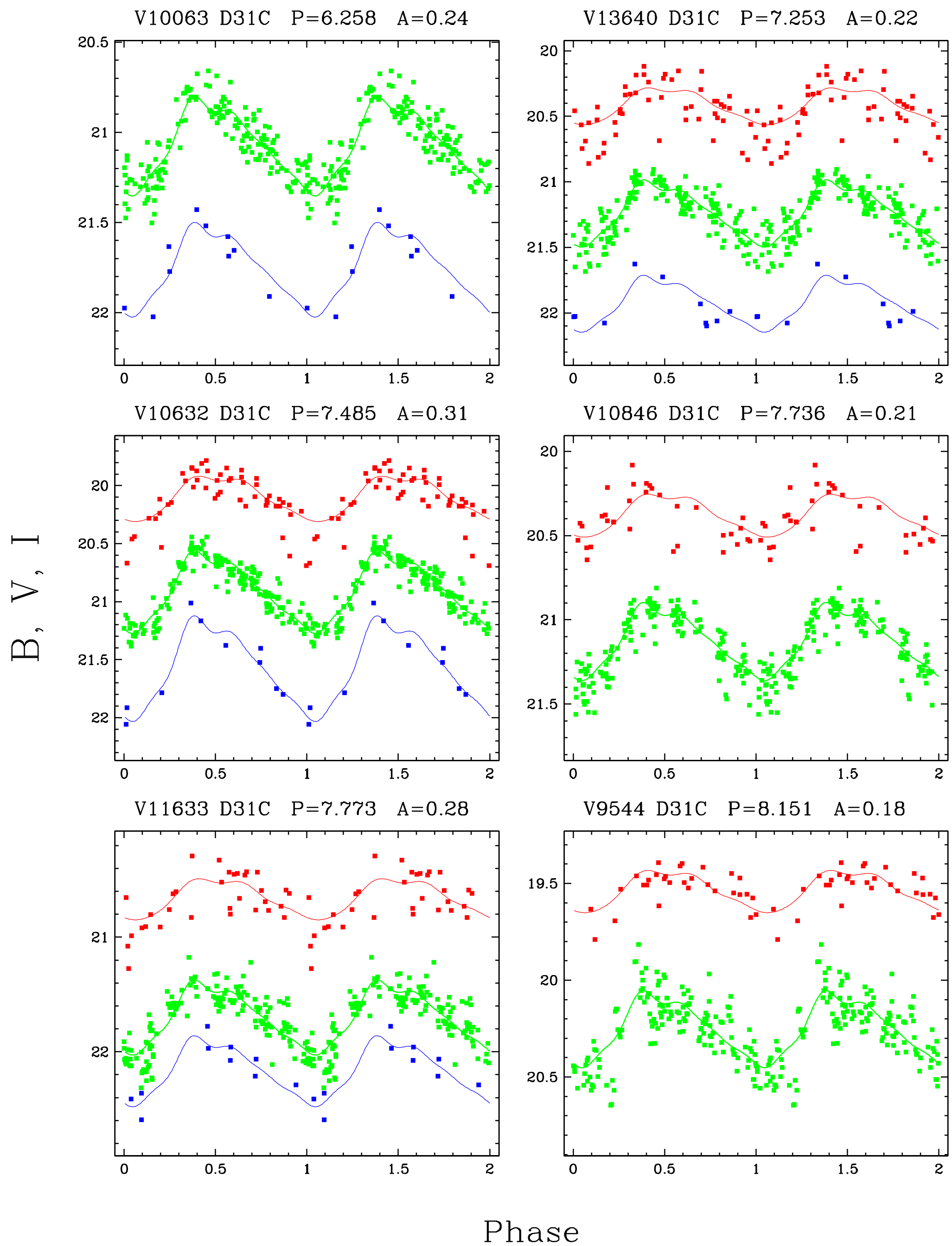

FIG. 5.—*Continued*

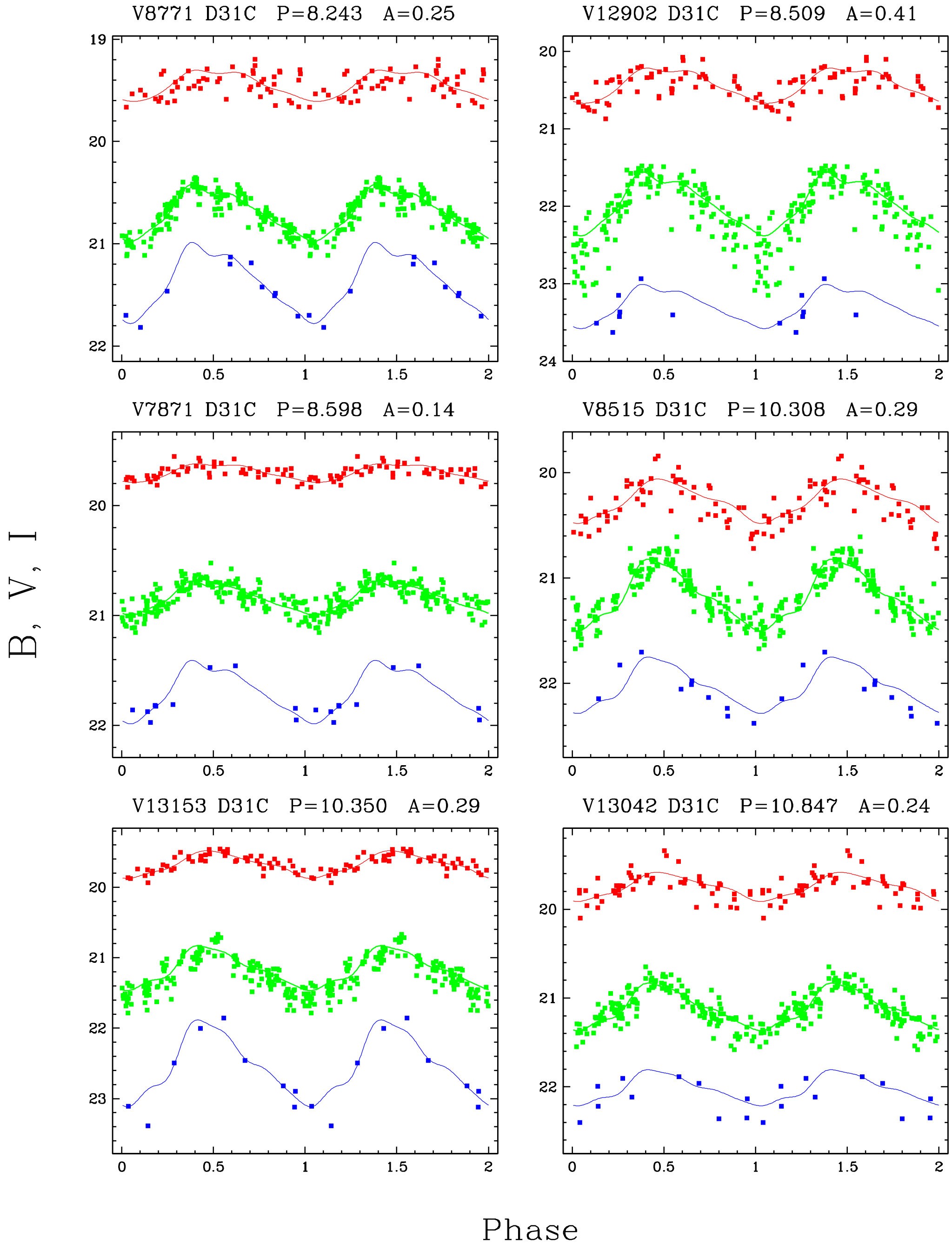

FIG. 5.—*Continued*

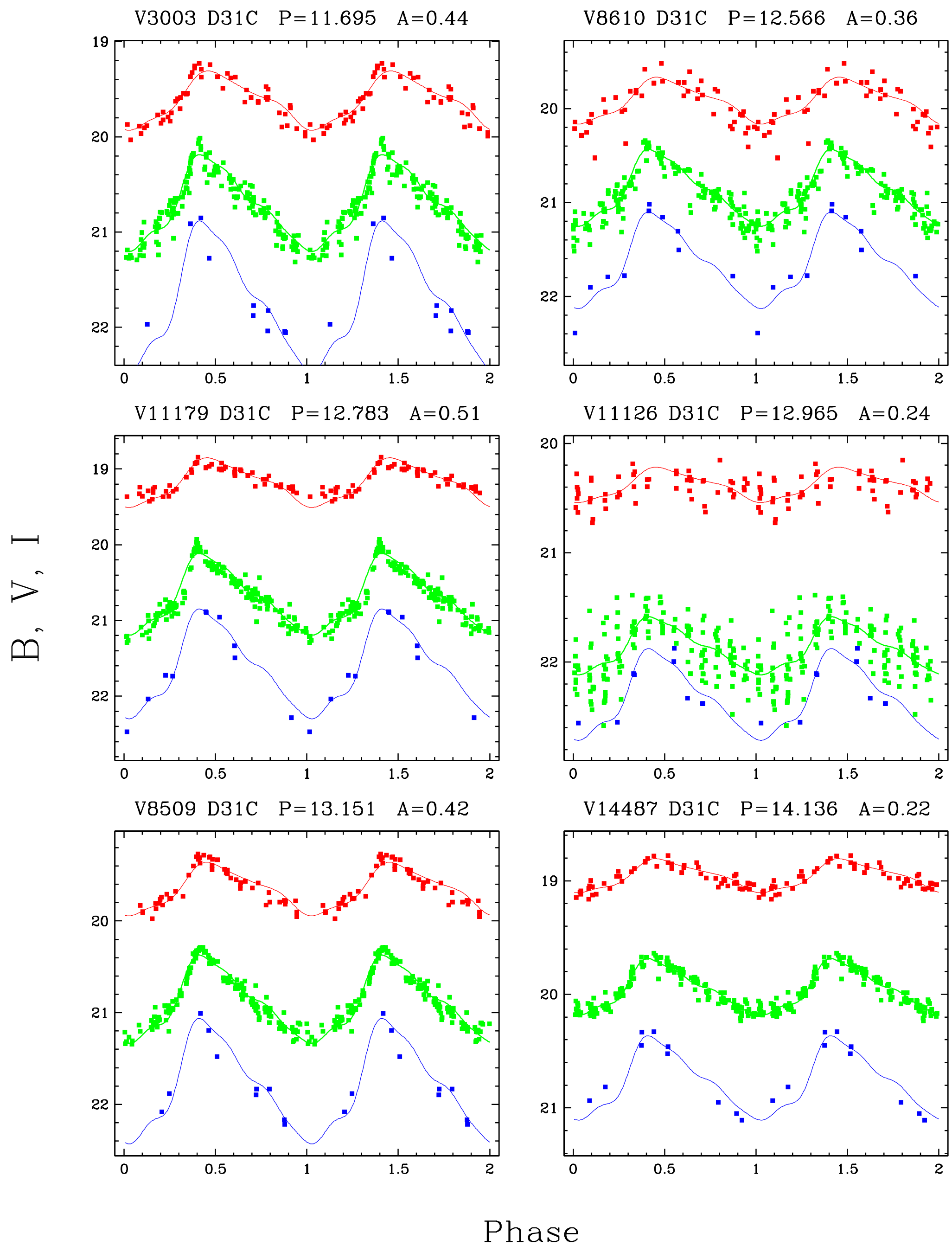

FIG. 5.—*Continued*

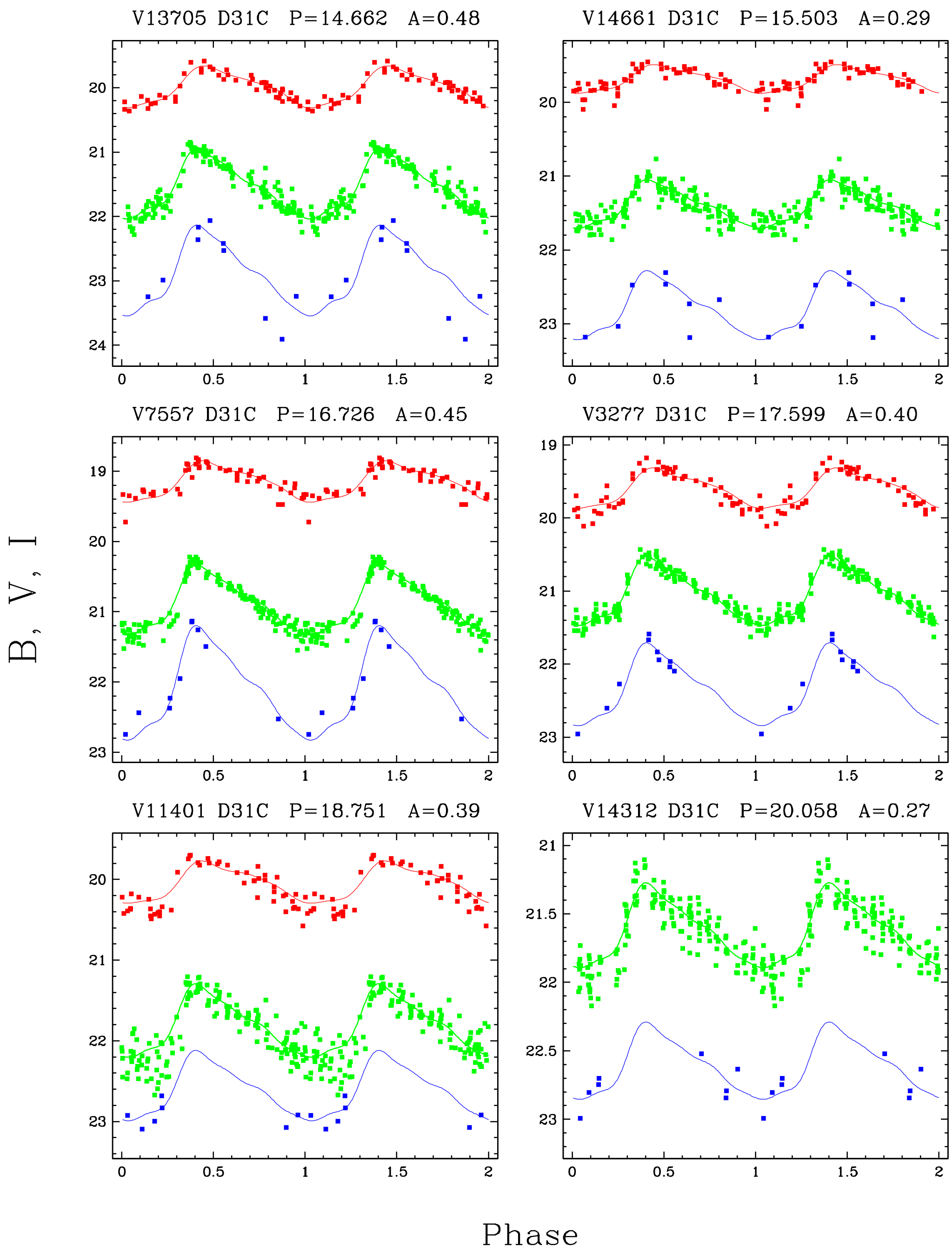

FIG. 5.—*Continued*

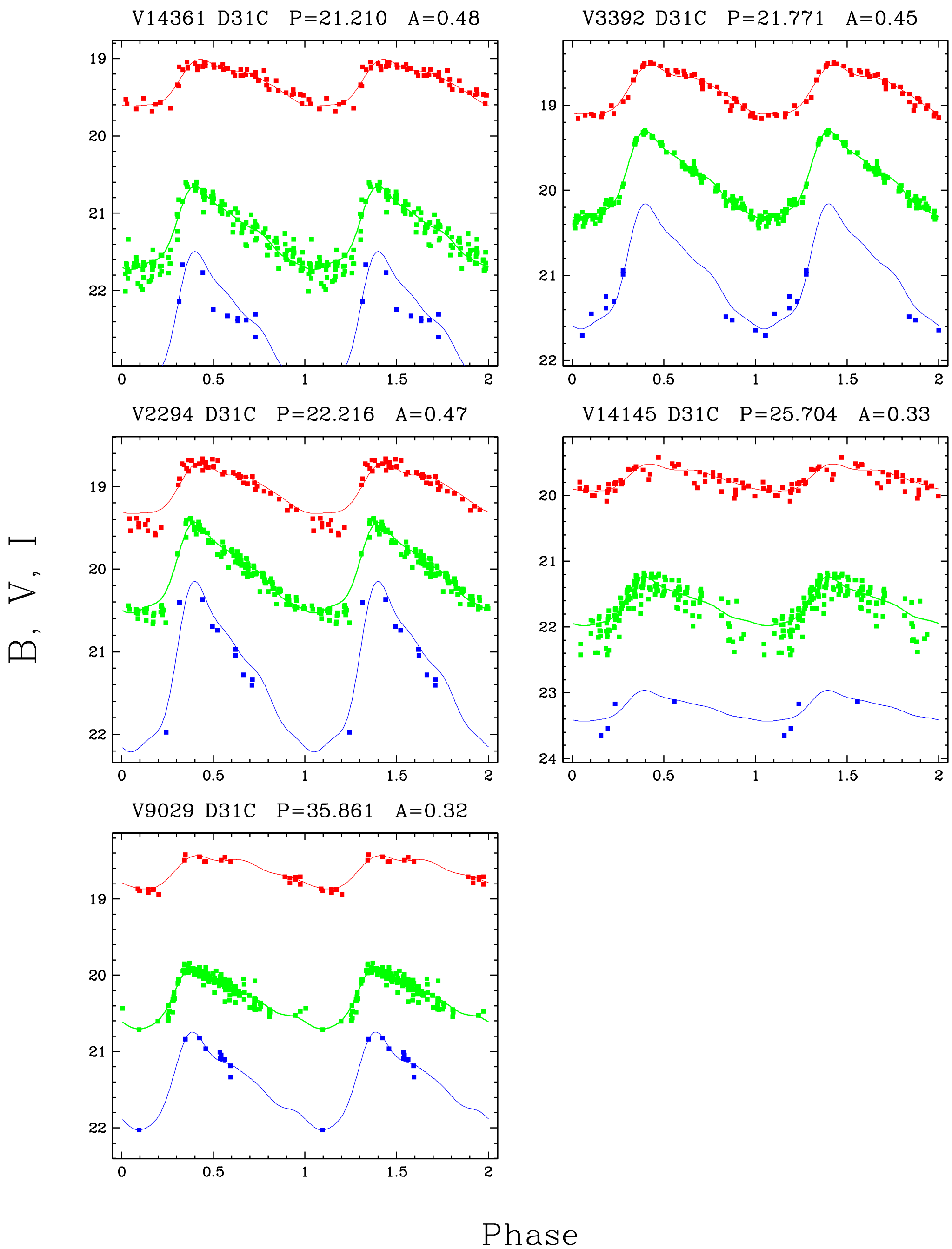

FIG. 5.—*Continued*

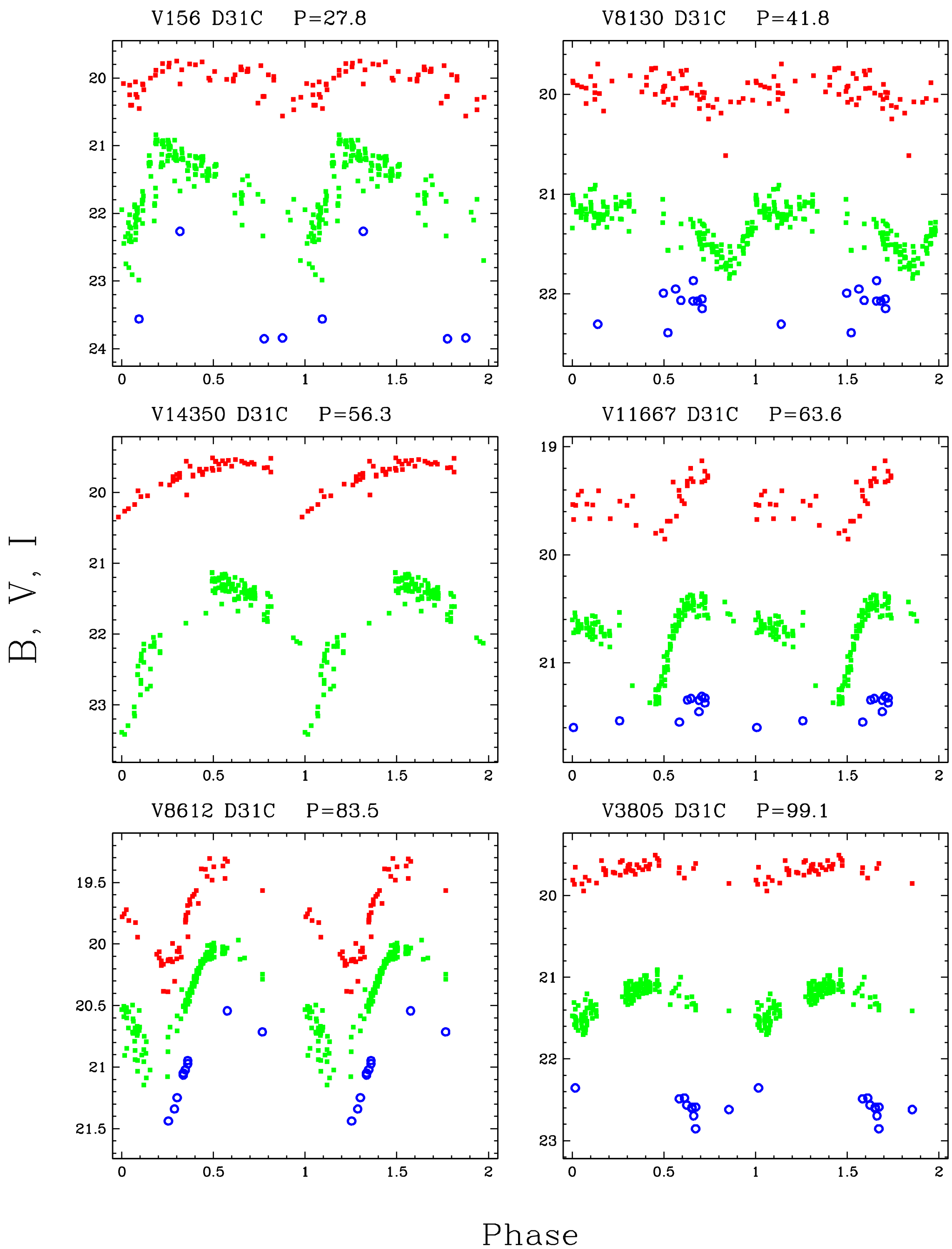

FIG. 6.—*BVI* light curves of selected other periodic variables found in the field M31C. *B*-band data (shown with the open circles, if present) is usually the faintest, and *I* (if present) is usually the brightest.

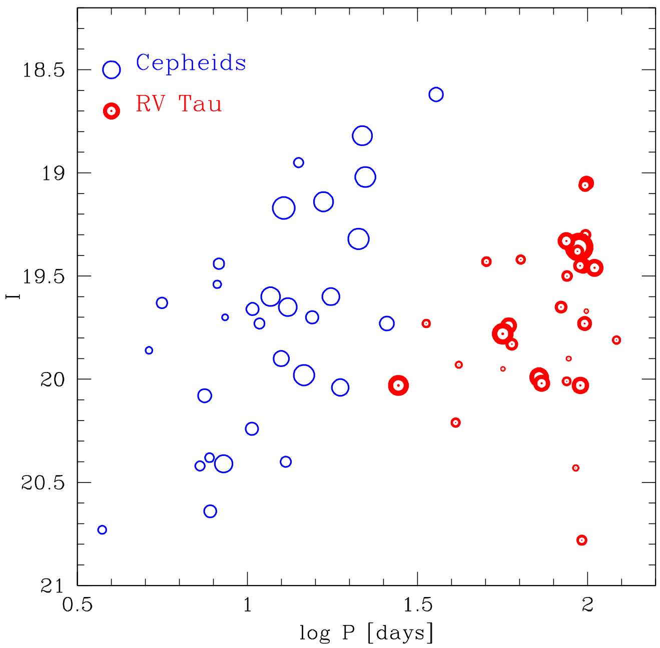

FIG. 7.—Diagram of log P vs. I for the Cepheids (*open circles*) and RV Tauri (*dotted circles*) variables. The sizes of the circles are proportional to the V amplitude of the variability.

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 17 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 the light curve is very noisy/chaotic. We decided to remove five dubious eclipsing binaries. The remaining 12 EBs with their parameters and light curves are presented in the § 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 100 variables passing all of the criteria (Papers I and II), but after investigating the CCD frames we removed 28 dubious "Cepheids," which leaves us with 62 probable Cepheids. Their parameters and light curves are presented in §§ 6.2 and 6.3.

After the preliminary selection of 17 eclipsing binaries and 100 possible Cepheids, we were left with 197 "other" variable stars. After raising the threshold of the variability index to $J_{S,\mathrm{min}} = 1.2$ (Paper I), we are left with 61 variables. After investigating the CCD frames we removed 30 dubious variables from the sample, which leaves 31 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 115 variable stars discovered by our survey in the field M31C.[5] The variable stars are named according to the following convention: letter V for "variable," the number of the star in the V data base, then the letter "D" for our project, DIRECT, followed by the name of the field, in this case (M)31C, e.g., V9037 D31C. 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" column by "Ma97 ID," where the "ID" is the identification number assigned by Ma97. We also cross-identify several variables found by us in Paper I.

6.1. *Eclipsing Binaries*

In Table 1, we present the parameters of the 12 eclipsing binaries in the M31C field. The BVI 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.

One of the eclipsing binaries found, V9037 D31C, is a very good DEB candidate, with deep eclipses and the ellipticity indicating that the system is young and unevolved. However, much better light curves are necessary to accurately establish the properties of the system. Two other systems, V10732 and V14662 D31C, also seem to be detached, but they are significantly fainter than V9037 D31C and therefore less suitable for follow-up.

Inspection of the V, $B-V$ color-magnitude diagram (Fig. 4) reveals that one of the candidate eclipsing binaries lands close to the Cepheid portion of the color-magnitude diagram (CMD). It turns out that this variable, V14396 D31C, is only marginally better fitted by a eclipsing binary light curve than by a Cepheid light curve with roughly half of the period, but we decided to keep it classified as an eclipsing binary.

6.2. *Cepheids*

In Table 2 we present the parameters of 35 Cepheids in the M31C field, sorted by the period P. For each Cepheid we present its name, J2000.0 coordinates, period P, flux-weighted mean magnitudes $\langle V \rangle$, and (when available) $\langle I \rangle$, and $\langle B \rangle$, and the V-band amplitude of the variation A. In Figure 5 we show the phased BVI 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

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

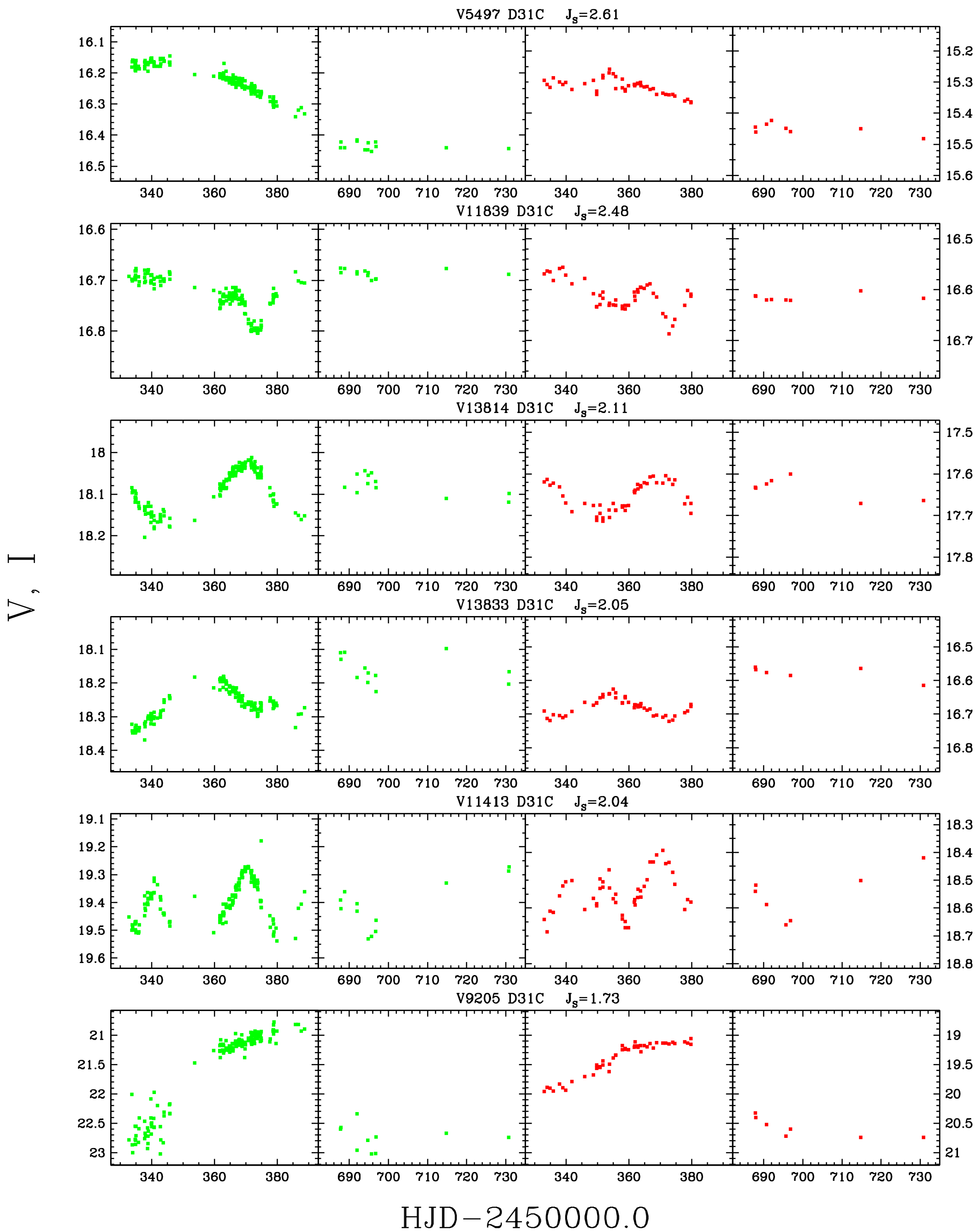

FIG. 8.—*VI* light curves of selected miscellaneous variables found in the field M31C. *I* (if present) is plotted in the two right-hand panels. *B*-band data are not shown.

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 preliminary classified as Cepheids we decided upon closer examination to classify them as "other periodic variables." In Table 3 we present the parameters of 37 possible periodic variables, other than Cepheids and eclipsing binaries, in the M31C field, sorted by the increasing period *P*. In Figure 6, 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 *VIB* 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.

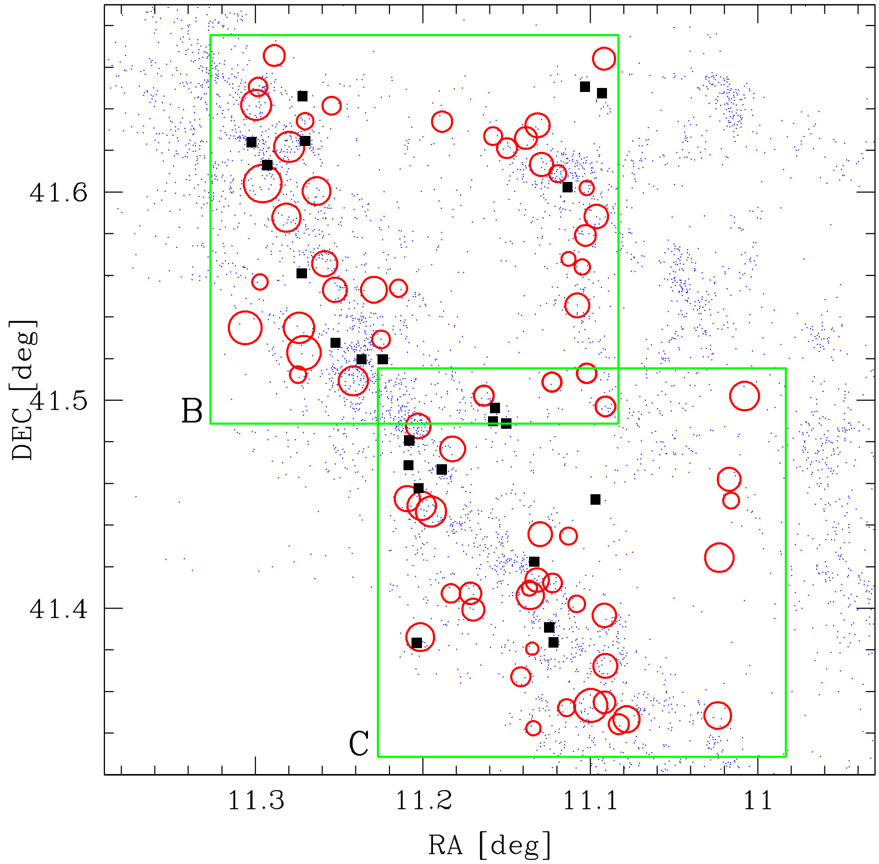

FIG. 9.—Location of eclipsing binaries (*squares*) and Cepheids (*circles*) in the fields M31C and M31B, along with the blue stars ($B-V<0.4$) selected from the photometric survey of M31 by Magnier et al. (1992) and Haiman et al. (1994). The sizes of the circles representing the Cepheids variables are proportional to the logarithm of their 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. 7).

6.4. *Miscellaneous Variables*

In Table 4, we present the parameters of 31 miscellaneous variables in the M31C field, sorted by increasing value of the mean magnitude V. In Figure 8 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 VIB 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; and Ir, irregular variable.

Most of the miscellaneous variables seem to represent the LP type of variability, with few variables showing irregular variations. However, inspection of the CMD (Fig. 4) reveals that many of the miscellaneous variables land in the CMD in the same area as the RV Tauri variables, which suggests they are Type II Cepheids.

6.5. *Comparison with Other Catalogs*

The area of M31C field has not been observed frequently before, and the only overlapping variable star catalog is given by Ma97. Out of 14 variable stars in Ma97 which are located in our M31C field, we cross-identified 13. Of these 13 stars, four (Ma97 79, 84, 88, 91) we did not classify as variables ($J_S = 0.72$, -0.04, 0.34, 0.43). Of the remaining nine stars we have classified eight as Cepheids and one as an eclipsing binary (see Tables 1 and 2 for cross-identifications.).

There was also by design a slight overlap between the M31C and M31B fields (Fig. 9). There were four Cepheids from the M31C field in the overlap region, and they were all cross-identified in the M31B catalog, with very similar properties of their light curves (see Table 2). There was only one eclipsing binary in the overlap from the M31C field, V12594 D31C, and it was cross-identified as V2763 D31B, again with very similar properties of its light curve (see Table 1). We also cross-identified one miscellaneous variable (see Table 4), out of three detected in the M31B field and one detected in the M31C field, which fell into the overlap region.

7. DISCUSSION

In Figure 4 we show V, $V-I$ and V, $B-V$ CMDs for the variable stars found in the field M31C. The eclipsing binaries and Cepheids are plotted in the left-hand panels, and the other periodic variables and miscellaneous variables are plotted in the right-hand panels. As expected, most of the eclipsing binaries occupy the blue upper main sequence of M31 stars, with the exception of the bright, probably foreground, W UMa system V13944 D31C. The Cepheid variables group near $B-V \sim 1.0$, with considerable scatter probably due to differential reddening across the field. The other periodic variable stars have positions on the CMD similar to the Cepheids. 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. Several brightest miscellaneous variables are probably foreground stars belonging to our Galaxy.

In Figure 9 we plot the location of eclipsing binaries and Cepheids in the fields M31C 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 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 the future paper (Sasselov et al. 1999).

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