THE ASTRONOMICAL JOURNAL, 118:2211–2228, 1999 November

DIRECT DISTANCES TO NEARBY GALAXIES USING DETACHED ECLIPSING BINARIES AND CEPHEIDS. V. VARIABLES IN THE FIELD M31F[1]

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Received 1999 May 3; accepted 1999 July 14

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 September 1996 and October 1997 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 fifth in the series, we present the catalog of variable stars found in the field M31F $[(\alpha, \delta) = (10\overset{\circ}{.}10, 40\overset{\circ}{.}72)$, J2000.0]. We have found 64 variable stars: four eclipsing binaries, 52 Cepheids and eight 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 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 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 is long overdue. Recently, Magnier et al. (1997, hereafter Ma97) surveyed large portions of M31 that have previously been ignored and found some 130 new Cepheid

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

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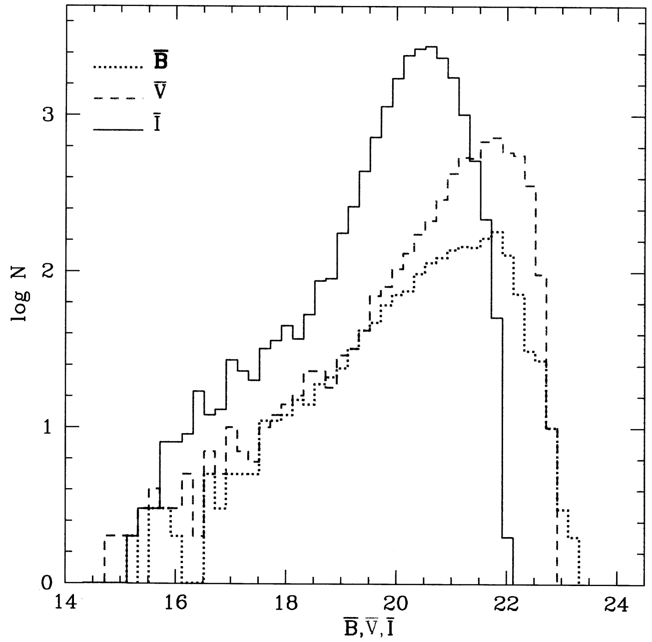

FIG. 1.—Distributions in *B* (*dotted line*), *V* (*dashed line*), and *I* (*continuous line*) of stars in the field M31F.

variable candidates. Their light curves are rather sparsely sampled, however, and only in the *V*-band.

In Kaluzny et al. (1998, 1999, hereafter Paper I and Paper IV) and Stanek et al. (1998, 1999, hereafter Paper II and Paper III), the first four papers of the series, we presented the catalogs of variable stars found in four fields in M31, called M31B, M31A, M31C, and M31D. Here we present the catalog of variables from the field M31F. 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 a brief discussion of the results in § 7.

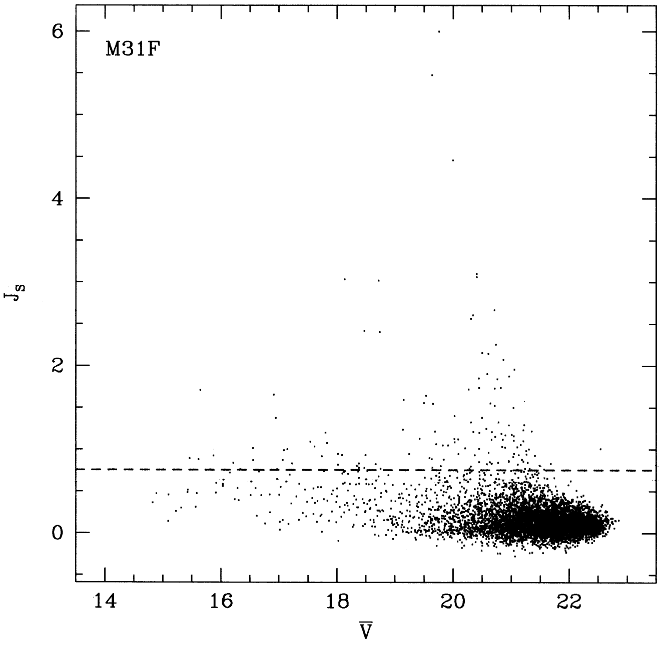

FIG. 2.—Variability index J_S vs. $\bar{V}$ magnitude for 5838 stars in the field M31F with $N_{\rm good} > 54$. Dashed line at $J_S = 0.75$ defines the cutoff applied for variability.

2. FIELDS SELECTION AND OBSERVATIONS

M31 was primarily observed in 1996 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 $0\farcs32$ pixel^{-1} and field of view of roughly 11 × 11 arcmin^2. 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 Paper I, Fig. 1). We selected six 11′ × 11′ fields, M31A–F, 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 1965).

In this paper we present the results for the M31F field. We obtained useful data for this field during 29 nights at the MDM, collecting a total of 28 × 900 s exposures in *V* and 2 × 600 s exposures in *I*. We also obtained useful data for this field during 22 nights at the FLWO in 1996 and 1997, collecting a total of 80 × 900 s exposures in *V*, 67 × 600 s exposures in *I*, and 7 × 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 common instrumental system of the appropriate "template" image. Assuming that all the effects of point-spread function (PSF) variability were modeled correctly on

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[3] The complete list of exposures for this field and related data files are available through the 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 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 National Science Foundation.

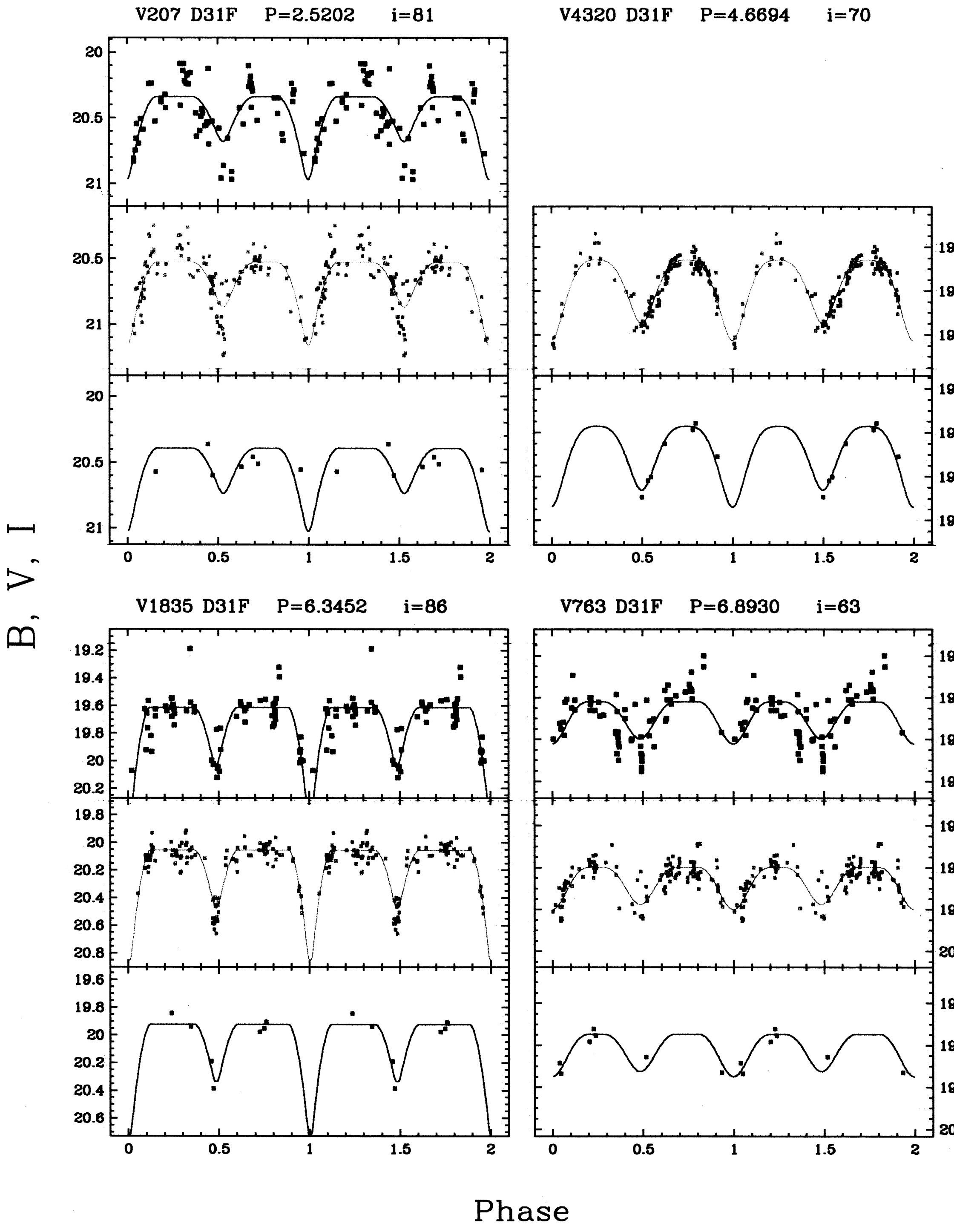

FIG. 3.—*BVI* light curves of eclipsing binaries found in the field M31F. The thin continuous line represents the best fit model for each star and photometric band. The *B*-band light curve is shown in the bottom panel and *I*-band light curve (when present) is shown in the top panel.

TABLE 1

DIRECT ECLIPSING BINARIES IN M31F

Name (D31F)	$\alpha_{J2000.0}$ (deg)	$\delta_{J2000.0}$ (deg)	P (days)	V_{max}	I_{max}	B_{max}	R_1	R_2	i (deg)	e	Comments
V207..........	10.2157	40.6399	2.5202	20.53	20.34	20.40	0.48	0.39	81	0.05	
V4320	10.1076	40.7456	4.6694	19.46	...	19.17	0.58	0.42	70	0.00	
V1835	10.1433	40.7184	6.3452	20.06	19.62	19.93	0.37	0.30	86	0.03	DEB
V763..........	10.1807	40.7263	6.8930	19.60	19.42	19.55	0.64	0.31	63	0.02	W UMa

TABLE 2

DIRECT Cepheids in M31F

Name (D31F)	$\alpha_{J2000.0}$ (deg)	$\delta_{J2000.0}$ (deg)	P (days)	$\langle V\rangle$	$\langle I\rangle$	$\langle B\rangle$	A
V3441	10.1201	40.7667	4.678	21.28	20.52	21.18	0.35
V4254	10.1111	40.6766	5.718	21.48	20.50	21.99	0.36
V7832	9.9963	40.7972	5.814	21.39	20.47	22.02	0.41
V3732	10.1189	40.6764	6.070	20.98	19.96	21.05	0.37
V3054	10.1243	40.7911	6.105	21.09	20.13	...	0.31
V893	10.1716	40.7771	6.505	21.64	20.71	...	0.40
V7441	10.0247	40.6533	6.514	21.43	19.88	...	0.37
V3860	10.1154	40.7284	6.529	21.24	19.65	22.08	0.36
V1599	10.1470	40.7687	6.640	20.94	19.86	21.78	0.28
V5856	10.0799	40.6725	6.660	21.24	20.37	21.99	0.32
V5711	10.0828	40.6802	6.707	21.07	20.10	21.87	0.43
V6623	10.0591	40.6814	6.999	20.86	20.04	...	0.35
V5886	10.0788	40.6903	7.458	21.12	20.54	21.91	0.36
V6406	10.0662	40.6569	7.563	20.95	20.24	...	0.35
V3289	10.1232	40.7453	7.599	20.89	19.76	20.77	0.27
V5893	10.0797	40.6513	7.655	21.00	20.02	21.70	0.34
V6962	10.0462	40.6923	7.782	21.31	20.47	...	0.24
V7741	10.0076	40.6885	8.099	21.03	20.17	20.81	0.24
V6098	10.0748	40.6395	8.471	20.52	19.52	...	0.28
V4855	10.0966	40.8035	9.064	20.70	19.70	...	0.30
V5498	10.0883	40.6611	9.387	20.72	20.27	20.98	0.24
V7074	10.0388	40.7778	9.478	20.78	19.70	21.51	0.30
V5097	10.0967	40.6804	9.662	20.66	19.92	21.16	0.25
V6483	10.0637	40.6739	9.736	20.83	20.13	21.20	0.23
V5994	10.0774	40.6532	9.886	20.67	19.53	21.45	0.22
V4556	10.1054	40.7022	9.894	20.54	19.41	21.20	0.25
V6195	10.0722	40.6463	9.924	21.21	20.05	22.54	0.35
V5178	10.0949	40.6807	9.932	20.30	19.30	20.18	0.22
V7393	10.0278	40.6364	9.937	20.50	19.51	21.15	0.31
V3550	10.1188	40.7607	10.468	20.55	19.85	21.03	0.32
V2320	10.1341	40.7656	10.868	20.27	19.54	20.60	0.34
V4125	10.1109	40.7332	11.139	20.46	19.63	21.11	0.31
V1549	10.1488	40.7569	11.764	20.72	19.68	21.49	0.35
V5442	10.0892	40.6766	11.902	19.65	18.58	19.45	0.16
V5696	10.0806	40.7520	12.287	20.74	19.54	21.62	0.43
V5598	10.0855	40.6741	12.311	20.34	19.45	20.96	0.37
V6267	10.0684	40.6995	12.324	20.38	19.30	19.27	0.17
V2156	10.1353	40.7925	12.831	20.37	19.40	20.76	0.27
V3373	10.1199	40.7971	12.872	20.94	19.55	21.81	0.41
V4955	10.0959	40.7808	13.034	20.70	19.67	21.45	0.41
V1633	10.1461	40.7760	13.043	21.30	19.85	...	0.45
V1619	10.1503	40.6545	13.141	20.61	19.45	21.47	0.34
V4682	10.1046	40.6552	13.297	20.73	19.30	21.72	0.34
V6640	10.0593	40.6558	13.761	19.67	...	...	0.18
V4861	10.0972	40.7849	13.991	20.47	19.31	21.22	0.41
V6503	10.0615	40.7215	15.210	20.77	19.55	21.44	0.38
V4708	10.1039	40.6631	15.690	20.50	19.33	21.38	0.35
V1893	10.1415	40.7417	16.756	18.79	17.47	19.54	0.18
V6208	10.0714	40.6561	17.572	19.74	18.78	20.28	0.48
V821	10.1760	40.7640	20.547	21.35	19.61	...	0.55
V602	10.1880	40.7392	31.416	21.05	19.12	...	0.31
V2203	10.1369	40.7306	55.373	17.94	17.17	18.32	0.17

TABLE 3

DIRECT Other Periodic Variables in M31F

Name (D31F)	$\alpha_{J2000.0}$ (deg)	$\delta_{J2000.0}$ (deg)	P (days)	$\bar{V}$	$\bar{I}$	$\bar{B}$	σ_V	σ_I	σ_B	Comments
V7438	10.0252	40.6442	5.1	20.41	19.41	21.02	0.15	0.11	0.13	Cepheid?

Note.—V7438 was identified by Baade & Swope (1965) as Cepheid variable 232 with $P = 5.12$ days.

TABLE 4

DIRECT Miscellaneous Variables in M31F

Name (D31F)	$\alpha_{J2000.0}$ (deg)	$\delta_{J2000.0}$ (deg)	$\bar{V}$	$\bar{I}$	$\bar{B}$	σ_V	σ_I	σ_B	Comments
V244	10.2103	40.7380	18.39	16.68	19.87	0.12	0.07	0.05	LP
V1665......	10.1460	40.7562	19.27	16.01	21.40	0.20	0.16	0.10	LP
V1724......	10.1446	40.7499	19.63	16.34	0.00	0.24	0.13	0.00	LP
V2285......	10.1373	40.6841	19.67	18.81	19.94	0.08	0.07	0.08	RV Tau?
V1229......	10.1590	40.7389	20.47	19.57	21.07	0.23	0.10	0.18	RV Tau?
V764	10.1775	40.8110	20.51	0.00	0.00	0.35	0.00	0.00	LP
V667	10.1852	40.7265	21.18	19.33	0.00	0.35	0.22	0.00	RV Tau?

the template frame, only an offset would be needed to accomplish the transformation. Since usually the PSF for the other frames was not as good as for the template, the offsets were computed locally for each star to compensate for this effect. For each star an individual offset was determined from bright stars with $\sigma_V < 0.03$ mag located within a radius of 500 pixels. If enough stars could not be found, the procedure was repeated within a radius of 750 pixels, and if that did not help a globally determined median offset

TABLE 5

Light Curves of Eclipsing Binaries in M31F

Name	Filter	HJD (2,450,000)	Mag	$\sigma_{\rm mag}$
V207 D31F......	B	705.9893	20.575	0.032
		706.7090	20.366	0.118
		706.7809	20.602	0.113
		714.7400	20.538	0.023
		714.9022	20.464	0.036
		714.9726	20.516	0.037
		730.6889	20.559	0.164
V207 D31F......	I	341.8947	20.423	0.114
		348.7354	20.600	0.127
		349.7707	20.352	0.096
		349.8176	20.469	0.106
		350.7771	20.325	0.113
		350.7787	20.427	0.113
		351.7003	20.911	0.243
		351.7018	20.971	0.262
		352.7022	20.775	0.191
		354.9341	20.677	0.221
		355.7594	20.383	0.117
		355.7605	20.356	0.120
		356.8498	20.427	0.115
		357.8992	20.814	0.123
		357.9216	20.750	0.121
		357.9370	20.548	0.114
		358.7571	20.466	0.107
		358.7672	20.646	0.120
		359.9603	20.626	0.133
		364.9481	20.351	0.124
		705.9810	20.528	0.124
		706.7248	20.127	0.127
		706.7726	20.531	0.126
		706.8702	20.582	0.129
		706.9021	20.963	0.180
		706.9341	20.865	0.194
		706.9905	20.661	0.259
		707.8790	20.240	0.132
		707.8978	20.380	0.126
		707.9061	20.322	0.125
		707.9143	20.289	0.129
		708.8468	20.092	0.108
		708.8551	20.407	0.133
		708.8875	20.145	0.134
		708.9024	20.090	0.114
		708.9106	20.221	0.107
		708.9366	20.239	0.136
		708.9448	20.177	0.127
		708.9531	20.170	0.114

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 M31F

Name	Filter	HJD (2,450,000)	Mag	$\sigma_{\rm mag}$
V602 D31F	I	341.8947	19.061	0.042
		348.7354	19.209	0.048
		349.7707	19.202	0.049
		349.8176	19.196	0.045
		350.7771	19.202	0.044
		350.7787	19.242	0.055
		351.7003	19.231	0.052
		351.7018	19.220	0.056
		352.7022	19.201	0.055
		353.7654	19.435	0.083
		353.7737	19.295	0.089
		354.9341	19.223	0.067
		355.7594	19.270	0.055
		355.7605	19.288	0.057
		356.8498	19.295	0.052
		357.8992	19.336	0.051
		357.9216	19.291	0.046
		357.9370	19.289	0.046
		358.7571	19.329	0.052
		358.7672	19.304	0.058
		359.9603	19.346	0.055
		364.9481	19.156	0.057
		705.9810	19.345	0.057
		706.7248	19.276	0.060
		706.7726	19.284	0.054
		706.8702	19.370	0.060
		706.9021	19.367	0.051
		706.9341	19.308	0.058
		706.9905	19.294	0.093
		707.8790	19.226	0.055
		707.8978	19.278	0.059
		707.9061	19.259	0.056
		707.9143	19.268	0.056
		708.8468	19.271	0.052
		708.8551	19.177	0.055
		708.8875	19.230	0.058
		708.9024	19.194	0.052
		708.9106	19.166	0.057
		708.9366	19.260	0.054
		708.9448	19.191	0.049
		708.9531	19.154	0.052
		708.9614	19.223	0.055
		708.9931	19.201	0.058
		709.8022	19.041	0.044
		709.8105	19.108	0.054
		709.8237	19.158	0.051
		709.8319	19.142	0.055

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.

TABLE 7

Light Curves of Other Periodic Variables in M31F

Name	Filter	HJD (2,450,000)	mag	$\sigma_{\rm mag}$
V7438 D31F	B	705.9893	21.220	0.059
		706.7090	21.140	0.245
		706.7809	21.321	0.206
		714.7400	20.955	0.035
		714.9022	21.013	0.042
		714.9726	21.057	0.053
		730.6889	20.994	0.050
V7438 D31F	I	341.8947	19.293	0.062
		348.7354	19.467	0.067
		349.7707	19.561	0.064
		349.8176	19.631	0.061
		350.7771	19.351	0.060
		350.7787	19.329	0.067
		351.7003	19.427	0.072
		351.7018	19.480	0.109
		352.7022	19.443	0.080
		353.7737	19.551	0.119
		354.9341	19.624	0.113
		355.7594	19.563	0.078
		355.7605	19.528	0.072
		356.8498	19.412	0.066
		357.8992	19.517	0.064
		357.9216	19.540	0.061
		357.9370	19.582	0.069
		358.7571	19.376	0.063
		358.7672	19.385	0.066
		359.9603	19.509	0.075
		364.9481	19.524	0.076
		705.9810	19.472	0.061
		706.7248	19.429	0.076
		706.7726	19.482	0.072
		706.8702	19.521	0.076
		706.9021	19.592	0.075
		706.9341	19.582	0.076
		706.9905	19.460	0.109
		707.8790	19.276	0.074
		707.8978	19.504	0.086
		707.9061	19.451	0.076
		707.9143	19.395	0.072
		708.8468	19.225	0.066
		708.8551	19.258	0.072
		708.8875	19.306	0.075
		708.9024	19.375	0.072
		708.9106	19.242	0.066
		708.9366	19.280	0.064
		708.9448	19.260	0.066

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 M31F

Name	Filter	HJD (2,450,000)	Mag	$\sigma_{\rm mag}$
V244 D31F	B	705.9893	19.841	0.019
		706.7090	19.843	0.069
		706.7809	19.784	0.047
		714.7400	19.864	0.013
		714.9022	19.890	0.020
		714.9726	19.848	0.020
		730.6889	19.947	0.018
V244 D31F	I	341.8947	16.602	0.011
		348.7354	16.582	0.011
		349.7707	16.594	0.013
		349.8176	16.594	0.015
		350.7771	16.576	0.011
		350.7787	16.585	0.013
		351.7003	16.582	0.011
		351.7018	16.584	0.013
		352.7022	16.592	0.015
		353.7654	16.603	0.015
		353.7737	16.608	0.011
		354.9341	16.592	0.011
		355.7594	16.581	0.011
		355.7605	16.593	0.009
		356.8498	16.616	0.015
		357.8992	16.609	0.011
		357.9216	16.590	0.019
		357.9370	16.601	0.015
		358.7571	16.606	0.011
		358.7672	16.604	0.009
		359.9603	16.601	0.011
		364.9481	16.616	0.013
		705.9810	16.727	0.011
		706.7248	16.726	0.015
		706.7726	16.705	0.013
		706.8702	16.709	0.013
		706.9021	16.783	0.017
		706.9341	16.700	0.013
		706.9905	16.721	0.017
		707.8790	16.732	0.015
		707.8978	16.752	0.015
		707.9061	16.729	0.015
		707.9143	16.746	0.017
		708.8468	16.730	0.015
		708.8551	16.736	0.019
		708.8875	16.749	0.015
		708.9024	16.740	0.017
		708.9106	16.729	0.017
		708.9366	16.708	0.015
		708.9448	16.731	0.017
		708.9531	16.684	0.015
		708.9614	16.736	0.013
		708.9931	16.750	0.017

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.

was used. Photometry obtained for the B, V, and I filters was combined into separate databases. M31F I-band images obtained at the MDM were reduced using FLWO "templates." Two templates were used in the case of V-band images. An MDM template was used to fix the positions of the stars. The V photometry was transformed to the instrumental system of an FLWO template.

The photometric VI calibration of the MDM data was discussed in Paper I. In addition, for the field M31F 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 -0.020 mag in V and 0.057 mag in $V-I$ between the FLWO and the MDM calibration. The V offset is well within our estimate of the total 0.05 mag systematic error discussed in Paper I, and the $V-I$ offset falls slightly above.

We also derived equatorial coordinates for all objects included in the database for the V filter. The transformation from rectangular coordinates to equatorial coordinates was derived using 79 stars identified in the USNO-A2.0 catalog (Monet et al. 1996). We compared the resulting coordinates

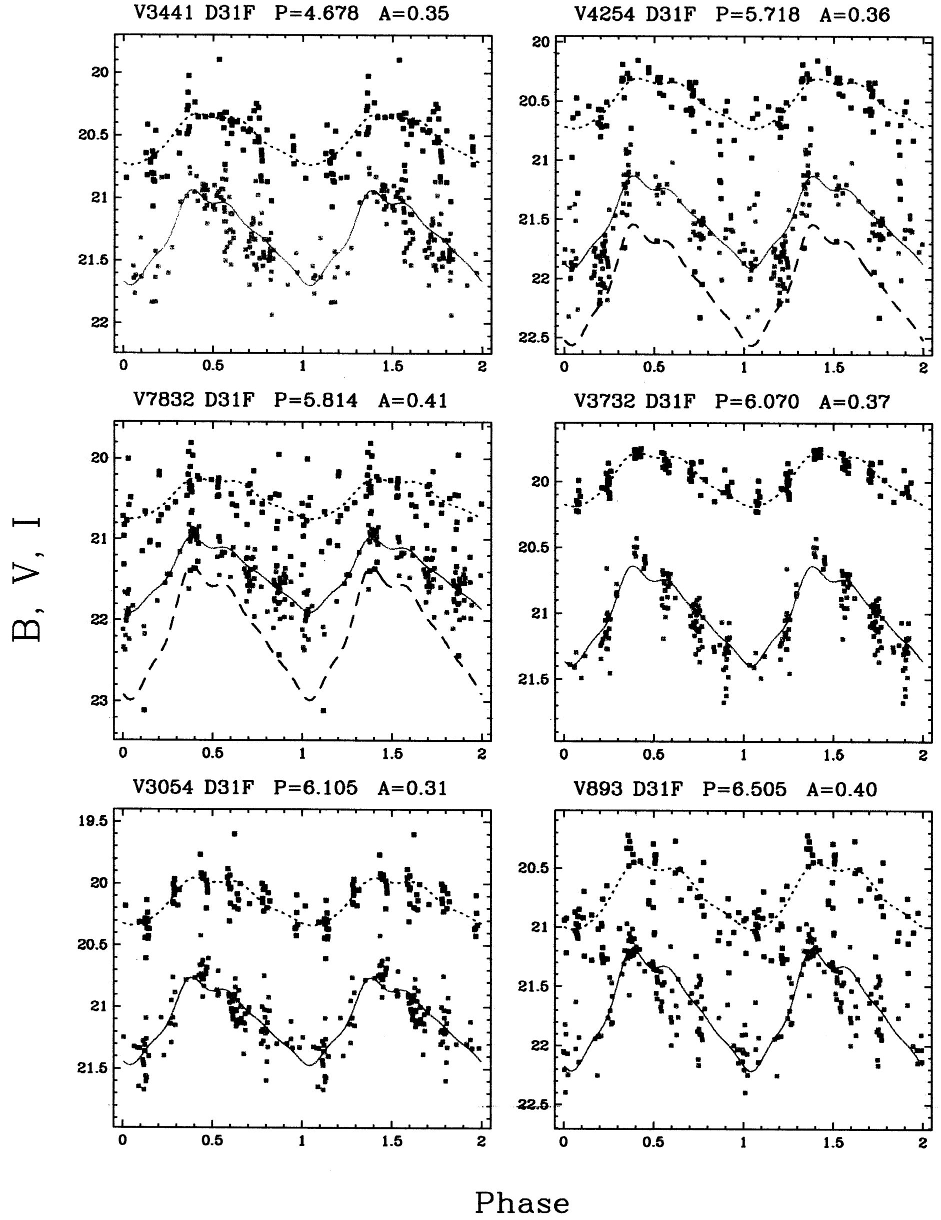

FIG. 4.—*BVI* light curves of Cepheid variables found in the field M31F. The thin continuous line represents the best-fit Cepheid template for each star and photometric band. *B* (if present) is usually the faintest and *I* (if present) is usually the brightest.

with those given by Magnier et al. (1992) and find good agreement. The average difference for the 66 stars found in both catalogs is 0".5 ± 0".1.

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 calibrated *BVI* magnitudes and their standard errors. The *V* database for M31F field contains 7997 stars with up to 108 measurements, the *I* database contains 26,540 stars with up to 69 measurements, and the *B* database contains 3382 stars with up to seven measurements. Figure 1 shows the distributions of stars as a function of $\bar{B}$, $\bar{V}$, and $\bar{I}$ magnitudes. As can be seen from the shape of the histograms, our completeness starts to drop rapidly at about $\bar{B} \sim 22$, $\bar{V} \sim 22$, 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.

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 10 points are removed, leaving the majority of stars with roughly $N_{\rm good} \sim 95$–105 *V* measurements. For further analysis we use only those stars that have at least $N_{\rm good} > N_{\rm max}/2$ (= 54) measurements. There are 5838 such stars in the *V* database of the M31F 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), which is also described in Paper I. In short, for each

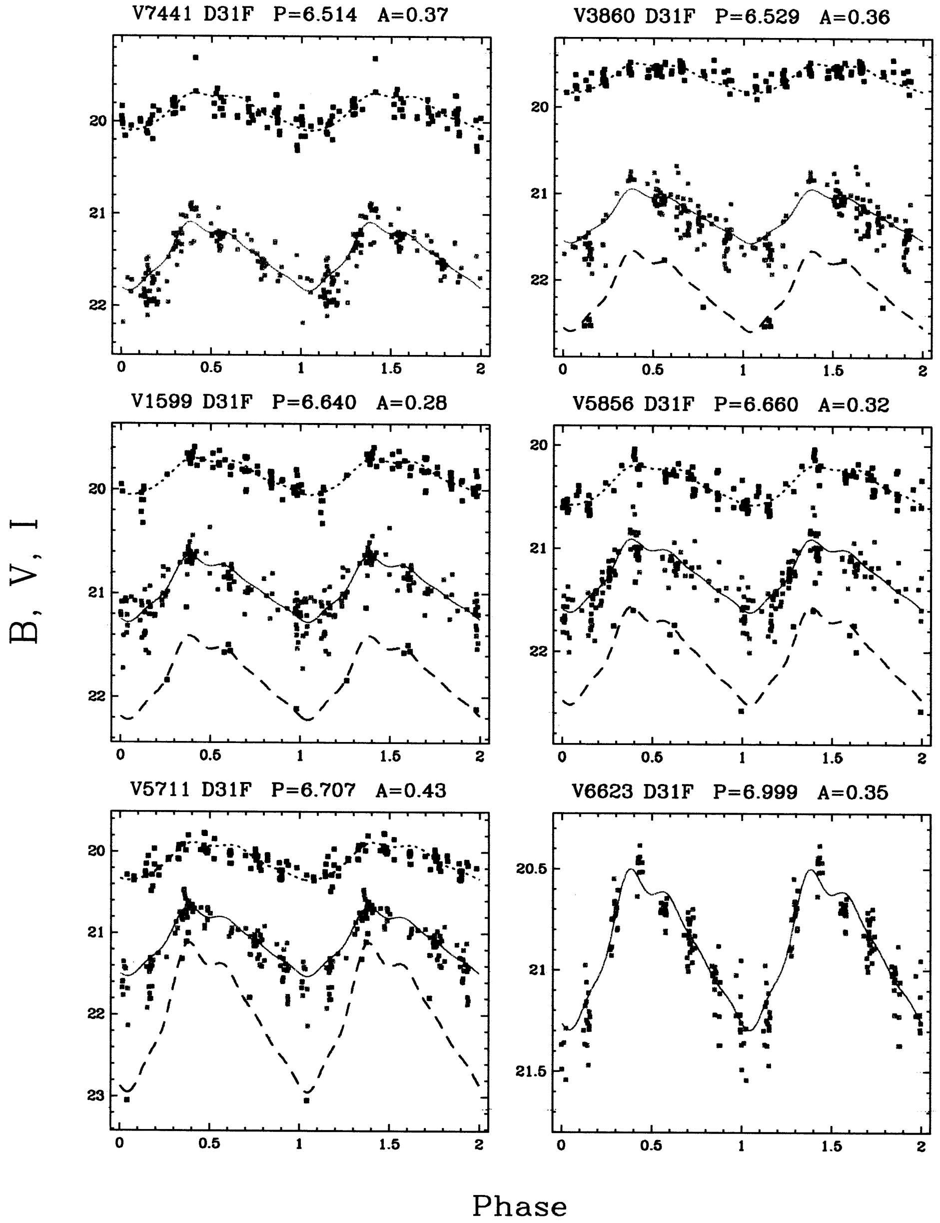

FIG. 4.—*Continued*

star we compute the Stetson's variability index J_S (Paper I, eq. [7]), and stars with values exceeding some minimum value $J_{S,\mathrm{min}}$ 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 a 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 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 variable stars by computing the value of J_S for the stars in our V database. We used a cutoff of $J_{S,\mathrm{min}} = 0.75$ and additional cuts described in Paper I to select 122 candidate variable stars (about 2% of the total number of 5838). In Figure 2 we plot the variability index J_S versus apparent visual magnitude $\bar{V}$ for the 5838 stars with $N_{\mathrm{good}} > 54$.

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 BI-bands data for the field, up to 69 I-band epochs and up to 7 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 therefore did not use the BI data for the period determination and broad classification of the variables. We did, however, use the BI data for the "final" classification of some variables.

Next we searched for the periodicities for all 122 candidate variables, using a variant of the Lafler & Kinman (1965) string-length technique proposed by Stetson (1996).

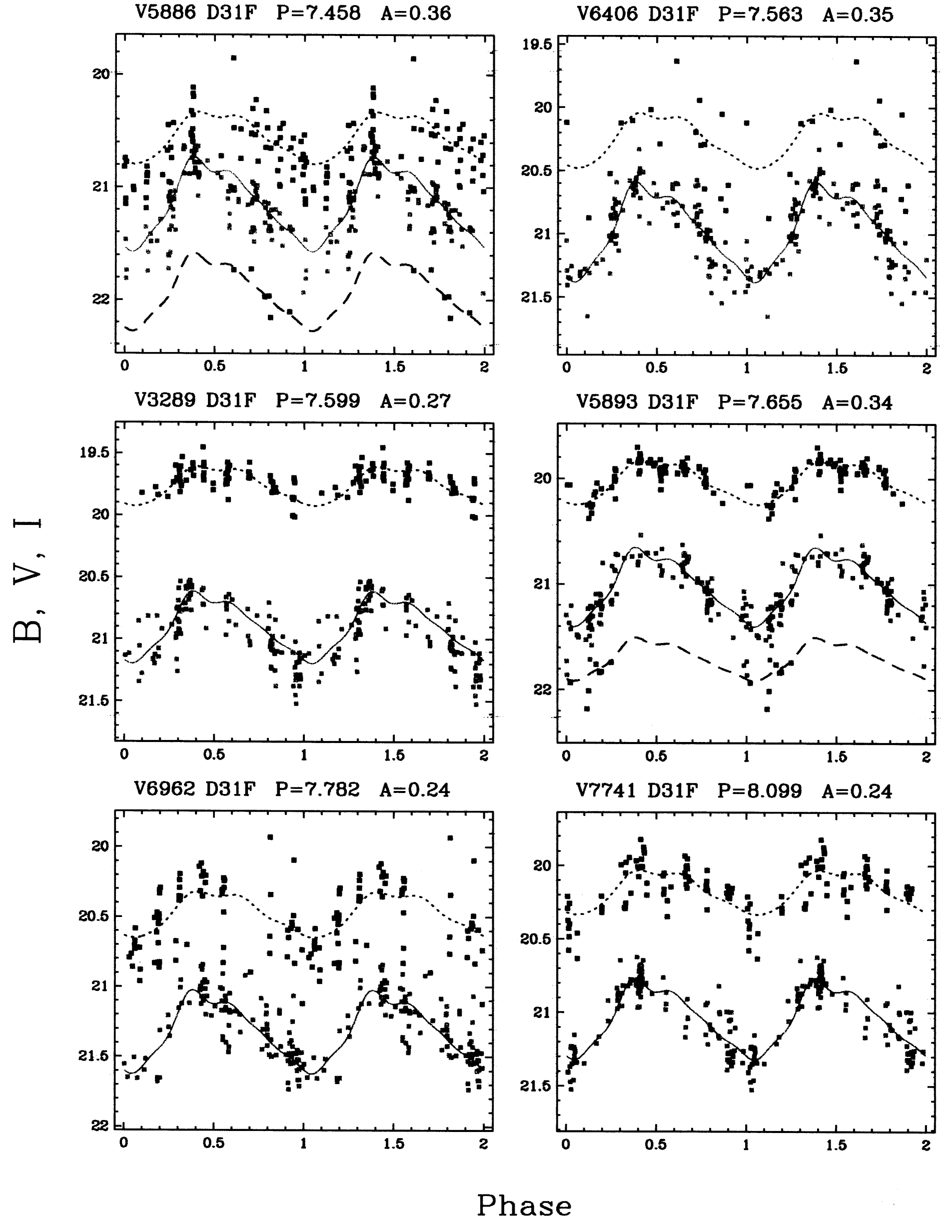

FIG. 4.—*Continued*

Starting with the minimum period of 0.25 days, successive trial periods are chosen so that

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

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 before, for the broad classification of variables we restricted ourselves to the V-band data. Nonetheless we present and use the BI-bands 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 six 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. In cases when the light curve was very noisy or chaotic and the object was located in the proximity of a bright star or a defect on the frame, it was rejected. We decided to remove one dubious eclipsing binary. We also reclassified another eclipsing binary as a periodic variable with half the determined period, based on the shape of its light curve. The light curve is presented in § 6.3. The remain-

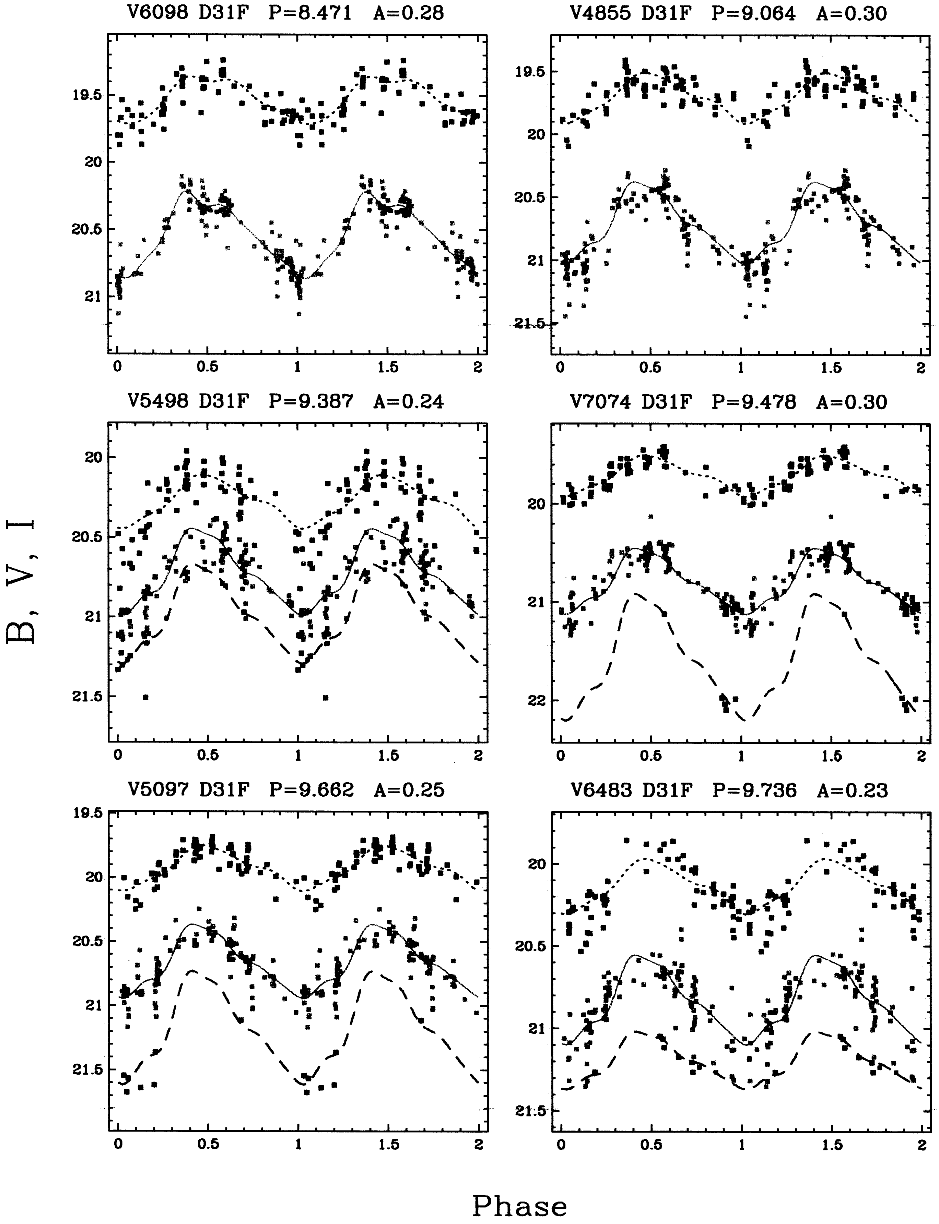

FIG. 4.—*Continued*

ing four 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 were a total of 64 variables passing all of the criteria (Paper I and Paper II), but after investigating the CCD frames we removed 12 dubious "Cepheids," which leaves us with 52 probable Cepheids. Their parameters and light curves are presented in § 6.2.

After the selection of four eclipsing binaries, 52 Cepheids, and one periodic variable, we were left with 65 "other" variable stars. After raising the threshold of the variability index to $J_{S,\mathrm{min}} = 1.2$ (Paper I) we are left with 17 variables. After investigating the CCD frames we removed 10 dubious variables from the sample, which leaves seven 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 64 variable stars discovered by our survey in the field M31F.[5] The variable stars are named according to the following convention: the 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)31F, e.g., V244 D31F. 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."

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[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 at http://cfa-www.harvard.edu/~kstanek/DIRECT/.

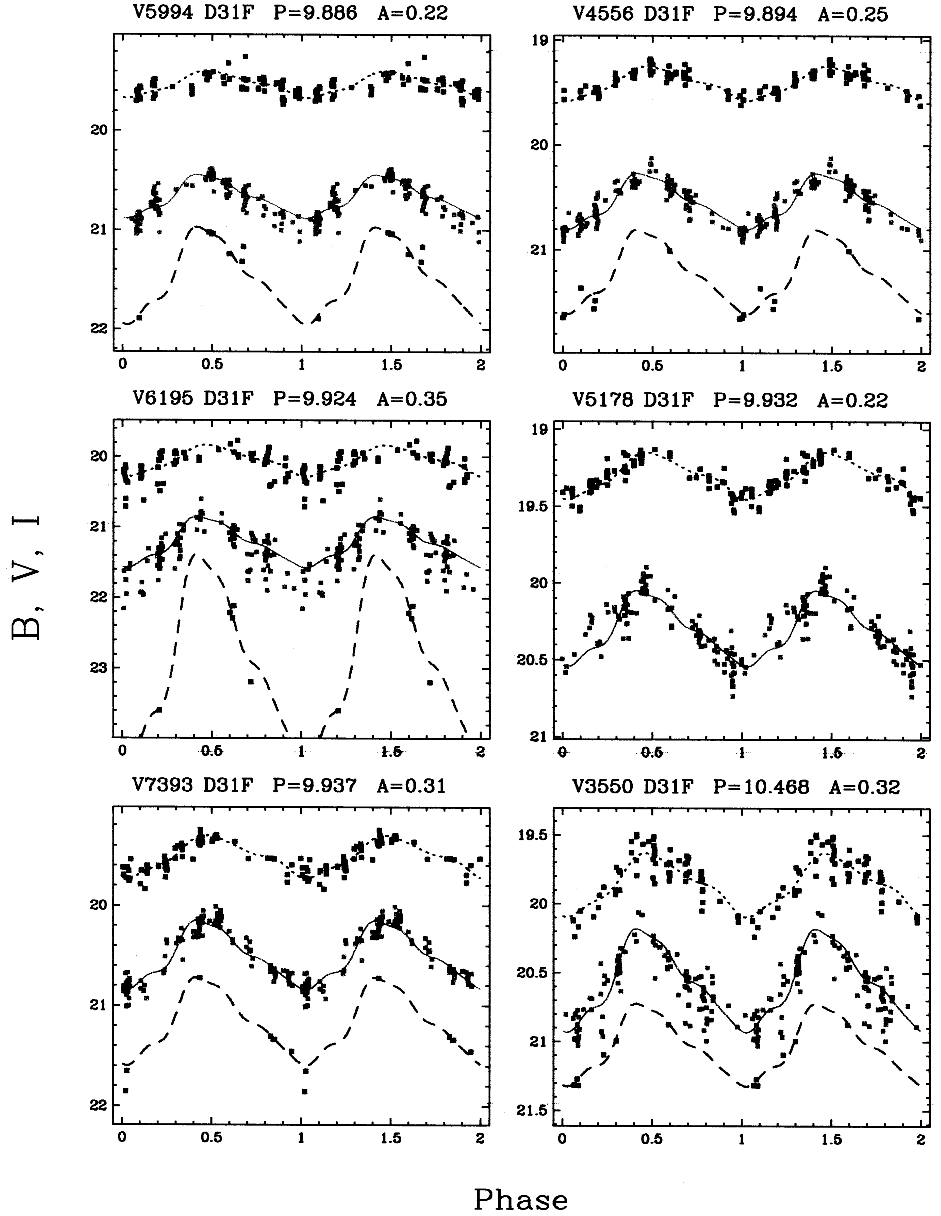

FIG. 4.—*Continued*

6.1. *Eclipsing Binaries*

In Table 1 we present the parameters of the four eclipsing binaries in the M31F field. The light curves of these variables are shown in Figure 3, along with the simple eclipsing binary models discussed in Paper I and Paper 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 $V_{\rm max}$, $I_{\rm max}$, and $B_{\rm max}$ of the system outside of the eclipse, and the radii of the binary components R_1 and R_2 in 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 $V_{\rm max}$, $I_{\rm max}$, $B_{\rm max}$, 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, V1835 D31F, is a good DEB candidate. However, a much better light curve is necessary to accurately establish the properties of the system.

6.2. *Cepheids*

In Table 2 we present the parameters of 52 Cepheids in the M31F field, sorted by 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 4 we show the phased B, V, I light curves of our Cepheids (see also Table 6). Also shown are the best-fit template light curves (Stetson 1996). First we solved for the four V template parameters (the period, the zero point of phase, the amplitude, and the mean magnitude). Then, using the parameters from the V fit, the I data were fitted, adjusting only the zero-point offset. For the B-band data, lacking

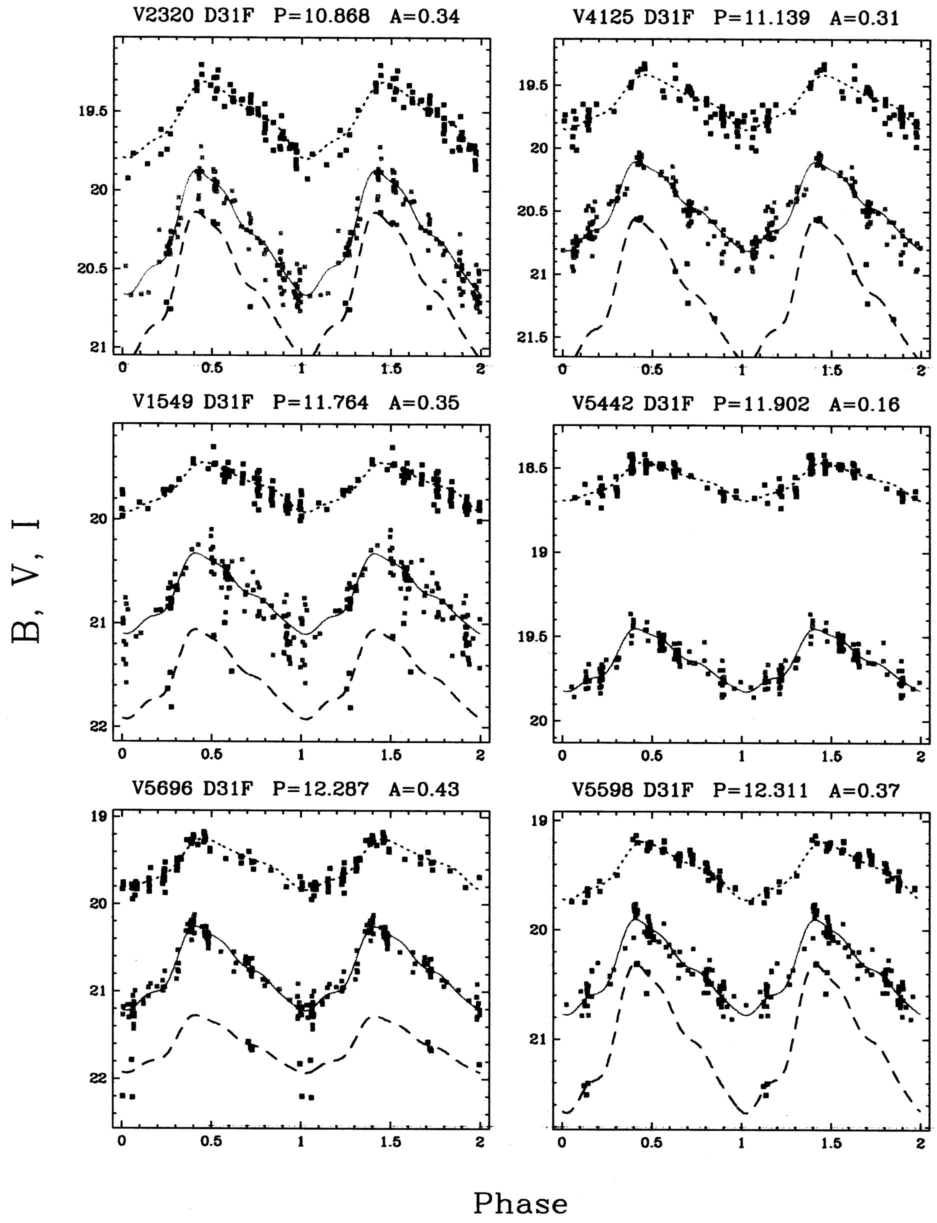

FIG. 4.—*Continued*

the template light-curve parameterization (Stetson 1996), we used the *V*-band template, allowing for different zero points and amplitudes. With our limited amount 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.

Some Cepheids seem to be brighter in the *B* band than in *V*. This effect is most likely caused by blending, since these variables are located in regions densely populated by stars, but it could also be due to blue binary companions of Cepheids (Evans 1994; Evans & Udalski 1994).

6.3. *Other Periodic Variables*

For one of the variables preliminarily classified as an eclipsing binary we decided upon closer examination to classify it as an " other periodic variable."

In Table 3 we present the name, J2000.0 coordinates, period *P*, and error-weighted mean magnitudes $\bar{V}$, $\bar{I}$, and $\bar{B}$ of this possible periodic variable. 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. In Figure 5 we show its phased *BVI* light curves (see also Table 7).

The period of V7438 D31F was taken to be half of the period determined by fitting a simple eclipsing binary light curve, so it should only be treated as a first approximation of its true value. Inspection of the *V*, $V-I$ and *V*, $B-V$ color-magnitude diagrams (Fig. 6) reveals that the variable is located in the region occupied by Cepheids. V7438 D31F has been previously identified by Baade & Swope (1965) as a Cepheid with a period of 5.12 days, very close to our value. In the P-L diagram (Fig. 7), however, it is located above the region occupied by Cepheid variables, indicating that it is possibly a blend. Another fact that may favor this

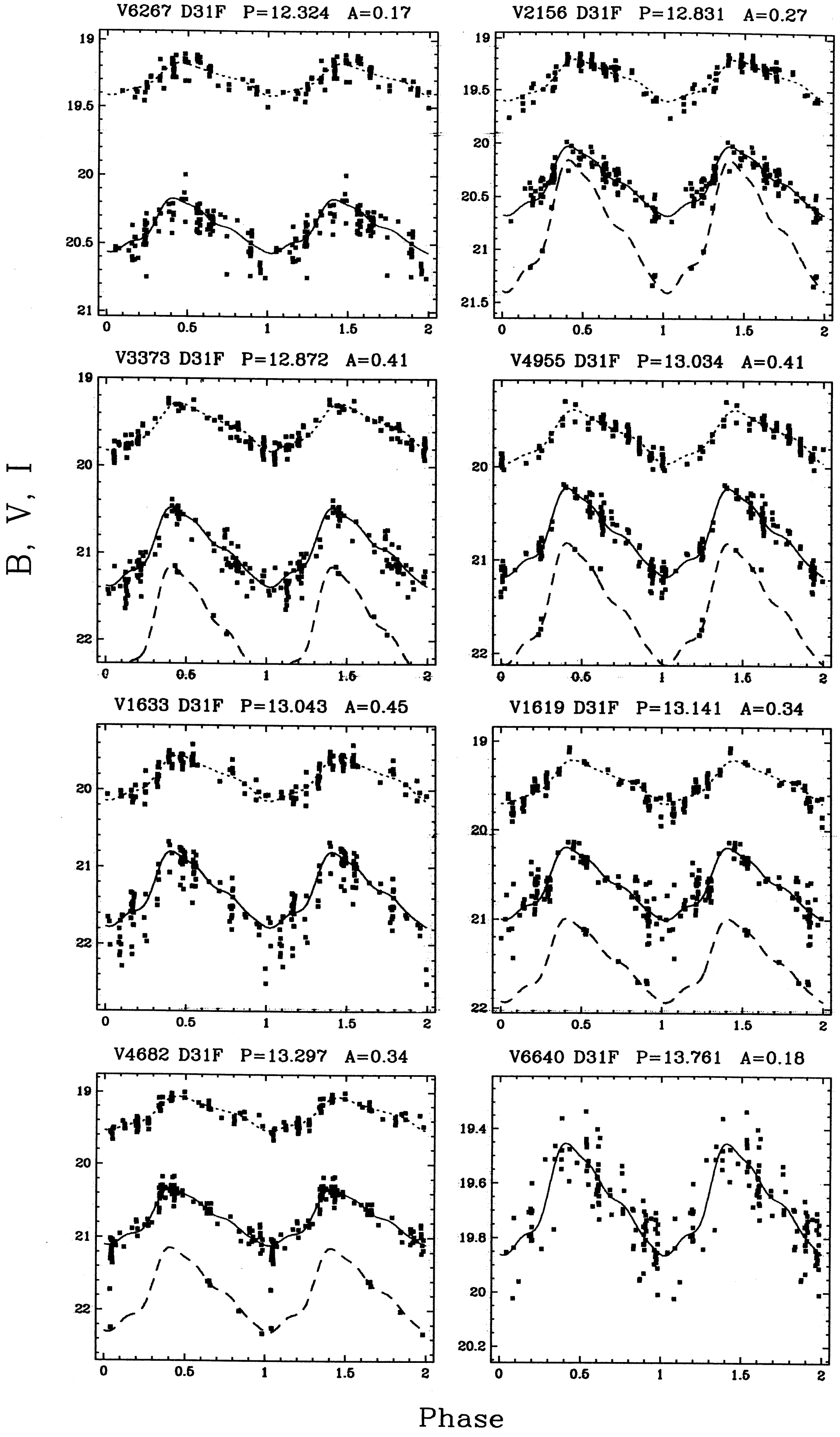

FIG. 4.—*Continued*

explanation is the small amplitude of its variability relative to its period.

6.4. *Miscellaneous Variables*

In Table 4 we present the parameters of seven miscellaneous variables in the M31F field, sorted by increasing value of the mean magnitude $\bar{V}$. In Figure 8 we show the unphased *VI* light curves of the miscellaneous variables (see also Table 8). For each variable we present its name, J2000.0 coordinates, and mean magnitudes $\bar{V}$, $\bar{I}$, and $\bar{B}$. To quantify the amplitude of the variability, we also give the standard deviations of the measurements in the *BVI* bands,

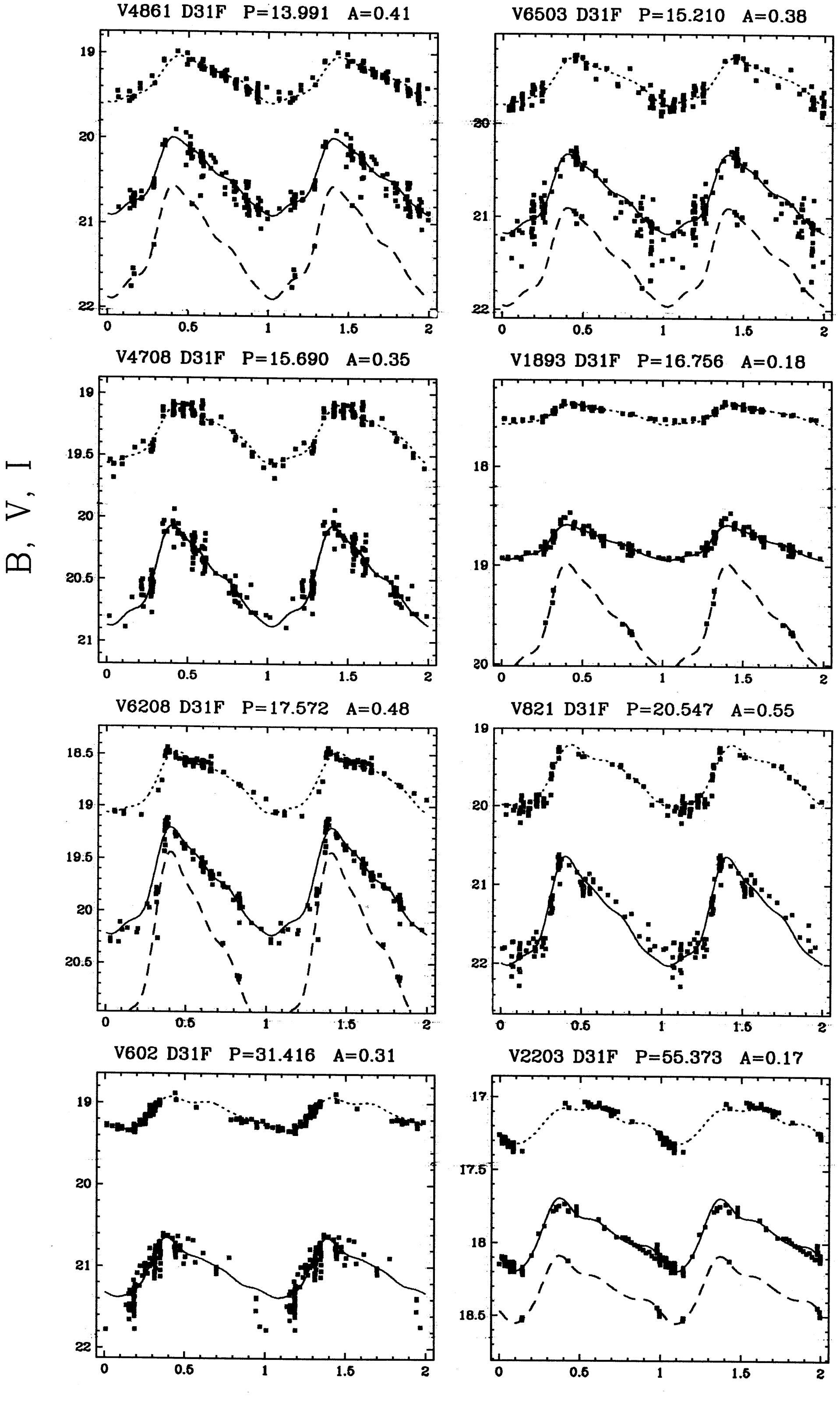

FIG. 4.—*Continued*

σ_V, σ_I, and σ_B. In the "Comments" column we give a rather broad subclassification of the variability.

All of the variables seem to represent the LP type of variability. A closer inspection of the color-magnitude diagrams (Fig. 6) reveals that three variables (V667, V1229, and V2285 D31F) land in the same area as Cepheids. Based on their light curves it was possible to roughly estimate the periods of the first two to be around 90 and 100 days, respectively. Using these periods to place the stars on the P-L diagram (Fig. 7) suggests they may be RV Tauri type

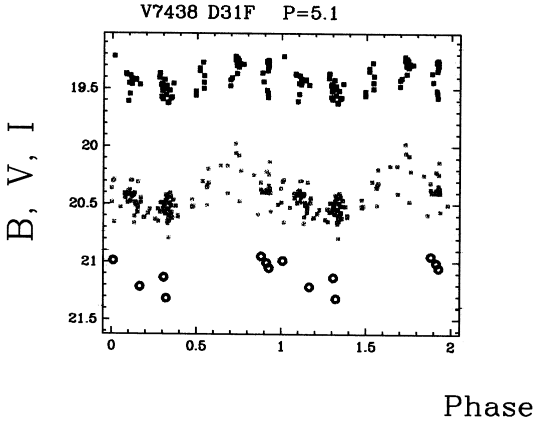

FIG. 5.—*BVI* light curves of the other periodic variable found in the field M31F. *B*-band data (*open circles*) is the faintest and *I* is the brightest.

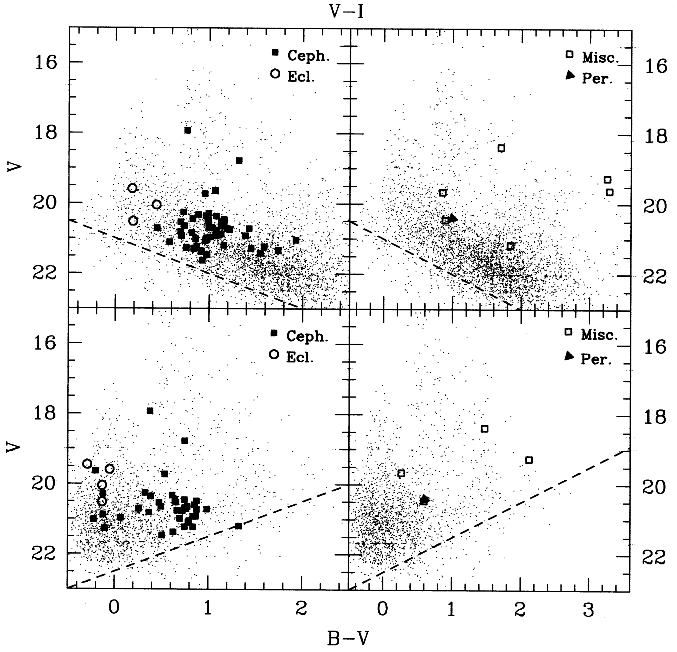

FIG. 6.—*V*, *V*−*I* (*top panels*) and *V*, *B*−*V* (*bottom panels*) color-magnitude diagrams for the variable stars found in the field M31F. The eclipsing binaries and Cepheids are plotted in the left panels and the other periodic variables and miscellaneous variables are plotted in the right panels. The maximum light magnitude is plotted for the eclipsing binaries, the flux-weighted mean magnitude for the Cepheids, and the mean *V* magnitude for the periodic and miscellaneous variables. The dashed lines correspond to the *I* detection limit of $I \sim 21$ mag (*top panels*) and the *B* detection limit of $B \sim 22.5$. mag (*bottom panels*).

variables. V1665 and V1724 D31F are most likely Mira-type variables, based on their location in the color-magnitude diagrams.

6.5. *Comparison with Other Catalogs*

The area of the M31F field coincides with two overlapping fields observed by Baade. The catalogs of variable stars discovered in those fields are given by Gaposchkin (1962, field II) and Baade & Swope (1965, field III). We succeeded in the cross-identification of all but one of the 55 Cepheid variables found in field III with stars on our template. We have discovered 27 of those Cepheids independently and found a very good agreement between the period determinations. We have also confirmed the periods of 27 other Cepheids that eluded our detection, in large part because of their faintness and the strict criteria we have imposed in our process of Cepheid selection (see Table 9 for cross-identifications).

Out of the 38 unique Cepheid variables listed in the field II catalog and located within our M31F field, we have found 11 Cepheids and confirmed the periods of an additional two. The remaining field II Cepheids have evaded positive cross-identification with our template stars.

Another overlapping variable star catalog is given by Magnier et al. (1997). Out of the three variable stars in Ma97 that are in our M31F field, we cross-identified one, also classifying it as a Cepheid. The other two did not qualify as variable star candidates because of low J_S values.

7. DISCUSSION

In Figure 6 we show *V*, *V*−*I* and *V*, *B*−*V* color-magnitude diagrams for the variable stars found in the field M31F. 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. 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 is located on the CMD in the part occupied by Cepheids. The miscellaneous variables are scattered throughout the CMDs and represent several classes of variability. Two of them are very red with $V-I > 2.0$, and are probably Mira variables.

In Figure 9 we plot the location of eclipsing binaries and Cepheids in the field M31F, along with the blue stars

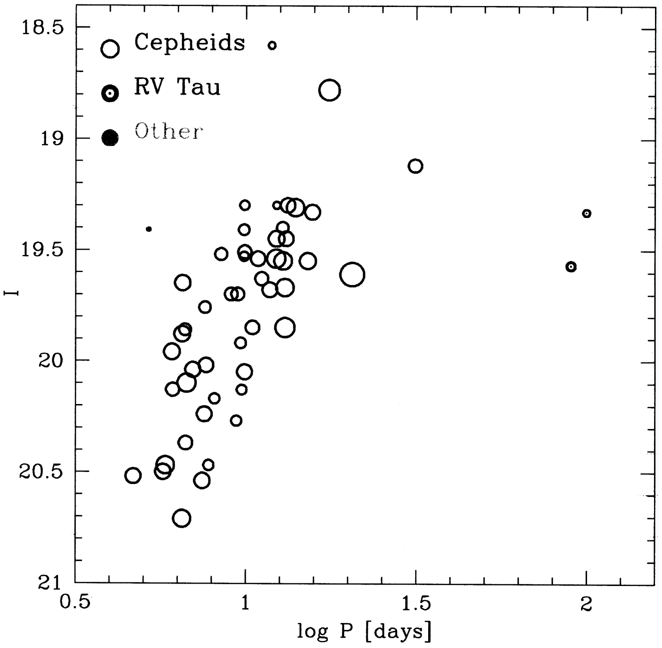

FIG. 7.—Diagram of log *P* vs. *I* for the Cepheids (*open circles*), RV Tau (dotted circles) variables and the other periodic variable (*filled circle*). The sizes of the circles are proportional to the *V* amplitude of the variability.

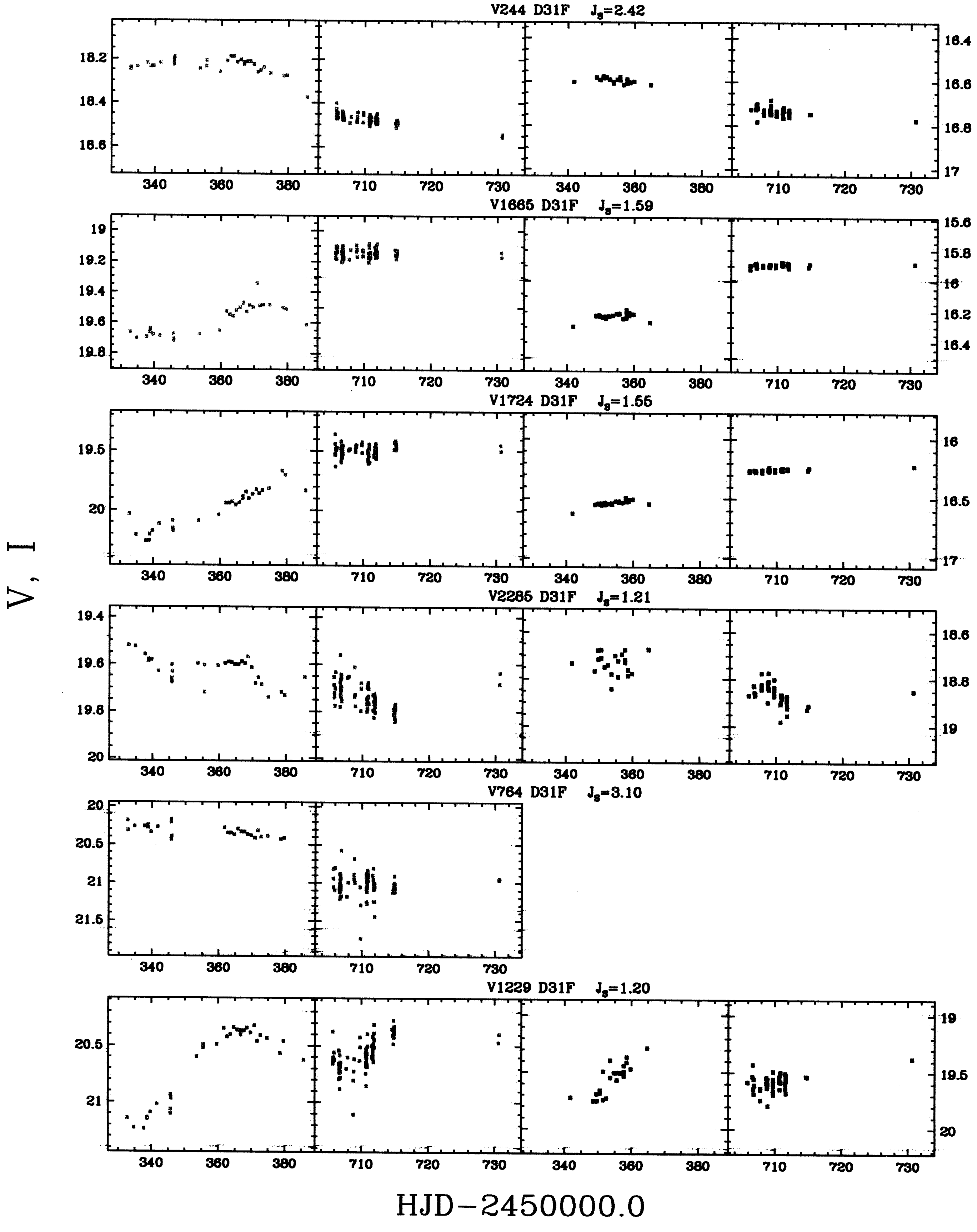

FIG. 8.—*VI* light curves of the miscellaneous variables found in the field M31F. *I* (if present) is plotted in the two right panels. *B*-band data is not shown.

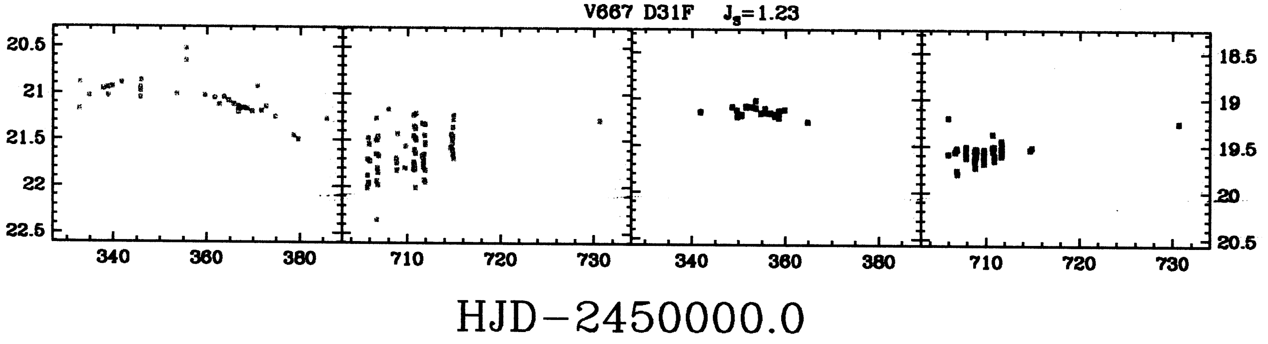

FIG. 8.—*Continued*

TABLE 9

CROSS-IDENTIFICATIONS OF THE DIRECT CEPHEID VARIABLES IN M31F

Name (D31F)	*P*(days)	Field II	*P* (*days*)	Field III	*P* (days)	Other	*P* (days)
V3441.........	4.678			108	5.000		
V4254	5.718	351	5.719	153	5.721		
V3732	6.070	352	6.071	175	6.074		
V3054	6.105			92	6.101		
V7441	6.514	230	6.508				
V3860	6.529			24	6.526		
V1599	6.640			145	6.637		
V5856	6.660	328	6.660	30	6.700		
V5711	6.707	330	6.709	29	6.708		
V6623	6.999	326	7.000				
V5886	7.458	332	7.457	70	7.463		
V6406	7.563	319	7.553				
V5893	7.655	320	7.823				
V6962	7.782	225	7.780				
V7741	8.099	222	8.094				
V6098	8.471	315	8.464				
V4855	9.064			51	9.085		
V5097	9.662	348	9.662	68	9.678		
V6483	9.736	325	9.483				
V4556	9.894	341	9.881	60	9.870		
V6195	9.924	318	9.921				
V7393	9.937	234	9.933			Ma97 4	9.0
V3550	10.468			72	10.461		
V2320	10.868			109	10.858		
V4125	11.139			20	11.147		
V1549	11.764			54	11.766		
V5696	12.287			17	12.286		
V5598	12.311	329	12.312	135	12.358		
V6267	12.324	334	12.294	133	12.284		
V2156	12.831			128	12.821		
V4955	13.034			14	13.051		
V1633	13.043			107	13.021		
V1619	13.141	415	13.125	31	0.000		
V4682	13.297	357	13.293				
V4861	13.991			74	13.966		
V6503	15.210	339	15.232	150	15.216		
V4708	15.690	355	15.699	114	15.625		
V6208	17.572		17.569			H22	17.60

NOTE.—Field II refers to the catalog published by Gaposchkin (1962), field III to Baade & Swope (1965), Ma97 to Magnier et al. (1997), and H to Hubble (1929).

($B-V < 0.4$) 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. Many Cepheid variables are located in the star-forming region NGC 206. We will explore various properties of our sample of Cepheids in a future paper (Sasselov et al. 2000).

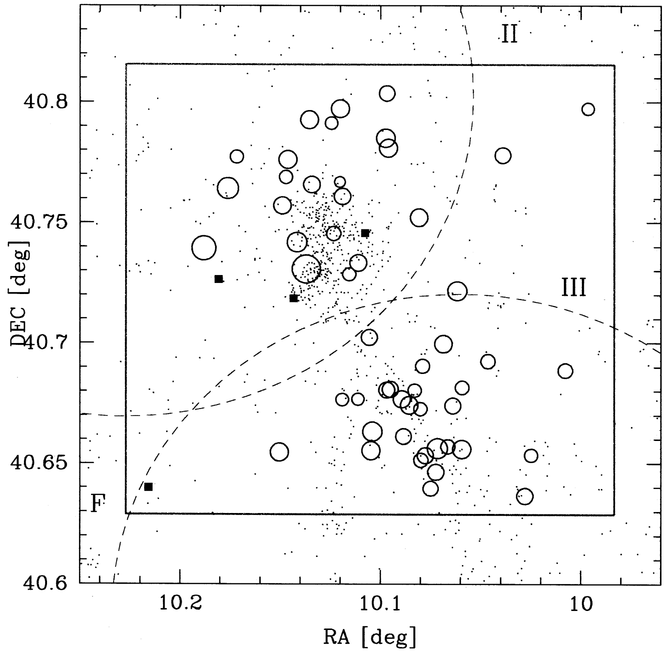

FIG. 9.—Location of eclipsing binaries (*squares*) and Cepheids (*circles*) in the field M31F, along with the blue stars ($B-V < 0.4$) selected from the photometric survey of M31 by Magnier et al. (1992) and Haiman et al. (1994). The sizes of the circles representing the Cepheid variables are proportional to the logarithm of their period. Fields II and III observed by Baade are marked with dashed lines.

We would like to thank the TAC of the Michigan-Dartmouth-MIT (MDM) Observatory and the TAC of the F. L. Whipple Observatory (FLWO) for the generous amounts of telescope time devoted to this project. We are very grateful to Bohdan Paczyński for motivating us to undertake this project and for his always helpful comments and suggestions. We thank Lucas Macri for taking some of the data described in this paper, Przemek Woźniak for his FITS-manipulation programs, and Eugene Magnier for the Cepheid catalogs. The staffs of the MDM and the FLWO observatories are thanked for their support during the long observing runs. We thank the referee, John Pritchard, for most useful and very careful and detailed comments. K. Z. S. was supported by the Harvard-Smithsonian Center for Astrophysics Fellowship. J. K. was supported by NSF grant AST 95-28096 to Bohdan Paczyński and by the Polish KBN grant 2P03D003.17.

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