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Cool carbon stars in the halo and in dwarf galaxies: $H\alpha$, colours, and variability^{★,★★}

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ABSTRACT

The population of cool carbon (C) stars located far from the galactic plane is probably made of debris of small galaxies such as the Sagittarius dwarf spheroidal galaxy (Sgr), which are disrupted by the gravitational field of the Galaxy. We aim to know this population better through spectroscopy, 2MASS photometric colours, and variability data. When possible, we compared the halo results to C star populations in the Fornax dwarf spheroidal galaxy, Sgr, and the solar neighbourhood. We first present a few new discoveries of C stars in the halo and in Fornax. The number of spectra of halo C stars is now 125. Forty percent show $H\alpha$ in emission. The narrow location in the *JHK* diagram of the halo C stars is found to differ from that of similar C stars in the above galaxies. The light curves of the Catalina and LINEAR variability databases were exploited to derive the pulsation periods of 66 halo C stars. A few supplementary periods were obtained with the TAROT telescopes. We confirm that the period distribution of the halo strongly resembles that of Fornax, and we found that it is very different from the C stars in the solar neighbourhood. There is a larger proportion of short-period Mira/SRA variables in the halo than in Sgr, but the survey for C stars in this dwarf galaxy is not complete, and the study of their variability needs to be continued to investigate the link between Sgr and the cool halo C stars.

Key words. stars: carbon – Galaxy: halo – Galaxy: stellar content

1. Introduction

Carbon stars found at high galactic latitude comprise several types of objects, such as asymptotic giant star (AGB) N-type carbon (C) stars, CH-type giants, carbon dwarfs, or very metal-poor carbon-rich objects. The AGB C stars in the Galactic disc have been known for a long time, are present in large quantity (several thousands) and are well documented (for reviews, see, e.g. Wallerstein & Knapp 1998; Lloyd Evans 2010). In contrast, their counterparts found in the halo are rare, with ~ 150 objects, and their origin is not entirely clear. The goal of this paper is to consider these halo AGB C stars as a population and to study some of its properties.

The first discoveries of faint, red C-rich objects residing out of the galactic plane were achieved with objective prism surveys (Mac Alpine & Lewis 1978; Sanduleak & Pesch 1988), and Bothun et al. (1991) emphasized the importance of these objects

* Based on observations made with the NTT and 3.6 m telescope at the European Southern Observatory (La Silla, Chile; programs 084.D-0302 and 070.D-0203), with the TAROT telescopes at La Silla and at Observatoire de la Côte d'Azur (France), and on the exploitation of the Catalina Sky Survey and the LINEAR variability databases.

** Appendix A is available in electronic form at <http://www.aanda.org>

for studying the halo properties. Searching for debris of tidally captured and dislocated systems, Totten and Irwin (1998; see also Totten et al. 2000) carried out a systematic survey for faint high galactic latitude C stars, with a selection of objects based on their very red colour measured on Schmidt plates. They achieved slit spectroscopy of candidates and found ~ 40 objects comprised of CH-type and N-type stars. Together with results of previous observations, the distances and radial velocities of these objects were a decisive step that led Ibata et al. (2001) to discover the Sagittarius (Sgr) Stream and discuss the halo oblateness.

These developments underscored the need to increase the number of halo C stars as much as possible, whether they are AGB or CH-type objects. Our previous works (Mauron et al. 2004, 2005, 2007; Mauron 2008, hereafter Papers I to IV) showed that these C stars can be selected on the basis of their near-infrared 2MASS photometry followed by slit spectroscopy. More than 100 new C stars were discovered in this way, with some of them located as far as ~ 80 – 130 kpc from us and used as probes of the distant halo (Deason et al. 2012). At the same time, the search based on the Byurakan prism-objective plates still continues (Gigoyan et al. 2001, 2012), providing us with a similar number of interesting cases, although less distant in general. The Sloan survey has also produced several distant N-type stars (Green 2013).

These surveys for halo C stars are not completed yet, but it is interesting to study the properties of this population, and to compare it with other C populations in the Local Group. The AGB C stars are generally used as metallicity indicators and/or tracers of intermediate-age star formation episodes (see e.g. Mouhcine & Lançon 2003; Groenewegen 2007). Located in the halo that is old, our C stars are trespassers (Battinelli & Demers 2012). From their sample of halo carbon stars of CH or AGB type, Ibata et al. (2001) showed that a large portion of the AGB objects trace the Sgr stream, but one can ask whether they have the same history as those in Sgr, and from where the others originate. For almost all galaxies close to the Milky Way, specific surveys of AGB stars (including C stars) have been achieved, but much remains to be done. For example, the surveys of C stars in Sgr and in Fornax are not complete, despite large efforts devoted to these systems recently (Whitelock et al. 2009; Battinelli & Demers 2013).

In this paper, we focus on three properties of the halo C stars: $H\alpha$ emission, the positions in the 2MASS JHK two-colour diagram, and pulsation periods. Our approach is also to compare when possible the halo population to Fornax, Sgr, the Magellanic Clouds, and the solar neighbourhood. Concerning variability, we build on the pioneering works of Battinelli & Demers (2012, 2013) and take advantage of two huge, recently released databases providing stellar light curves, that is the Catalina Sky Survey (hereafter simply Catalina; Drake et al. 2009, 2013) and the LINEAR survey (Sesar et al. 2011, 2013). We also acquired some photometric monitoring with the TAROT telescopes. These data allow us to compare the period distributions of halo C stars and other populations with a better statistics than previously available.

In Sect. 2, we first present a few new discoveries of C stars in the halo and in the Fornax dwarf galaxy from ESO observations. The optical monitoring of halo C stars is also described. Some spectroscopic results are given in Sect. 3. In Sect. 4, we study the location of halo C stars in the 2MASS JHK ¹ two-colour diagram. The light curves of the Catalina and LINEAR databases and those obtained with the TAROT telescopes are exploited in Sect. 5 to derive the variability classification² and the period of 74 halo C stars. In the discussion (Sect. 6), we confirm that the period distribution for Fornax and the halo are very similar. Comparison with Sgr and the solar neighbourhood is also provided. The implications on the origin of halo C stars are discussed, before we conclude in Sect. 7.

2. Observations

2.1. Spectroscopic observations

Spectroscopy of halo candidate³ C stars was achieved at ESO (La Silla) on 17–18 October 2009 at the NTT telescope equipped with the EFOSC2 instrument. Grism # 5 of 300 gr mm⁻¹ was used, providing spectra in the range 5200–9300 Å. A slit of 1''0 was chosen, leading to a resolution of ~16 Å. The detector was a Loral 2060 × 2060 CCD chip with 15- μ m pixels. The frames were binned 2 × 2, and the resulting

dispersion is 4.1 Å per binned pixel. We were able to secure the spectra of 25 candidates with exposure times of generally a few minutes, and eventually, eight were found to be C-rich. We also observed three carbon stars in the Carina dwarf galaxy because they were erroneously believed to be in the halo, and for comparison APM 2225–1401, a C star from the list of Totten and Irwin (1998).

The reductions included bias subtraction, flat-fielding, extraction of object and sky one-dimension spectra, cleaning of cosmic-ray hits, and wavelength calibration. No spectrophotometric standard star was observed, but an approximate calibration was achieved as follows: one of our candidates, 2MASS J234442.57+090902.0, turned out to be a brown dwarf. Its spectral features were almost identical to those of the L1 template 2MASS J143928.36+192914.9, for which spectrophotometry is available (Kirkpatrick et al. 1999). We therefore smoothly rectified all our spectra in the red region (≥ 6700 –9300 Å) so that the L-star spectrum fitted the L1 template relative intensity. In the region 5700–6700 Å, we again smoothly modified the general shape of our spectra so that the intensity ratio between 7000 Å and 5700 Å for APM 2225–1401 became identical to that in Fig. 5 of Totten and Irwin (1998). Finally, to derive an absolute calibration, we considered five (presumably non-variable) candidates found to be M dwarfs, and we used their USNOC-A2 R magnitudes to derive an average scaling factor and obtain $f_\lambda(7000 \text{ \AA})$. The spectra (in the appendix and Fig. 1) are plotted in relative intensity, but the factors to convert them to units of erg s⁻¹ cm⁻² Å⁻¹ are given in the appendix.

We found spectra that covered the $H\alpha$ region for four halo stars in the Byurakan Astrophysical Observatory archive. They were obtained with the BAO 2.6 m telescope and the ByuFOSC2 spectrograph. A slit of 2'' was used, together with a 600 gr mm⁻¹ grating, and the detector was a Tektronix 1024 CCD chip with 24 μ m pixels. The dispersion was 2.7 Å per pixel, and the resolution is ~8 Å. These spectra were taken on 28 March 1999, 12 June 2002, 11 May 2000, and 11 June 2000.

Concerning Fornax, spectra of C stars were found in the ESO Archive (program 70.D-0203, P.I. Marc Azzopardi). They were obtained on 5 November 2002 with the ESO 3.6 m telescope and the EFOSC instrument. The slit was 1''5 wide and grism #6 was used. The detector was a Loral chip with 2048 × 2048 15 μ m pixels that was binned 2 × 2, so that the dispersion was 4.19 Å per binned pixel, and the resolution is 23 Å. The spectral coverage is from 4000 Å to 7950 Å. Reductions of the raw data were carried out as mentioned above. Flux calibration was achieved with LTT 2415. All the spectra are shown in the appendix.

Table 1 gives information first on the eight C stars discovered in the halo by searching in the 2MASS catalogue. Then are listed the four halo C stars found in Byurakan. The C stars in Carina and Fornax follow. For halo stars that were selected through their position in the JHK two-colour diagram, the first column of Table 1 gives the running number following those of Maun (2008). For Fornax, the first column is an internal designation. The B and R magnitudes of F29 and F36 are not available in USNO-A2.0 and were derived from Supercosmos (Hambly et al. 2001). Similarly, those of F31 and F58 were derived from the USNO-B1.0 catalogue.

The K column of Table 1 deserves some comment. The K magnitudes are around 13.5 for stars in Fornax, and this dwarf galaxy is located at about 140 kpc from us (van den Bergh 2000). Our stars are at distances between 10 and 50 kpc if identical to those in Fornax regarding luminosity. Objects #103, #104, and #105 are at the periphery of the Large Magellanic Cloud,

¹ The “s” of the K_s band of 2MASS is omitted in this paper.

² We classified an object as a Mira if it is a regular (periodic) variable with a peak-to-peak amplitude of at least 2.5 mag in the V band, or 1.5, 0.9, and 0.4 mag in the R band, I band and K band, respectively. SR-type variables are periodic with lower amplitudes.

³ Candidates obey $J - K \geq 1.2$, $|b| \geq 20^\circ$ and $K \geq 7$. See Sect. 4 for more details on our selection of candidate C stars.

Table 1. Observed carbon stars in the halo and in the dwarf galaxies Carina and Fornax.

No.	2MASS name	l	b	B	R	$B-R$	J	H	K	$J-K$	Note
New halo C stars found in 2MASS											
102	2MASS J053053.22–182524.5	221.382	–25.773	20.2	12.9	7.3	10.064	8.628	7.636	2.428	
103	2MASS J062806.04–531105.2	261.889	–24.788	18.6	14.6	4.0	12.744	11.744	11.268	1.476	
104	2MASS J071218.53–633809.3	274.472	–21.877	18.2	16.5	1.7	13.583	12.156	11.067	2.516	
105	2MASS J072703.58–645912.3	276.392	–20.791	20.4	15.4	5.0	12.973	11.723	10.859	2.114	
106	2MASS J200144.00–302446.5	10.954	–27.553	16.9	14.0	2.9	11.659	10.832	10.358	1.301	
107	2MASS J200424.84–300651.1	11.466	–28.021	16.8	14.8	2.0	12.400	11.473	10.815	1.585	
108	2MASS J201818.84–665057.9	328.838	–33.281	16.4	13.9	2.5	10.818	9.677	8.977	1.841	
109	2MASS J203347.68–463620.5	353.398	–36.543	16.0	12.5	3.5	10.505	9.538	8.920	1.585	
Observed halo C stars from the Byurakan survey											
–	2MASS J134226.79–071522.9	324.513	+53.464	15.9	13.1	2.8	10.520	9.617	9.238	1.282	(1)
–	2MASS J151840.24+145903.1	20.976	+53.729	14.9	11.1	3.8	8.793	7.845	7.342	1.451	(2)
–	2MASS J161817.11–045641.9	8.321	+30.670	14.9	12.6	2.3	9.862	8.943	8.629	1.233	(3)
–	2MASS J162136.27–085318.8	5.246	+27.666	15.8	12.1	3.7	9.334	8.332	7.826	1.508	(4)
Observed C stars in Carina											
–	2MASS J064113.53–505425.0	260.033	–22.265	18.7	16.7	2.0	13.925	13.073	12.658	1.267	(5)
–	2MASS J064141.45–505808.0	260.119	–22.212	18.2	16.2	2.0	13.742	12.805	12.340	1.402	(6)
–	2MASS J064144.48–510020.9	260.160	–22.215	19.0	16.3	2.7	14.246	13.229	12.693	1.553	(7)
Observed C stars in Fornax											
F00	2MASS J023740.58–342008.1	237.037	–66.141	19.7	17.3	2.4	15.557	14.493	13.937	1.620	
F06	2MASS J023853.09–344919.9	238.097	–65.806	19.9	17.4	2.5	15.474	14.280	13.452	2.022	
F08	2MASS J023857.01–344634.0	237.981	–65.802	22.2	17.5	5.7	14.789	13.664	13.076	1.713	
F29	2MASS J023951.79–341717.4	236.729	–65.705	18.0	16.2	1.8	15.265	14.224	14.115	1.150	
F31	2MASS J023953.89–344402.8	237.791	–65.618	21.1	18.9	2.2	16.470	15.177	14.277	2.193	
F36	2MASS J024009.47–340625.7	236.271	–65.674	21.2	17.1	4.1	15.790	14.556	13.668	2.122	
F52	2MASS J024041.09–342354.9	236.923	–65.519	18.3	16.5	1.8	15.496	14.660	14.418	1.078	
F58	2MASS J024103.56–344805.4	237.845	–65.372	23.3	17.6	5.7	14.441	13.365	12.694	1.747	

Notes. Coordinates α and δ (J2000) are given in the object names (2MASS Jhhmmss.ss \pm ddmmss.s). Galactic coordinates l and b are given in degrees. B and R in mag. are generally taken from the USNO-A2 catalogue, with $1-\sigma$ uncertainties of 0.25 mag. The J, H, K data are near-infrared magnitudes from the 2MASS catalogue, with uncertainties of 0.02 to 0.04 mag. (1) FBS 1339–070; (2) FBS 1516+151; (3) FBS 1615–048; (4) FBS 1618–087; (5) ALW Carina 2 (Azzopardi et al. 1986); (6) C3 of Mould et al. (1982), also ALW Carina 6; (7) C4 of Mould et al. (1982), also ALW Carina 7.

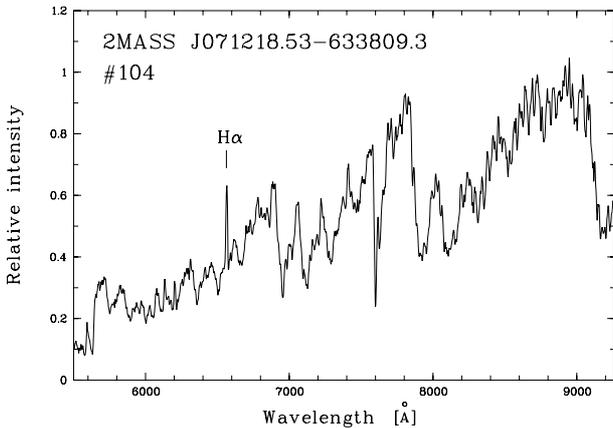


Fig. 1. Representative spectrum of halo C stars. Most of the features are due to C_2 and CN bands. $H\alpha$ is in emission. The strong absorption band at 7600 Å is due to telluric O_2 .

and a measurement of their radial velocity is necessary to check whether they belong to the halo or to this galaxy.

2.2. Photometric monitoring

Sixteen C stars were monitored with the ground-based 25 cm diameter TAROT telescopes (Klotz et al. 2008, 2009). This monitoring took place irregularly at ESO La Silla and Observatoire

de la Côte d’Azur (France) beginning in 2010. The studied objects were chosen from the list of Mauron (2008) complemented with a few sources known to have a very red $J-K$. The V and I passbands were used, and often R as well. The goal cadence was two or three measurements per week and per filter, but this was affected by technical problems. The reduction method of the TAROT observations is described in Damerджи et al. (2007). Periods were estimated by considering the dates of two maxima or two minima. A few objects were monitored both in Chile and in France, allowing a verification of this estimation. Seven objects were eventually found to have Catalina/LINEAR data, and this enabled us to find that most TAROT periods are known within 4% of relative uncertainty, which is quite enough for deriving histograms. The results are listed in Table 2, and all light curves are given in the Appendix. An example is shown in Fig. 2.

3. Spectroscopic results

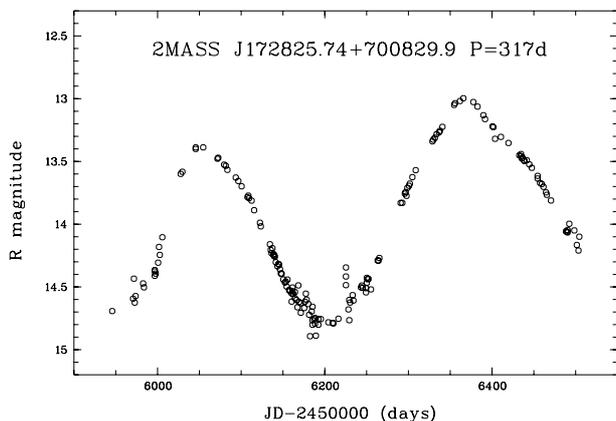
3.1. Spectra of Fornax C stars

The dearchived spectra of Fornax C stars need to be seen in perspective with previous works. Studying the red stars of this galaxy, Demers & Kunkel (1979) suggested that some of them could be C stars, which was verified by Aaronson & Mould (1980). Subsequently, many AGB C stars were discovered thanks to objective-prism spectroscopy (Frogel et al. 1982; Westerlund et al. 1987). The 2MASS survey provided homogeneous near-infrared photometry, which was exploited by

Table 2. TAROT observations of cool carbon stars and obtained periods (P in days).

Name	2MASS coord.	K	$J - K$	P	P_{CL}
m85	J021926.95+355058.9	8.52	3.20	474	
m86	J022432.00+372933.1	8.75	2.74	327	337
m87	J023904.88+345507.6	8.38	3.88	426	424
CGCS 6306	J084522.27+032711.2	6.25	3.41	325	
m34	J085418.70-120054.1	8.02	2.73	373	389
APM 1256+1656	J125833.51+164012.2	7.82	3.48	381	
m91	J133557.07+062354.9	10.57	1.69	242	243
CGCS 3716	J163631.69-032337.5	6.10	3.91	498	
m15	J172825.74+700829.9	9.02	2.52	317	301
m96	J181329.44+453117.5	6.71	3.81	348	
IZ Dra = m97	J184950.90+621725.4	7.49	1.31	316	
m16	J194219.01-351937.6	10.04	2.62	222	230
m77	J195840.17+774526.2	8.69	3.36	382	
m100	J202000.44-053550.6	8.61	3.43	397	424
m82	J215526.98+234214.4	5.50	3.39	318	
APM 2223+2548	J222619.32+260338.5	4.52	2.73	295:	

Notes. When available, periods derived from Catalina/LINEAR databases are also given (P_{CL} in days). K from 2MASS is indicated and is lower than 7.0 in five cases. These stars are too bright to be considered as halo C star with our criteria and are included here for completeness. These objects are ignored in the remainder of the paper. All objects have $|b| > 20^\circ$. For m16, Battinelli & Demers (2012) found $P = 229$ days.

**Fig. 2.** An example of light curve obtained with the TAROT telescopes.

Demers et al. (2002, hereafter DDB02), who identify candidate C stars with a $J - K$ between 1.4 and 2.0. More recently, Whitelock et al. (2009) presented a comprehensive study of the variable or non-variable AGB stars based on multi-epoch near-infrared photometry. Fornax C stars were also specifically sought by Groenewegen et al. (2009, hereafter GLM09) through infrared spectroscopy.

The eight spectra presented here reveal five new C stars. We collect in Table 3 various information about them. DDB02 included three of our objects: our spectra confirm their suggested classification as C stars. The five other stars are not in the DDB02 list because of their too faint or too strong $J - K$ colours. GLM09 also included three of our eight objects: their target selection criteria excluded F29 and F52, which are too blue. F31 is also absent from their sample, because the J -band uncertainty is larger than 0.12. It is unclear why F00 and F36 are not in GLM09, because their colours and flux uncertainties obey their criteria. We note, however, that the right ascension of F00 is lower than that of all GLM09 objects. F58 was found in Paper I to be a C star without $H\alpha$ in emission (on 30 August 2002), but this line is in emission in the spectrum presented here. This star is a low-amplitude Mira with a period of 280 days according to Whitelock et al. (2009).

Table 3. Properties of Fornax C stars.

	DDB02	GLM09	WMF09	Status
F00	#1	–	non variable	New C
F06	–	–	periodic red var.	New C
F08	#2	#32	var. with no per.	Known C
F29	–	–	non variable	New C
F31	–	–	var. with no per.	New C
F36	–	#15	–	Known C
F52	–	–	non variable	New C
F58	#25	#27	periodic red var.	Known C

Notes. Cross identifications with the lists of Demers et al. (2002, noted DDB02) and Groenewegen et al. (2009, noted GLM09) are given, followed by the indication that the star is variable, with or without period, from near-infrared observations by Whitelock et al. (2009, noted WMF09).

3.2. $H\alpha$ emission in the spectra of halo C stars

All eight spectra of 2MASS-selected C stars are presented in the appendix. In Fig. 1, we show one representative spectrum. Of the eight 2MASS halo objects, five present $H\alpha$ in emission, although faint in two cases (objects #105 and #109). The four FBS spectra are also shown in the appendix, with one displaying $H\alpha$ in emission. One can obtain a more meaningful statistics by considering all the halo C stars discovered in Paper I to IV, and the present paper as well. We can also add the 26 N-type stars found by Totten and Irwin (their Fig. 5), out of which six present $H\alpha$ in emission. We derive a total of 125 spectra of halo C stars (with a single spectrum per object), and 50 have this line in emission, which represents a proportion of 40%.

This relatively high proportion is connected with the presence of shock waves in the stellar atmospheres and the fraction of regularly pulsating stars in our sample. As a comparison, Lloyd Evans (2013, priv. comm.) performed a spectroscopic survey of carbon stars in the solar neighbourhood at moderate resolution (2\AA). This survey yields the following results when one considers the variability classifications from the *General Catalogue of Variable Stars* (hereafter GCVS;

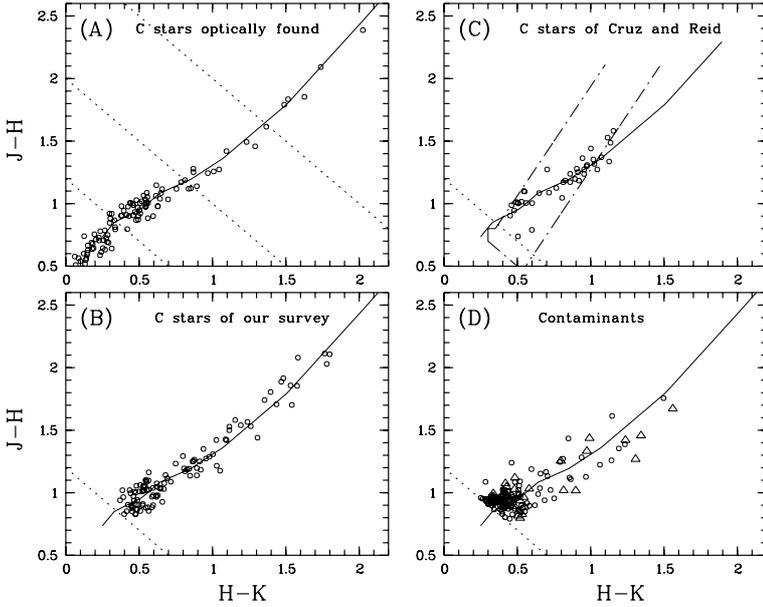


Fig. 3. Panel A: Halo C stars optically selected either through objective-prism plates or from optical photometry. The dotted lines indicate $J - K = 1.2, 2,$ and 3 . The $J - K = 1.2$ line is repeated in panels B, C, and D. Panel B: our 107 near-infrared (2MASS) selected C stars. Panel C: carbon stars discovered by Cruz and Reid during their survey for M, and L-type dwarfs; the colour domain searched by them is indicated by dash-dotted lines. Panel D: contaminants in our survey for halo C stars; most are M-type dwarfs, occasionally giants; a few non-M-type objects (L dwarfs, QSOs) are indicated by triangles. The solid line drawn in all panels is the best fit for all currently known halo C stars.

Samus et al. 2013): for Miras, 55 out of 79 spectra show $H\alpha$ in emission, that is 70%. For SRa type stars, the proportion is almost similar, 66% (31/47). For SRb and Lb type stars, it is $\sim 20\%$ (8/47 and 7/31, respectively). Finally, among spectra of stars classified simply “SR” or “SR?”, only 5% (2/40) show $H\alpha$ in emission.

4. Colour properties of halo C stars and comparison with C stars of some galaxies

4.1. Colour properties of halo C stars

In this section, we address the colour properties of cool halo C stars. Given that in our previous survey (Papers I to IV) the halo C stars were selected as lying within a very narrow band of the JHK two-colour diagram, we investigated whether we could have systematically missed other cool C stars that would be located outside this colour region.

In Fig. 3 (panel A), we show the position in the JHK colour–colour diagram of the C stars listed in Totten & Irwin (1998) and in Gigoyan et al. (2001). The vast majority of these 108 C stars were discovered through their properties at optical wavelengths, either thanks to their spectra on objective-prism plates or through their $B - R$ colour. All objects obey $|b| > 20^\circ$. The 2MASS JHK colours are not corrected for the galactic extinction because it is negligible in most cases. It can be seen that these optically selected C stars form a narrow sequence in this diagram. Our survey for new C stars is based on this property, and our discoveries in Papers I to IV are plotted in panel B. The solid line drawn in all panels is the mean locus of all known halo C stars with $K > 7$, $J - K > 1.2$ and $|b| > 20^\circ$ (this line is tabulated in the appendix). The distance of representative points from this line is called ϵ , with ϵ negative when the point is located below the line. It is found that $|\epsilon| < 0.13$ mag for most objects. So far, of 294 candidate objects for which slit spectra were obtained, we found 107 to be C objects.

In panel C, we plot the C stars listed in Cruz et al. (2003, 2007) and in Reid et al. (2008). These authors performed a survey for cool dwarfs of type M and L close to the Sun, and found these C stars as interlopers. Forty of these objects obey $|b| > 20^\circ$ and $J - K > 1.2$. The selection criteria used by these authors

to find cool dwarfs involve optical and infrared bands. In the JHK plane, the region where their targets are located is delineated with a dashed-dotted line. It can be noted that most of their C-type interlopers are clustered along the mean C line. Of their 40 objects, there are only two stars lying at some distance from this line (in the lower part of panel C). Their ϵ is -0.19 with $J - K = 1.24$ and 1.39 (lowest points in panel C). This suggests that with $|\epsilon| < 0.13$, we miss a very low fraction of halo C stars.

In panel D of Fig. 3, we plot the non-C stars (contaminants) that were examined, comprising objects found to be of type M and objects of other type (young stellar objects, and more rarely active galactic nuclei or L-type dwarfs). Their distances to the mean C line is larger than in panel (B). It can be seen also that these contaminants are more concentrated near the limit $J - K = 1.2$ than the C stars. This is because the majority of contaminants are M dwarfs and their main location in the JHK two-colour diagram is below the $J - K = 1.2$ line (see for example Fig. 2 of Cruz et al. 2003). Despite the high proportion of candidates with $J - K = 1.2$ to 1.3 , we found relatively few C stars in this colour interval.

4.2. Comparison of JHK colours between the halo and some galaxies

We have seen previously that we used $|\epsilon| < 0.13$ mag as a compromise to find halo C stars as efficiently as possible while limiting the number of candidates to be spectroscopically confirmed. Would this criterion select the C stars in Fornax? We show in Fig. 4 that this is mostly the case: of 52 Fornax C stars, 46 are selected, and some of the unselected ones were possibly discarded because of poor-quality 2MASS data. However, Fig. 4 also suggests that there is an offset between the Fornax and the halo distributions. We found that this offset cannot be reduced to zero by introducing the foreground interstellar extinction of Fornax for two reasons: first, the line of reddening makes a small angle with the JHK C star locus; secondly, the interstellar reddening to Fornax is low, $E(B - V) \sim 0.03$ (van den Bergh 2000).

To have a comparison with a galaxy with an order of magnitude more C stars but still a low foreground extinction, we considered the Small Magellanic Cloud (SMC). The C star catalogues of Morgan & Hatzidimitriou (1995) and of

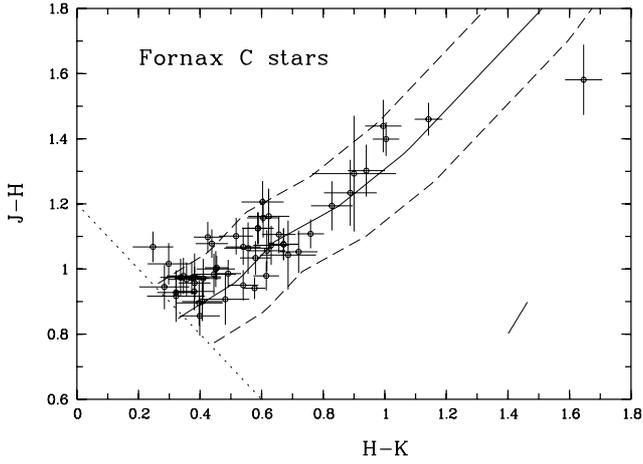


Fig. 4. Two-colour JHK diagram of the known Fornax C stars. The solid line indicates the mean locus of halo C stars ($\epsilon = 0$), and the dashed lines indicate $\epsilon = \pm 0.13$ mag. The small inclined bar in the lower right corner is a reddening vector for $A_V = 1$.

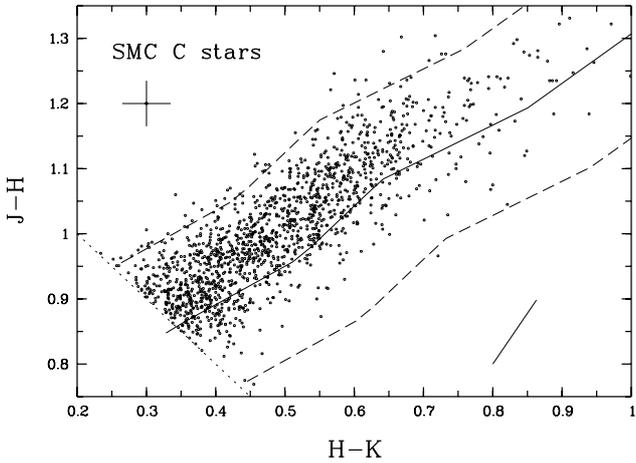


Fig. 5. Two-colour JHK diagram of optically identified C stars in the Small Magellanic Cloud (small dots). Typical error bars are shown in the upper left corner. The solid and dashed lines indicate $\epsilon = 0$ and $\epsilon = \pm 0.13$ mag, respectively, as in Fig. 4. The reddening bar in the lower right corner is for $A_V = 1$.

Rebeiro et al. (1993) were cross-matched with 2MASS with a matching radius of $2''$, producing a sample of ~ 1400 objects with relatively accurate photometry (JHK uncertainties < 0.03 mag.). We find in Fig. 5 that a vast majority (97%) of C stars in the SMC verify $|\epsilon| < 0.13$ mag, but again there is a systematic offset of the mean ϵ . This would be reduced to zero by adopting $E(B - V) = 0.3 - 0.4$ mag, but this amount of extinction is far above the currently admitted value $E(B - V) \sim 0.06$ mag (van den Bergh 2000).

In Fig. 6, we plot the histograms of ϵ for the halo, Fornax, Sgr, and the Magellanic Clouds (MC). Extinction was taken into account: for C stars in Sgr and the halo, the JHK colors were dereddened using the Schlegel et al. (1998) galactic extinctions to individual objects before calculating the distance ϵ to the halo mean line. For C stars in Fornax, in the SMC and in the LMC, we adopted $E(B - V) = 0.03, 0.06,$ and 0.13 mag, respectively (van den Bergh 2000). Our compilation of C stars in Sgr comes from the lists of Whitelock et al. (1999), Lagadec et al. (2009), and McDonald et al. (2012). The C stars of the LMC were taken

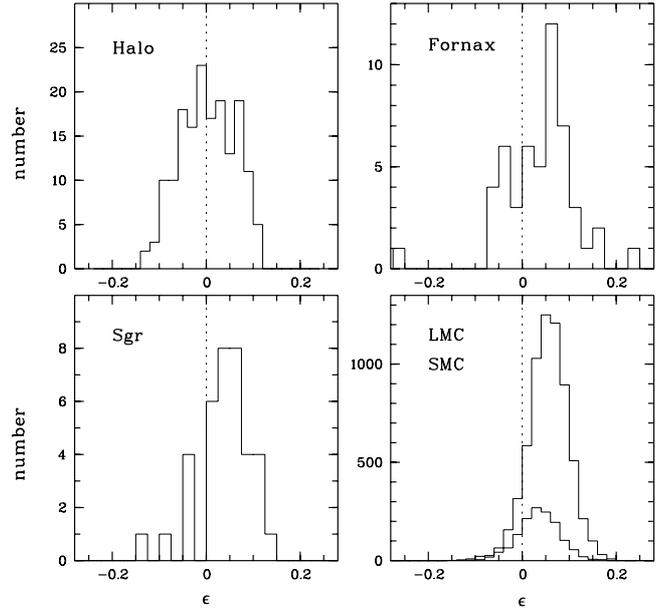


Fig. 6. Histograms of ϵ for C stars in the halo, Fornax, Sgr, and the Magellanic Clouds. ϵ is the distance to the mean locus of halo C stars in the JHK two-colour diagram. The distribution of ϵ is symmetric for the halo by construction. Galactic extinction has been taken into account for the four galaxies, but requires very small corrections.

from Kontizas et al. (2001). This figure shows that the colours of C stars in Fornax, Sgr, and the MCs are quite similar, but those of the halo are slightly different.

We also attempted to compare of halo C stars with AGB C stars of the solar neighbourhood regarding their position in the JHK diagram. However, we met with two major difficulties: first, the nearest AGB C stars have 2MASS measurements of very poor quality because of saturation. Secondly, when one imposes good-quality 2MASS data, the selected objects are fainter and therefore more distant. These distances, typically 2 kpc, imply that extinction is of the order of 0.3 mag in the K band. Then, the uncertainty on this extinction implies that the positions in the JHK diagram are also too uncertain, and this does not allow us to conclude.

To summarize, the halo C stars are bluer in $J - H$ for a given $H - K$ than those in Fornax, Sgr, and the MCs. This difference can be explained if halo C stars are slightly (0.03 mag) fainter only in the H band (for a given $J - K$) than in for instance Fornax. Alternatively, one could propose that the J - or K -band flux are brighter (by ~ 0.05 mag) in the halo C stars than in extragalactic C stars. It might be interesting to search for absorption bands in the H band of halo C stars that would not be present (or be fainter) in the C stars of the above mentioned galaxies. Because 2MASS photometry saturates for nearby, bright galactic C stars, a direct comparison is not possible with the results of Cohen et al. (1981). These authors found that SMC and LMC C stars are bluer in $J - H$ at a given $H - K$ with respect to galactic C stars. The same effect is seen for three high-velocity N-type stars in the Galaxy (Lloyd Evans 2011). This offset is interpreted as an effect of metallicity involving the CN absorption band in the J filter, because N is less abundant. If this is the case here, the location of the halo stars suggests that some of them might be more metal-poor than those in Fornax. This point certainly deserves further investigation.

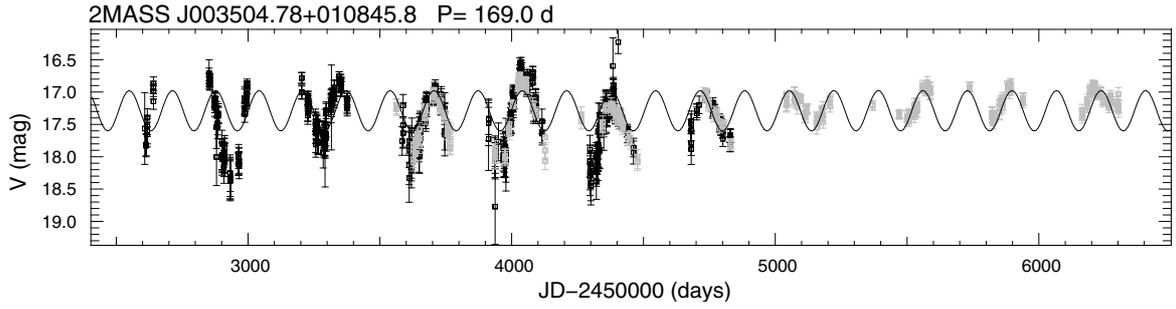


Fig. 7. Light curve of m59 with points in black from LINEAR and in grey from Catalina. The solid line is the best-fitting sinusoid. The obtained period is 169 days. This object has $K = 13.28$ and is as far away as ~ 110 kpc from the Sun (Paper III), illustrating the probed distance of Catalina/LINEAR databases with C stars. All LINEAR/Catalina light curves are shown in the appendix.

5. Variability of halo C stars: exploiting the Catalina and LINEAR databases

In addition to specific infrared colours, cool C stars have the property of being variable on long time scales, typically ~ 50 to 1000 days. In this section, we use this characteristic to study known halo C stars. A variability study has been conducted previously by Battinelli & Demers (2012). By monitoring 23 sources, these authors discovered 13 Miras and derived their periods. They also found that the Mira period distribution in the halo is quite similar to that of the Fornax dwarf spheroidal galaxy, although the statistics were poor. Here, we take the opportunity to investigate this similarity further by exploiting the recent release of two databases useful for variability studies: the Catalina Sky Survey database⁴ and the LINEAR database⁵.

Our goal is to extend the comparison of the halo and Fornax to more Miras and to SRa-type stars (i.e. small-amplitude Miras) with the benefit that better statistics are obtained. A disadvantage of considering SRa stars is that one has in general less information (than for Miras) of how the periods of these variables are related to the characteristics of a stellar population such as its age.

The Catalina database offers data for ~ 500 million objects. The sky coverage is limited by $-75^\circ < \delta < 70^\circ$ and $|b| \geq 15^\circ$, for an area of $\sim 33\,000$ square degrees. The database provides for each object the observation epoch, a Catalina V magnitude, and its error. Depending on the object position, a range of 30 to 400 epochs are given, and the observations cover a time span of about seven years (2005–2013). This database, initially aimed at the study of near-earth objects, is also of unique value for studying variable stars. For example, Drake et al. (2013) presented an analysis of a large number of RR Lyrae stars in the outer galactic halo with typical magnitudes $V \sim 19$. More details on the Catalina instrumentation and photometry can be found at the web site of the database or in the Drake et al. papers.

The LINEAR database offers measurements for ~ 25 million objects over the period 1998–2009. The sky coverage is smaller than that of Catalina, but extends over more than $\sim 10\,000$ deg² in the northern hemisphere. Light curves include an average of 250 measurements, and the errors are typically 0.2 mag at Sloan red magnitude $r \sim 18$. There is an overlapping interval of about three years between the Catalina data and the LINEAR measurements. More details on LINEAR can be found in Sesar et al. (2011, 2013).

To study the variability of halo C stars, we started with a list of 147 objects obeying our criteria and searched the

Table 4. Periods and peak-to-peak amplitudes for halo C Miras found by Battinelli and Demers (2012).

Name	2MASS coord.	P	P_{BD}	A_C	A_K
m31	J001655.77–440040.6	442	465	2.1	0.7
m41	J134723.04–344723.4	307	309	0.9	0.5
m52	J193734.13–353237.7	368	358	0.7	0.5
m16	J194219.01–351937.7	230	229	1.5	0.9
m17	J194221.31–321104.1	233	247	1.0	0.6
m18	J194850.65–305831.7	337	382	1.8	1.0
m19	J195330.18–383559.3	256	256	1.6	0.7
m24	J220653.67–250628.2	331	327	1.6	0.6

Notes. The quantities are noted P_{BD} (in days) and A_K (in K -band magnitudes), as determined by these authors. The periods found in this work are P (in days), and the Catalina amplitudes are A_C (in mag). The Catalina effective passband is discussed in the text.

Catalina database. Of these 147 objects, 143 were found to have data. This was complemented in about half of the cases by LINEAR measurements. No shift in magnitudes was found to be needed between Catalina and LINEAR magnitudes. A periodogram of the data was obtained first. Then, the best four periods were considered as starting points for four separate non-linear least-squares fits of a sinusoid on the data. We used the Levenberg-Marquardt method, and the four fitted quantities are period, amplitude, maximum date, and maximum magnitude. The fit providing the smallest χ^2 was then chosen and inspected by eye. We retained 66 objects with a clear periodicity, which represents a proportion of 45%. Other cases were rejected for several reasons: 1) the number of data points was too small ($n < 15$); 2) only weak light variation occurred given the magnitude errors; 3) the light curve was irregular and could not be fitted with a sinusoid.

The list of the retained 66 objects is provided in the appendix, where the light curves are also shown. An example of the data and fitted sinusoid is given in Fig. 7, where one can appreciate the quality of the data provided by Catalina and LINEAR. The periods we obtained range from 148 to 515 days with typical uncertainties of ≤ 3 days.

There are eight objects in common with the list of Battinelli & Demers (2012). Our periods generally agree well with theirs (see Table 4) and the differences are not large enough to affect their histograms. However, for m18, this difference reaches 45 days. For that particular case, the Catalina light curve is of very good quality, and inspection of their Fig. 2 suggests that they may have overestimated P due to an ill-defined first maximum.

⁴ <http://nesssi.cacr.caltech.edu/DataRelease>

⁵ <http://astroweb.lanl.gov/lineardb/>

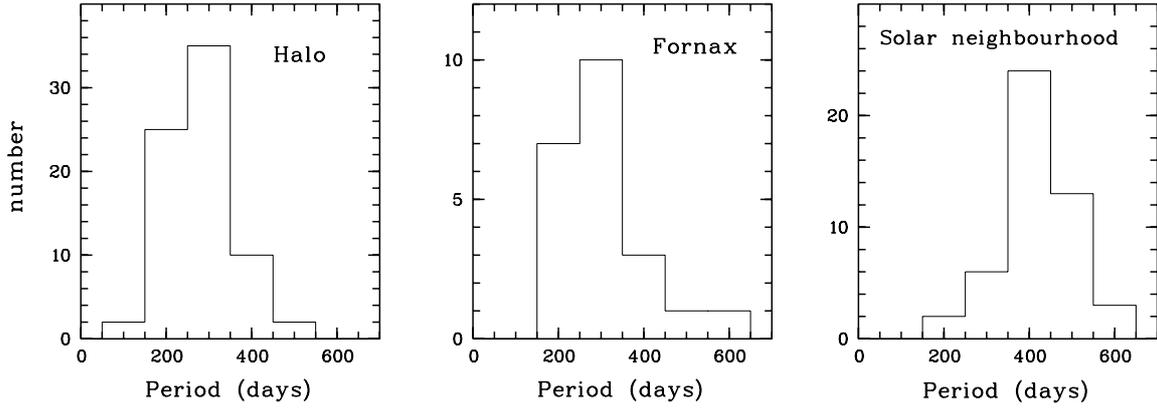


Fig. 8. Period histograms of Mira or SRa C stars in the halo (74 objects), Fornax (22 objects), and the solar neighbourhood (48 objects). For the latter, the flux-limited sample of Claussen et al. (1987) is considered. Note that the period bins are identical to those of Battinelli & Demers (2012, 2013), and that ordinates indicate the number of objects in each bin. See text for more details.

The amplitudes are generally 0.3 to 2.1 magnitudes, not taking into account flux drops probably caused by dust obscuration events (see e.g. Whitelock et al. 2006). If taken at face value, these amplitudes are small and no Miras would be identified. However, all Catalina images are taken unfiltered and our C stars are very red. Consequently, the effective passband of Catalina light curves may be significantly redder than the V band for our objects. This shift to the red of the effective wavelength is supported by the fact that Catalina magnitudes agree very well with those of LINEAR, which are r -band magnitudes. In addition, the Catalina amplitudes of the eight Miras of Battinelli & Demers (2012) mentioned above are between 0.7 and 2.1 mag (see Table 4). We have indicated in the appendix Table A.4 the 19 objects with Catalina amplitudes larger than 1.5 mag which we assume are Miras, the others in this table are of the SRa type.

6. Discussion

After collecting halo C star periods from the Catalina, LINEAR, and TAROT experiments, and adding those of Battinelli & Demers (2012), we obtain a total of 74 periodic objects (Mira and SRa types) and we can discuss their period distribution, with particular focus on a comparison with other populations. Here, we considered the AGB C population of Fornax, of the solar neighbourhood, and of Sagittarius.

6.1. Comparison with the long-period variables of Fornax

The Catalina sky coverage includes the Fornax field, but LINEAR does not. A list of C stars in Fornax was first built from the papers by Whitelock et al. (2009) and Groenewegen et al. (2009), in which both variable and non-variable sources were considered. We added the five objects discovered by us (see Sect. 2), yielding a total number of 63 C stars. We emphasize that no sources lacking slit-spectroscopic confirmation of being C rich were included. Data were extracted from the Catalina database and periods were searched as described previously. The result is reported in Table 5, where we have included objects not seen by Catalina, but studied by Whitelock et al. (2009). A total of 22 C stars have a period. When Catalina data are acceptable, there is a reasonable agreement between periods derived by us and periods of Whitelock et al. (2009). More precisely, for objects #38, 47, 58 and 62, our P are 298, 334, 225, and 240 days, while Whitelock et al. (2009) found 303, 320, 235, and 230 days. As shown in Fig. 8, the P distributions of Fornax and the halo are

Table 5. Fornax C stars with periods. K and $J - K$ are from 2MASS.

Id.	2MASS coord.	K	$J - K$	P	
For04	J023850.56–344031.9	12.88	3.22	350	W
For05	J023853.10–344919.9	13.45	2.02	242	
For06	J023857.01–344634.0	13.07	1.71	277	
For07	J023857.05–344748.9	13.56	1.25	190	
For09	J023912.33–343245.0	12.12	2.60	470	W
For18	J023937.39–343626.9	12.98	1.76	255	W
For22	J023941.60–343556.7	14.16	3.49	400	W
For23	J023948.45–343507.9	12.84	1.78	284	W
For33	J023958.62–342528.0	13.65	1.12	634	
For35	J024001.36–342018.9	13.34	1.34	230	
For36	J024002.52–342742.7	13.32	1.80	267	W
For38	J024002.74–343149.0	13.18	1.60	298	
For43	J024006.66–342322.3	12.61	1.86	335	
For47	J024010.17–343321.9	12.54	1.51	334	
For48	J024011.79–343245.5	13.43	1.32	220	
For49	J024012.08–342625.5	12.72	2.40	375	W
For51	J024015.62–343403.0	13.23	1.70	280	
For52	J024017.79–342735.8	13.18	2.24	275	
For54	J024019.95–343309.7	13.90	1.35	171	W
For58	J024025.05–342858.3	13.50	1.31	225	
For62	J024053.33–341213.0	13.26	1.77	240	
For63	J024103.56–344805.4	12.69	1.74	280	W

Notes. The period P is in days. The first column is an internal number. W indicates that P is from Whitelock et al. (2009), otherwise P is from this work.

almost identical. This fully confirms the findings of Battinelli & Demers (2012).

Following a suggestion of the referee, we can also compare the number ratio $N(\text{Miras})/N(\text{C stars})$ in the halo and in Fornax. There are 19 halo Miras indicated in Table A.4, and four detected with TAROT (m85, APM 1256+1656, m97, m77). Battinelli and Demers (2012) classified m06, m11, m35, m49, and m55 as Miras. They also classified m17, m41, and m52 as Miras, but we classify them SRa on the basis of Catalina amplitudes. Finally, m34, and m15 are Miras or SRa, depending on whether TAROT or Catalina observations are considered. In summary, we obtain between 28 and 33 Miras in the halo for a total of 147 halo C stars known. Therefore, the halo proportion $N(\text{Miras})/N(\text{C stars})$ is $\sim 20\%$. In Fornax, for 63 C stars known, there are 7 Miras listed in Whitelock et al. (2009). No additional Miras were found in this work from Catalina

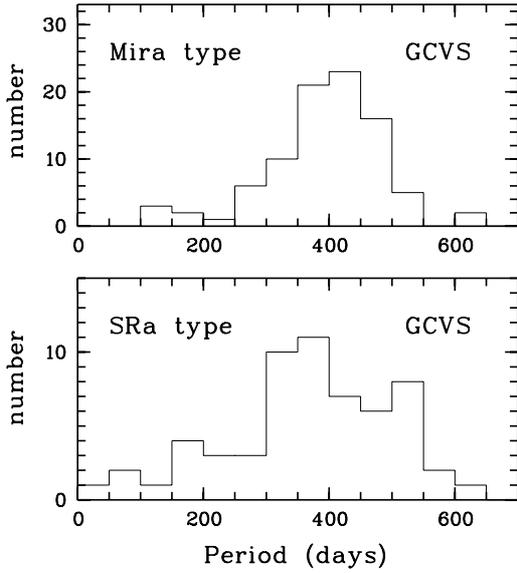


Fig. 9. Period distributions for carbon variables of Mira-type (89 objects) and SRa-type (59) in the General Catalogue of Variable stars (GCVS).

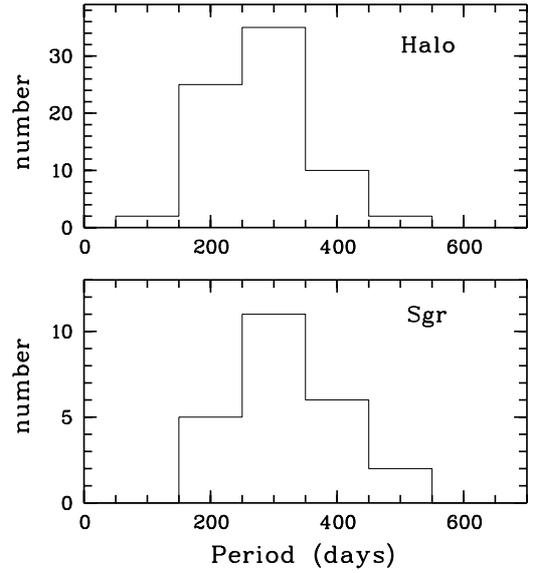


Fig. 10. Period distribution of Mira/SRa C stars in the halo (74 objects) and in Sgr (24 objects).

data because all amplitudes are smaller than 1.5 mag. Thus, in Fornax, $N(\text{Miras})/N(\text{C stars})$ is only 11%. This shows that although the period distributions of Miras + SRa variables are similar, there are clear differences between these two populations. This point deserves further study.

6.2. Comparison with the solar neighbourhood

Concerning periodic C-rich variables in the solar neighbourhood, we considered the flux-limited sample of Claussen et al. (1987). This sample is composed of 215 C stars with $K < 3$, with K from the *Two Micron Sky Survey* that have $-33^\circ < \delta < +81^\circ$. It is a statistically complete sample. Information on variability classification and especially periods can be found in the GCVS, but periods are not defined or not available for all objects. We found periods for 33 Miras and 15 SRa-type stars. Figure 8 shows the period histogram for these solar-neighbourhood objects. It can be seen that this histogram strongly peaks at ~ 400 days, with very few objects with $P < 350$ days, in contrast to the halo and Fornax distributions.

6.3. Comparison with Sagittarius

Concerning the link between halo and Sgr C stars, it would of course be desirable to compare the period distributions of Mira/SRa variables as rigorously as possible, that is, with the two populations observed and measured with the same instrument. Unfortunately, the Sgr galaxy is too close to the galactic plane and is not covered by the Catalina or the LINEAR experiments. We tentatively propose, however, to proceed as follows. Four C-rich Miras and one SR in Sgr have been reported by Whitelock et al. (1999) with measured periods, and six other C Miras were found by Lagadec et al. (2009). Recently, Battinelli & Demers (2013) identified and monitored 13 Miras and one SR in Sgr. Not all of the latter objects are spectroscopically confirmed C stars, but their near-infrared colours strongly favour this chemistry. One object of Battinelli & Demers (2013), called Sgr 13 (2MASS J185329.37–293824.1), is also in the list of Whitelock et al. (1999), and the period determinations

agree. In the end, 22 Miras and two SRs are known with periods available.

One point of concern is the low number of SRa stars (low-amplitude Miras) obtained above. Indeed, we have little information on the population of SRa-type C stars in Sgr, to say nothing of their P distribution. Here, we tentatively assume that this distribution is roughly similar to that of Miras. This point is mildly supported by the Miras and SRa of the GCVS as shown in Fig. 9. At least, the median periods of the two distributions are quite similar at ~ 400 days. To summarize, we have to keep in mind that the Sgr sample is incomplete.

The result is shown in Fig. 10, where we compare Miras/SRa in the halo and in Sgr. The distributions are somewhat different: the Sgr objects with $P \geq 350$ days are relatively more numerous, and there are fewer objects with $P \lesssim 250$ days.

6.4. Interpretation

The origin of the halo AGB C stars is not entirely clear. It is often assumed that these stars belong to the Sgr Stream, but this may not be the case of them all. Ibata et al. (2001) considered an optically selected sample of 75 faint, high-latitude C stars, with radial velocities and spectral classification CH or N-type. They showed that half of this sample (38 objects) traces the Sgr Stream. Similarly, Mauron et al. (2004) identified another sample of 28 halo AGB C stars by using their infrared colours, measured their radial velocities, and concluded that again half of them belong to this Stream. These findings suggest that halo C stars may have different origins. To explain the presence of the very red dust-enshrouded C star IRAS 08546+1732 far from the galactic plane, Cutri et al. (1989) mentioned several possibilities, and among them the hypothesis that some progenitors of C stars might be ejected from the galactic disc. Our comparison of period distributions for the halo and the solar neighbourhood strongly suggests that ejection from the disc is relatively minor, because if this were the case, we should see in the halo a larger portion of objects with ~ 400 day periods. Another source of C stars in the halo could originate in blue stragglers evolving up to the AGB phase that in turn originate in dissolved

globular clusters. This is qualitatively supported by the discovery of a long-period C Mira ($P = 515$ d) in the cluster Lynga 7 (Matsunaga 2006, Feast et al. 2013).

Concerning the similarity of P histograms of the halo and Fornax, it has to be noted that this similarity was previously noted by Battinelli & Demers (2012). Their histograms (in their Fig. 5) can be directly compared with ours in Fig. 7, since the bins in P are identical. The strongest point to note is that we have found a short-period population (with $P \leq 250$ days) that was not seen by them due in large part to their small-number statistics and in part because the optical light curves we used as opposed to near-infrared ones, permitted us to discover low-amplitude variables (about half of the variables with $P \leq 250$ days have Catalina amplitudes lower than 1.0 mag).

We know the link between C Miras of the galactic disc and their estimated ages relatively well (Feast et al. 2006), but this link is less well established for SRa type stars. However, assuming roughly the same relation, the P histogram of Fornax and the halo indicate, with most objects having $P \leq 350$ days, that their ages are older than ~ 3 Gyr. There is one halo object in our list with P as long as 515 days. This is 2MASS J124337.31+022130.2, with $K = 11.45$, $J - K = 1.54$, and $b = +65^\circ$. Its amplitude is only ~ 0.3 mag. Inspection of the light curve data suggests that this period might be a long secondary period of an irregular variable. We believe that this object is very different from a Mira.

The Sgr histogram contains a larger proportion of ~ 400 day periods than the halo or Fornax. This is qualitatively consistent with more star formation in Sgr in recent times due probably to a current disturbance. The best colour-magnitude diagrams of Sgr indeed show that multiple, young and intermediate-age populations exist in this galaxy with different metallicities (e.g. Siegel et al. 2007; Giuffrida et al. 2010). However, the Sgr histogram numbers are small. Whitelock et al. (1999) estimate the number of AGB C stars in this galaxy to be ~ 100 . If about half of these 100 stars are Mira/SRa type, as we found for the halo (cf. Sect. 5), the total number of these objects could be ~ 50 and the quality of the P distribution could be significantly improved. A systematic search and monitoring survey of cool variable populations in Sgr is of course highly desirable.

7. Conclusions

The main conclusions of this paper are listed below.

- (1) Several new AGB C stars were found in the halo and in Fornax, and their spectra were presented.
- (2) By considering the 125 spectra of halo C stars taken previously or in this work, we found that the halo C stars present $H\alpha$ in emission with a percentage of 40%. This fraction is smaller than that found for galactic AGB stars of Mira or SRa type, but clearly larger than found for galactic SRb or irregulars.
- (3) Our near-infrared criteria to search for halo C stars, in particular $|\epsilon| < 0.13$, do not exclude those that could be identical to the C stars of Fornax, of Sagittarius, or of the Magellanic Clouds. However, we found that the JHK colours of halo C stars differ slightly from those of C stars of these galaxies.
- (4) Thanks to the recently released Catalina and LINEAR databases, we were able to examine the light curves of 143 halo C stars and found 66 new periodic (Mira or SRa-type) variables among them, meaning that $\sim 45\%$ of these objects are periodic. Of these 66 objects, we find 19 objects

with Catalina amplitudes larger than 1.5 mag, which we propose are Mira variables.

- (5) We found 13 new red periodic variables in the Fornax dwarf galaxy. When these findings on the halo and Fornax are added to previous works, the distribution of periods in the halo and in Fornax are very similar, confirming with larger numbers the previous results of Battinelli & Demers (2012).
- (6) The halo period distribution is very different from that of the solar neighbourhood, implying that little pollution of halo C population arises from the disc of the Galaxy.
- (7) Finally, there is also a slight indication that Miras/SRa are older in the halo than in Sgr, but additional monitoring and confirmative spectroscopy of Sgr AGB stars are needed.

Note added in proof. The star SDSS Green #429 (2MASS 111320.64+221116.0), with $K = 14.50$ in Table A.4, was erroneously considered as a C star of the halo. It is actually a member of the LeoII dwarf spheroidal galaxy. The conclusions of the paper remain unchanged.

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Appendix A

This appendix presents the spectra of C stars listed in Table 1 of the paper (eight halo C stars, four FBS halo stars, three C stars in Carina, and eight Fornax C stars). The CN and C₂ bands dominate these spectra, occasionally with H α in emission (indicated). The strong absorption feature at 7600 Å is due to telluric O₂. The scaling factors f to obtain the ordinates in $\text{erg s}^{-1} \text{cm}^{-2} \text{Å}^{-1}$ is given in Table A.1. The FBS stars have no flux calibration. Note that almost all these stars are subject to variability.

Table A.2 presents the list of objects in the field of Fornax for which EFOSC2 spectroscopy was analysed and which are not C stars. These stars are mostly M-type foreground dwarfs, except for the object 2MASS J024000.78–341812.2, which appears fuzzy along the slit in the spectra and is probably a galaxy.

In Table A.4, the periodic variables found with Catalina and LINEAR data are listed. In the first column, the objects named “SDSS Green #nnn” are taken from Table 1 of Green (2013), where nnn is the object rank in his table. Similarly, the object named 2MASS Gizis #32 comes from Table 1 of Gizis (2002). The names “mxxx” come from the lists in Paper I to IV.

Table A.1. Scaling factors f for spectra shown in this appendix.

Name	f ($\text{erg s}^{-1} \text{cm}^{-2} \text{Å}^{-1}$)
Halo #102	1.6×10^{-15}
Halo #103	2.1×10^{-15}
Halo #104	4.4×10^{-15}
Halo #105	5.0×10^{-16}
Halo #106	5.5×10^{-15}
Halo #107	5.8×10^{-15}
Halo #108	1.6×10^{-14}
Halo #109	3.3×10^{-14}
Carina ALW 2	0.9×10^{-15}
Carina [MCA] C3	5.5×10^{-16}
Carina [MCA82] C4	1.0×10^{-15}
Fornax F00	2.4×10^{-16}
Fornax F06	1.6×10^{-16}
Fornax F08	2.4×10^{-16}
Fornax F29	3.0×10^{-16}
Fornax F31	0.97×10^{-16}
Fornax F36	1.55×10^{-16}
Fornax F52	2.7×10^{-16}
Fornax F58	4.0×10^{-16}

Table A.2. Objects in the direction of Fornax that are not carbon stars.

Identification	K	$J - K$	R	$B - R$
2MASS J023830.242–344503.07	14.319	1.157	17.2	1.6
2MASS J023850.934–341619.25	14.012	1.218	16.4	1.8
2MASS J023855.471–344916.60	13.103	1.135	16.4	2.3
2MASS J023859.919–344526.81	14.268	1.002	17.1	1.7
2MASS J023908.628–342740.78	13.444	1.067	16.4	0.3
2MASS J023911.288–345302.11	14.112	0.990	16.7	1.5
2MASS J023912.019–343741.44	14.256	0.929	17.1	1.9
2MASS J023921.337–342329.22	14.121	1.038	17.2	1.6
2MASS J023929.844–342723.21	13.760	1.124	16.9	2.3
2MASS J023930.656–342407.86	13.956	1.160	16.9	2.0
2MASS J023931.452–342258.67	13.987	1.180	17.2	1.6
2MASS J023937.523–342500.07	13.675	1.111	15.6	1.3
2MASS J023940.112–343402.43	14.094	1.146	17.2	1.9
2MASS J023940.941–343256.92	13.747	1.092	16.1	1.5
2MASS J023943.364–341348.59	14.096	1.052	16.7	2.1
2MASS J023944.088–342610.11	13.857	1.088	16.9	1.4
2MASS J023951.447–343912.65	14.025	1.188	16.9	1.6
2MASS J023952.001–341712.40	14.101	1.204	16.6	2.2
2MASS J023959.516–343243.29	14.017	1.133	16.9	1.7
2MASS J024000.782–341812.29	14.465	1.947	16.9	0.3
2MASS J024001.815–344403.93	14.276	0.970	16.9	1.5
2MASS J024008.194–342605.63	13.576	1.216	17.0	1.7
2MASS J024012.469–343905.80	13.727	1.094	17.1	2.1
2MASS J024014.037–342331.66	13.868	1.224	16.9	1.9
2MASS J024015.956–343529.39	13.895	1.220	16.9	1.9
2MASS J024022.672–344037.32	14.049	1.130	17.1	1.8
2MASS J024023.541–341520.42	14.201	1.157	17.0	1.7
2MASS J024023.898–341810.82	13.929	1.179	17.0	1.8
2MASS J024031.954–342048.75	13.854	1.154	17.1	1.8
2MASS J024036.689–341713.73	14.100	1.069	17.0	1.7
2MASS J024039.071–342646.15	14.321	0.987	16.4	1.2
2MASS J024039.570–343609.51	14.066	1.135	16.7	2.0
2MASS J024040.040–342937.08	13.955	1.031	16.9	1.4
2MASS J024050.051–342558.07	13.560	1.237	16.8	1.9
2MASS J024052.884–342830.39	14.343	1.363	16.0	0.0
2MASS J024055.364–342725.27	14.066	1.347	17.1	2.0
2MASS J024056.877–342709.31	13.943	1.207	17.1	1.5
2MASS J024105.935–342731.89	13.870	1.204	17.1	1.7
2MASS J024122.424–341129.64	14.173	1.057	17.0	1.8

Notes. K and $J - K$ are taken from 2MASS. R and $B - R$ are taken from the USNO-A2 catalogue.

Table A.3. Average 2MASS JHK colours of halo carbon stars.

$H - K$ (mag)	$J - H$ (mag)
0.330	0.850
0.520	0.962
0.640	1.083
0.850	1.193
1.070	1.360
1.510	1.798
2.050	2.495
2.300	2.830
2.860	3.340

Notes. This table defines the line from which the distance ϵ is determined.

Table A.4. Halo C stars with periods.

Name	2MASS Ident.	l	b	K	$J - K$	P	A_C	M/SR	Note
APM 0000+3021	2MASS J000300.86+303823.3	110.769	-31.086	8.90	2.00	305.3	0.8		
m31	2MASS J001655.77-440040.6	323.074	-71.742	7.07	2.75	441.9	2.1	Mira	
m59	2MASS J003504.78+010845.8	114.351	-61.453	13.28	1.34	168.9	0.6		L
FBS 0158+095	2MASS J020056.14+094535.6	149.845	-49.446	7.17	3.10	393.2	1.6	Mira	
APM 0207-0211	2MASS J021012.06-015739.0	163.123	-58.546	10.01	1.50	160.8	0.9		
m86	2MASS J022431.99+372933.1	142.664	-21.786	8.75	2.74	337.0	1.6	Mira	
m87	2MASS J023904.88+345507.6	146.697	-22.937	8.39	3.88	424.0	1.9	Mira	
m64	2MASS J030011.34+164940.2	162.049	-36.082	10.29	1.34	220.0	0.5		
IRAS 03242+1429	2MASS J032659.92+143956.9	169.816	-33.690	8.21	3.41	373.6	1.6	Mira	
APM 0340+0701	2MASS J034328.79+071058.8	179.778	-36.062	8.32	1.46	296.8	1.0		
m65	2MASS J034828.13+165703.2	172.347	-28.475	11.10	2.00	223.9	1.1		
m88	2MASS J035955.96+091904.4	181.024	-31.584	10.11	2.64	255.2	1.5	Mira	
m69	2MASS J042638.78+142516.2	181.245	-23.296	11.20	2.01	318.8	1.3		
m103	2MASS J062806.04-531105.3	261.889	-24.788	11.27	1.48	222.2	0.6		
APM 0713+5016	2MASS J071736.25+501041.6	167.306	+24.529	7.73	1.68	267.5	1.3		
FBS 0729+269	2MASS J073232.74+264715.6	192.427	+20.319	8.15	1.73	148.8	1.2		
SDSS Green #134	2MASS J075855.89+335838.1	186.898	+27.973	13.21	1.39	209.7	1.2		
m03	2MASS J082915.12+182307.4	206.225	+29.566	7.07	1.68	323.3	1.4		
HE 1008-0636	2MASS J082929.03+104624.2	214.181	+26.613	8.14	2.12	294.0	1.0		
m04	2MASS J085418.70-120054.1	239.096	+20.472	8.02	2.73	388.7	1.2		
IRAS 08546+1732	2MASS J085725.83+172051.9	210.261	+35.437	10.71	4.41	394.8	1.2		L
SDSS Green #232	2MASS J090546.36+202438.1	207.519	+38.347	12.29	2.82	257.6	1.9	Mira	L
m03	2MASS J091505.21+191737.8	209.815	+40.043	8.50	1.70	257.1	1.1		L
HE 1008-0636	2MASS J101036.99-065113.6	248.123	+38.348	8.53	1.42	334.9	1.3		
m04	2MASS J101525.93-020431.8	244.495	+42.428	11.95	2.10	340.8	1.4		L
SDSS Green #429	2MASS J111320.64+221116.0	220.056	+67.212	14.50	1.35	184.3	0.9		L
m07	2MASS J111719.00-172915.4	273.180	+39.885	11.22	1.43	314.8	1.2		
m08	2MASS J120925.03+151618.4	261.330	+74.639	9.83	1.35	256.0	0.7		L
APM 1211-0844	2MASS J121416.95-090050.0	287.661	+52.753	11.88	1.35	156.8	1.1		
APM 1225-0011	2MASS J122740.05-002750.7	290.267	+61.822	10.55	2.21	284.4	1.8	Mira	L
2MASS Gizis #32	2MASS J123829.27-405609.0	300.297	+21.869	12.73	2.64	265.9	2.1	Mira	
APM 1241+0237	2MASS J124337.31+022130.2	298.280	+65.159	11.45	1.54	515.6	0.3		L
m09	2MASS J124904.78+132035.4	300.526	+76.204	11.17	1.43	238.5	1.0		L
APM 1249+0146	2MASS J125149.87+013001.8	303.159	+64.372	10.20	1.87	278.9	1.4		L
SDSS Green #638	2MASS J130155.85+083631.8	311.052	+71.315	12.07	2.64	263.5	1.1		L
m91	2MASS J133557.08+062355.0	331.973	+66.727	10.57	1.70	243.1	1.3		L
m41	2MASS J134723.04-344723.4	315.767	+26.684	10.10	1.98	307.3	0.9		
APM 1350+0101	2MASS J135301.31+004714.1	334.780	+59.795	11.08	1.57	239.3	0.6		L
m10	2MASS J135602.37-013626.2	333.930	+57.324	11.31	1.59	215.0	0.4		L
APM 1429-0518	2MASS J143228.75-053117.8	343.501	+49.225	11.24	2.75	289.9	1.5	Mira	
m42	2MASS J143758.36-041336.1	346.372	+49.445	10.90	1.36	260.7	0.5		
SDSS Green #853	2MASS J144631.07-005500.3	352.235	+50.600	11.05	1.36	229.4	1.6	Mira	L
m92	2MASS J144644.19+051238.1	359.497	+54.876	11.35	2.29	238.1	1.2		L
m44	2MASS J145726.98+051603.5	2.520	+52.890	11.44	2.80	217.7	1.3		L
m12	2MASS J150106.93-053138.8	351.628	+44.738	11.50	2.09	253.9	0.8		
FBS 1502+359	2MASS J150455.30+354757.6	58.321	+60.407	9.69	2.32	309.9	1.2		L
APM 1511-0342	2MASS J151341.56-035348.0	356.357	+43.734	11.31	1.43	224.1	0.7		
m13	2MASS J151511.07-133227.9	348.096	+36.427	10.80	1.80	241.9	1.7	Mira	
APM 1519-0614	2MASS J152236.57-062534.2	356.004	+40.379	11.42	1.37	195.2	0.8		
m45	2MASS J152244.43-123749.5	350.551	+35.893	11.43	1.65	233.7	0.4		
m15	2MASS J172825.74+700829.9	100.829	+32.411	9.02	2.52	301.3	0.9		L
m52	2MASS J193734.13-353237.7	3.862	-24.196	9.12	2.14	367.6	0.7		
m16	2MASS J194219.01-351937.7	4.398	-25.059	10.04	2.62	230.4	1.5	Mira	
m17	2MASS J194221.31-321104.1	7.701	-24.132	9.98	1.98	232.6	1.0		
m18	2MASS J194850.65-305831.7	9.433	-25.076	10.21	3.39	337.0	1.8	Mira	
m19	2MASS J195330.18-383559.3	1.518	-28.070	9.26	2.03	256.0	1.6	Mira	
m106	2MASS J200144.00-302446.5	10.954	-27.553	10.36	1.30	166.1	0.9		
m99	2MASS J200303.83-194903.9	22.189	-24.332	9.11	1.42	186.5	1.5	Mira	
m100	2MASS J202000.43-053550.7	38.153	-22.230	8.61	3.43	424.5	1.8	Mira	
m109	2MASS J203347.68-463620.6	353.398	-36.543	8.92	1.59	240.3	0.9		
m23	2MASS J220514.58+000846.0	60.313	-41.674	9.30	2.24	219.5	1.0		L
m24	2MASS J220653.67-250628.2	26.546	-53.173	8.95	1.98	330.9	1.6	Mira	
m25	2MASS J221709.92-260703.3	25.636	-55.642	8.88	2.16	311.7	1.6	Mira	
m83	2MASS J222301.20+221656.5	83.298	-28.940	9.52	2.09	322.6	1.4		
APM 2225-1401	2MASS J222810.68-134622.4	47.457	-54.048	9.90	1.97	286.1	1.4		
m27	2MASS J231935.54-185623.9	49.282	-67.385	9.97	1.53	147.6	0.9		

Notes. l and b are given in degrees and periods P in days. The Catalina amplitude A_C (in mag) is that of the fitted sinusoid. Mira is indicated in the M/SR column when $A_C > 1.5$ mag. We consider all others as SRa type variables. In the Note column, L means that LINEAR data were used in addition to those of Catalina.

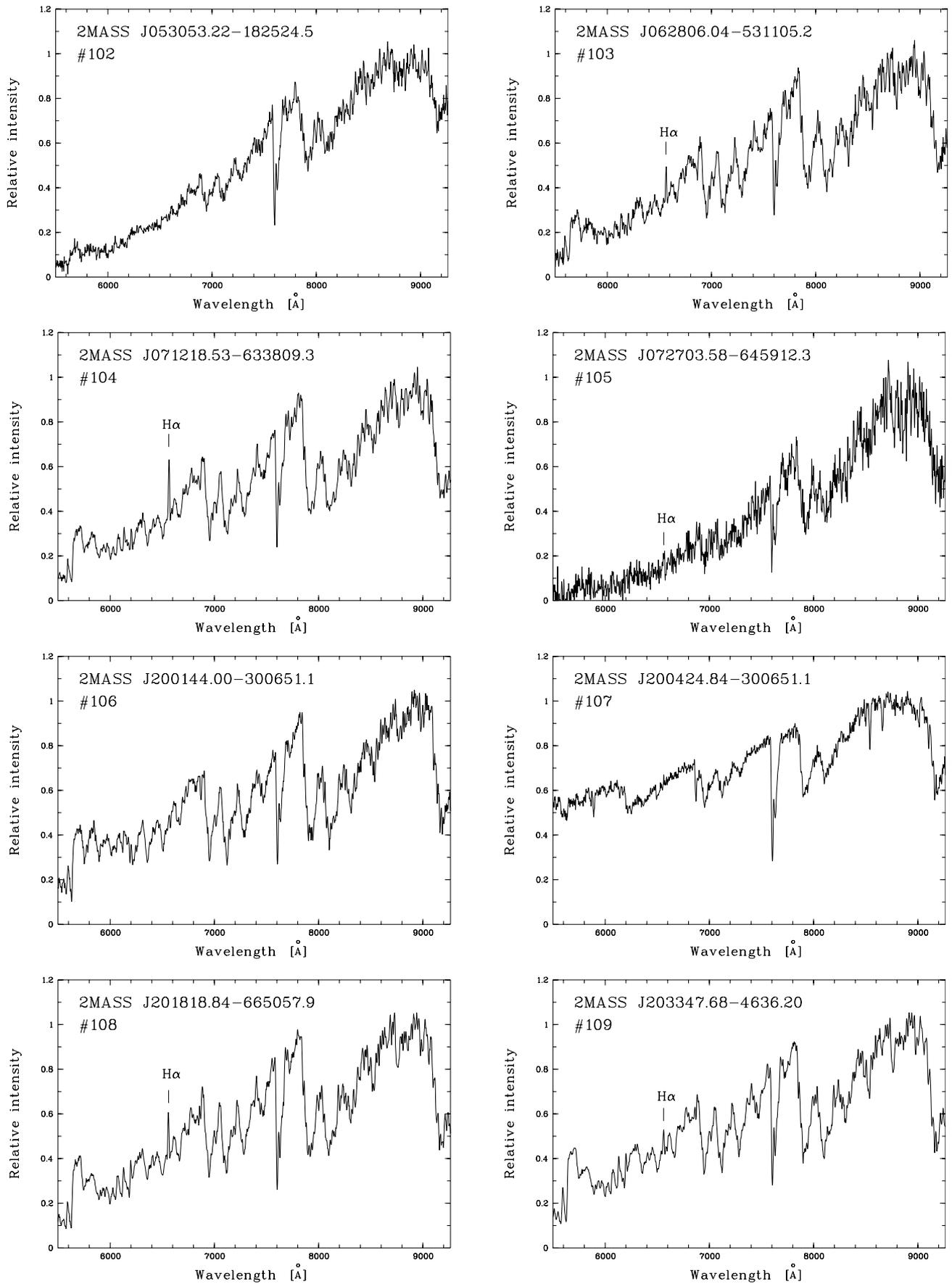


Fig. A.1. Spectra of halo carbon stars.

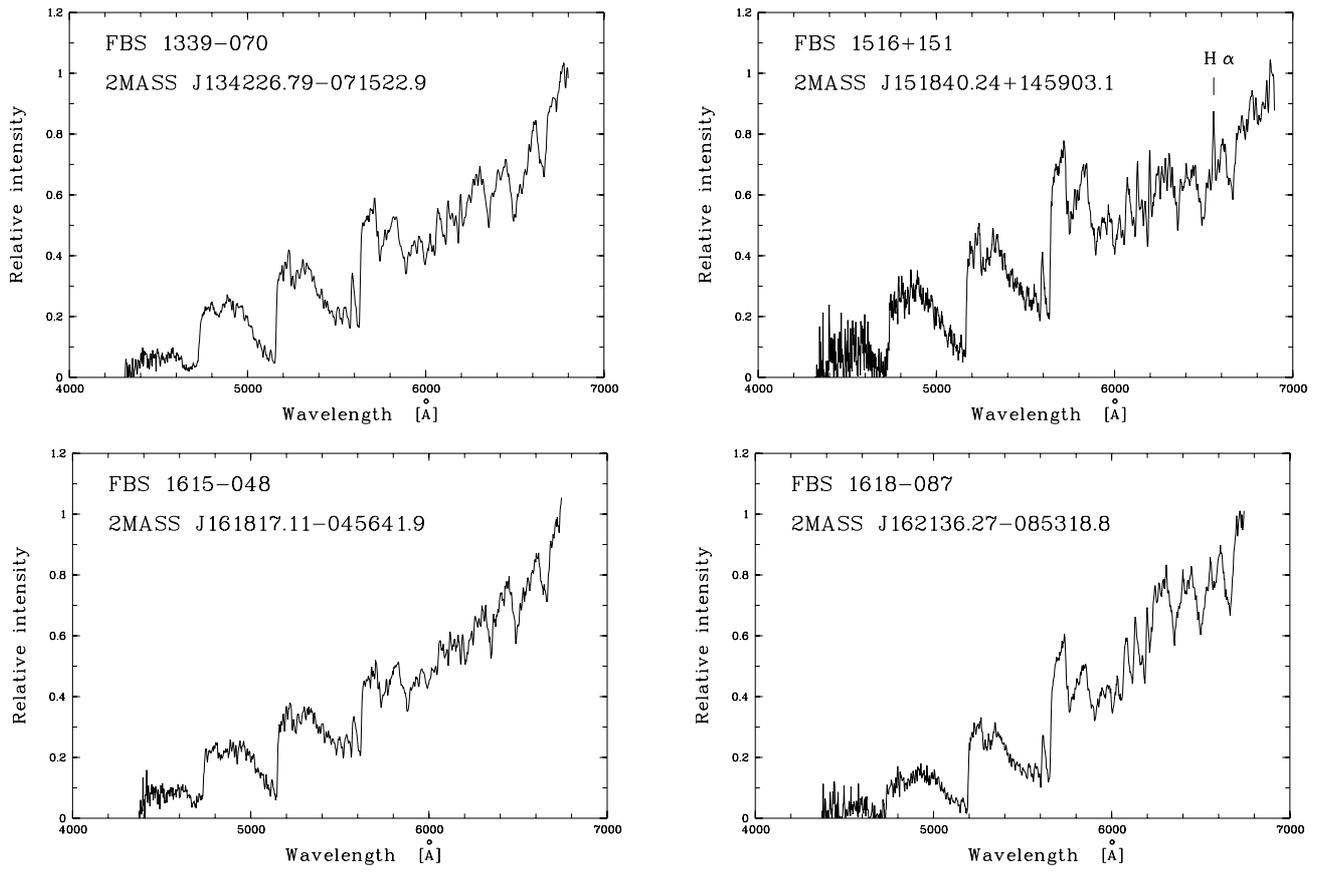


Fig. A.2. Spectra of FBS halo carbon stars.

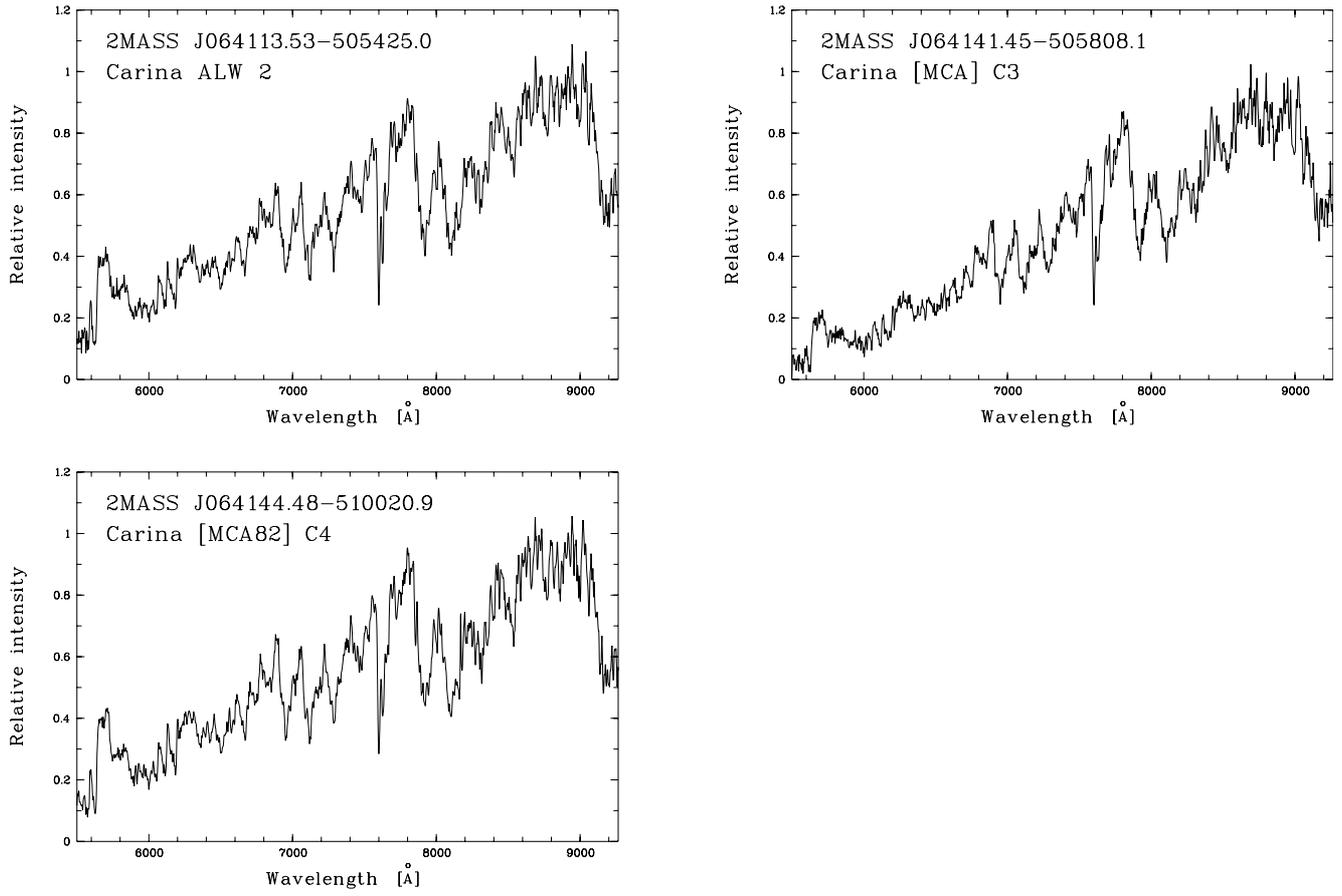


Fig. A.3. Spectra of Carina carbon stars.

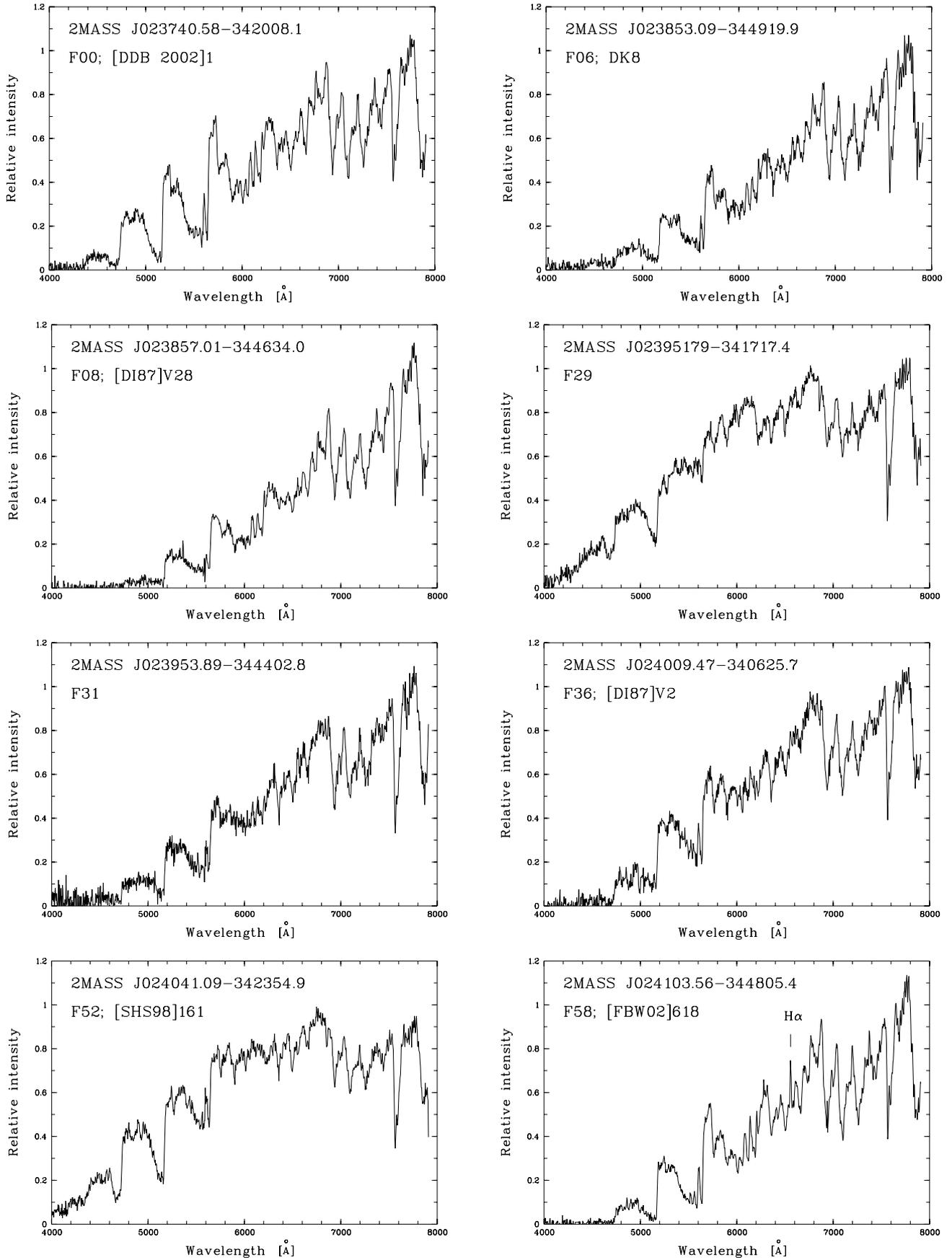


Fig. A.4. Spectra of Fornax carbon stars.

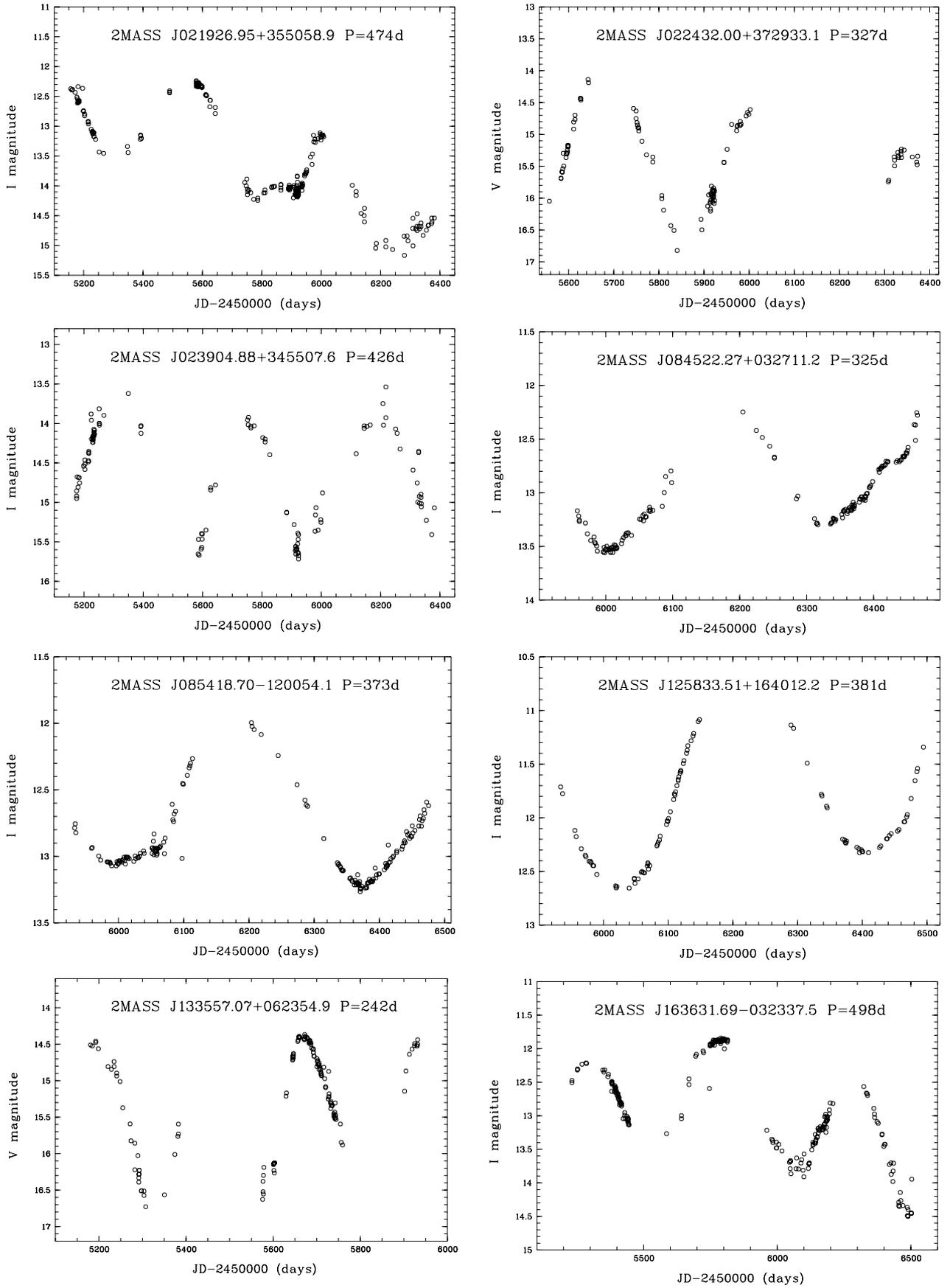


Fig. A.5. TAROT light curves of halo carbon stars.

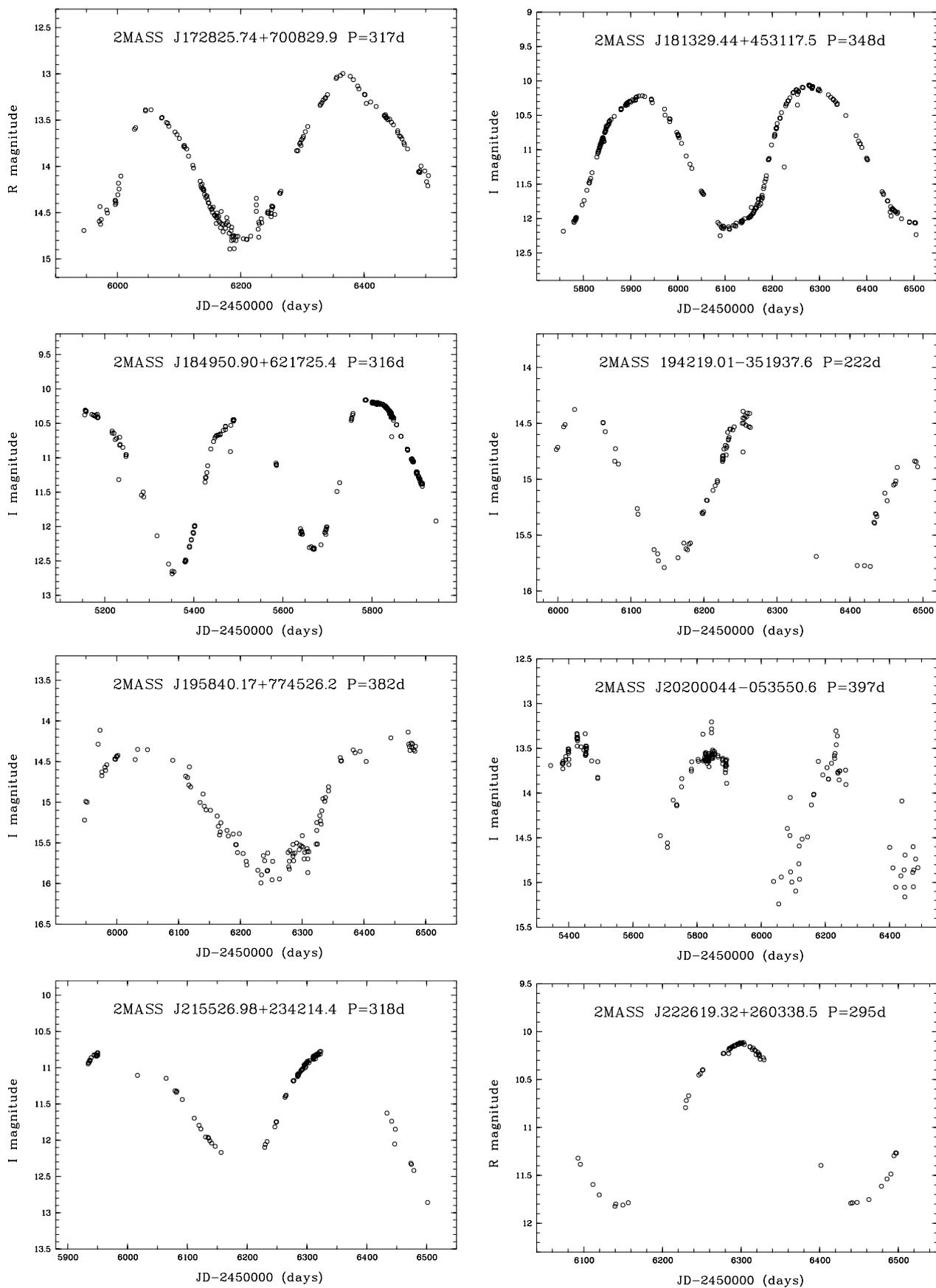


Fig. A.5. continued.

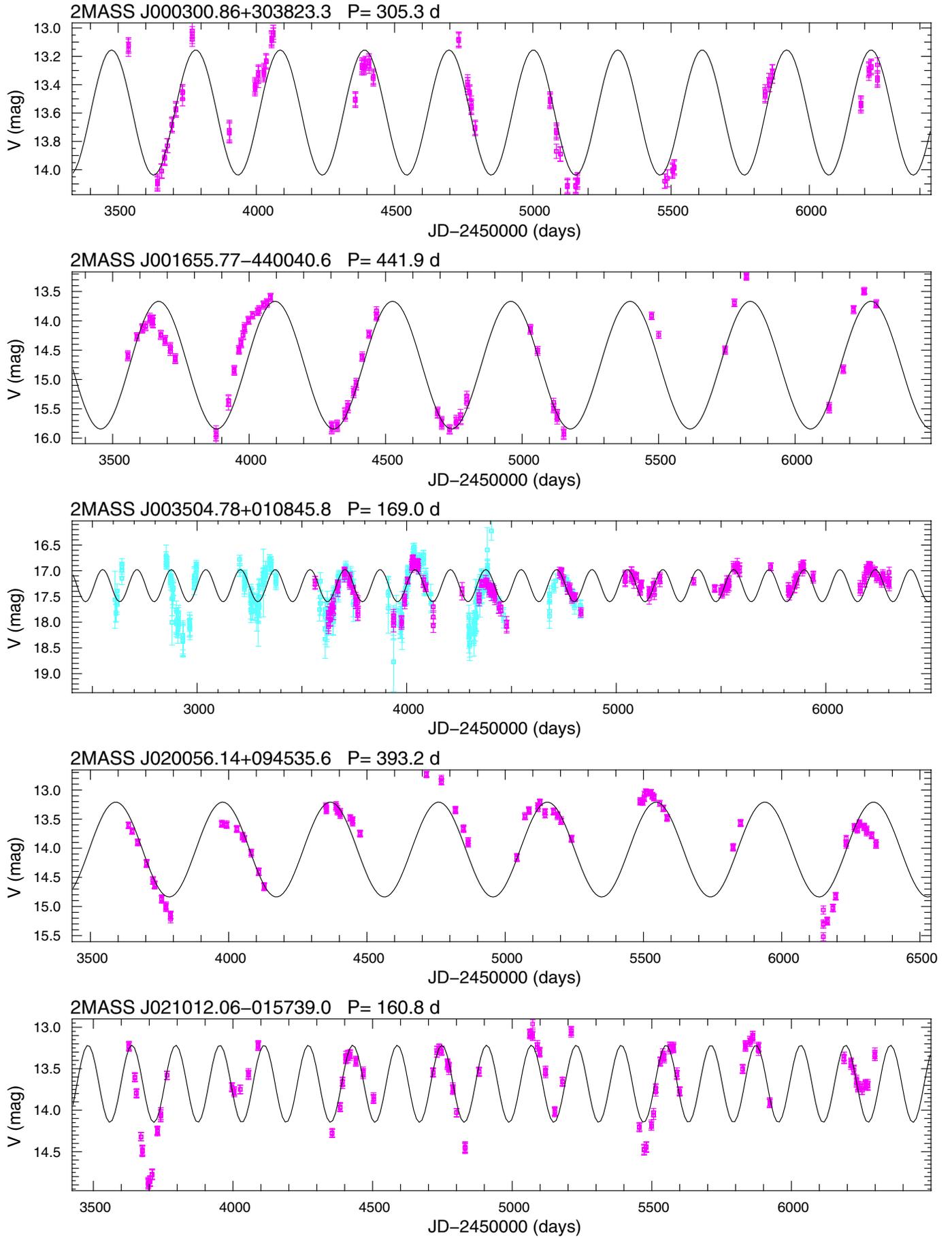


Fig. A.6. Atlas of light curves with LINEAR (colored in cyan) and Catalina (in magenta), and fitted sinusoids.

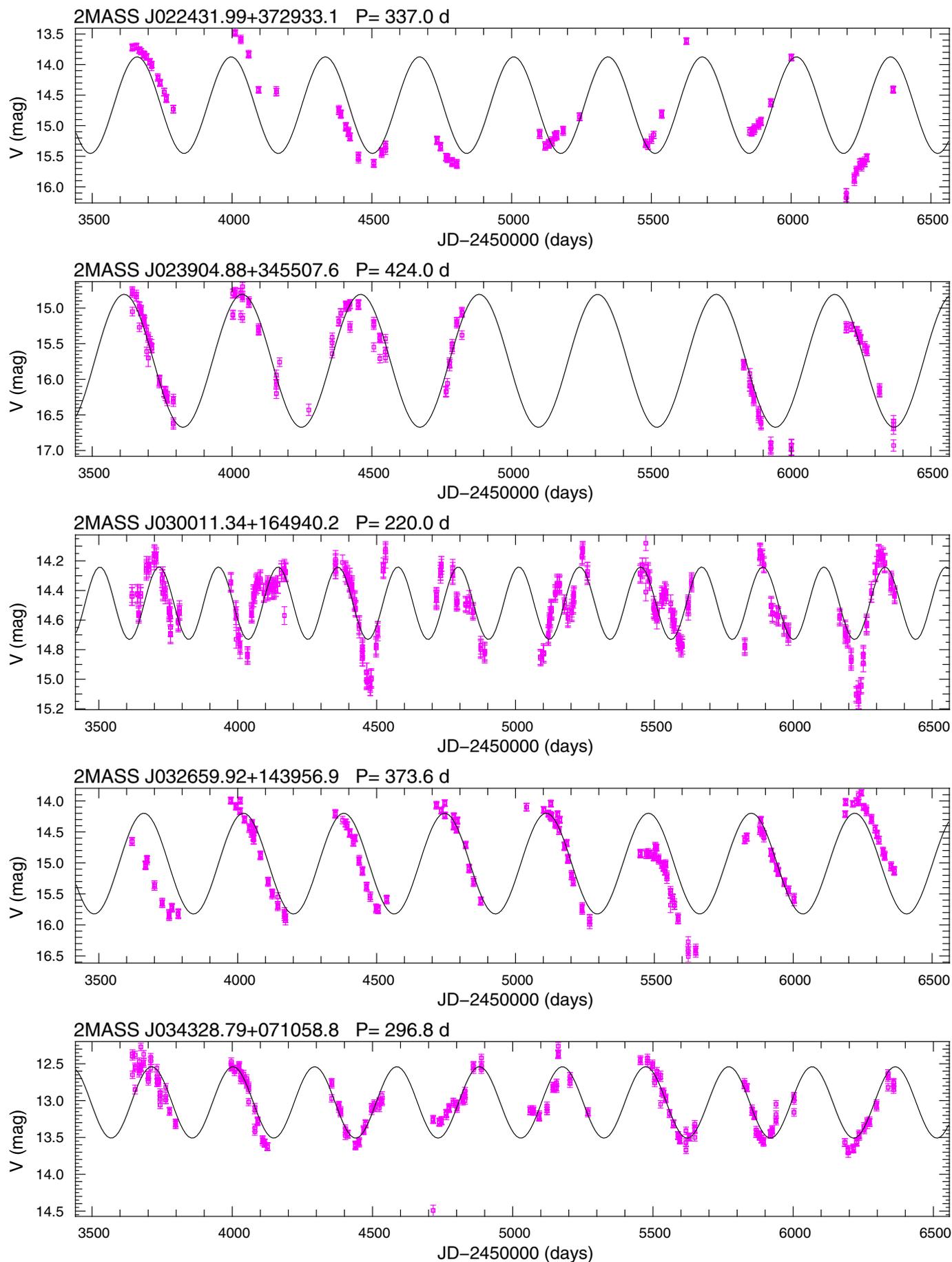


Fig. A.6. continued.

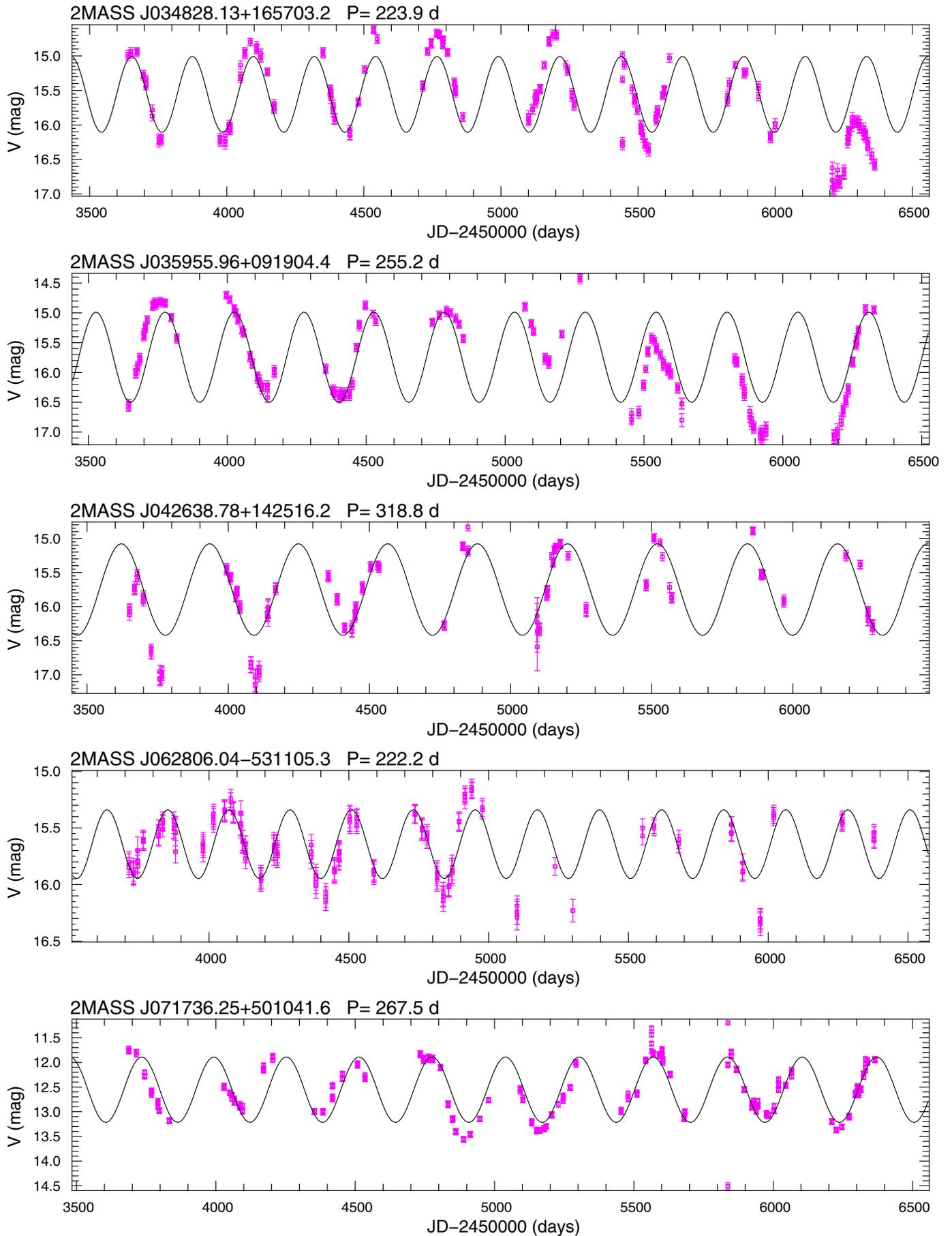


Fig. A.6. continued.

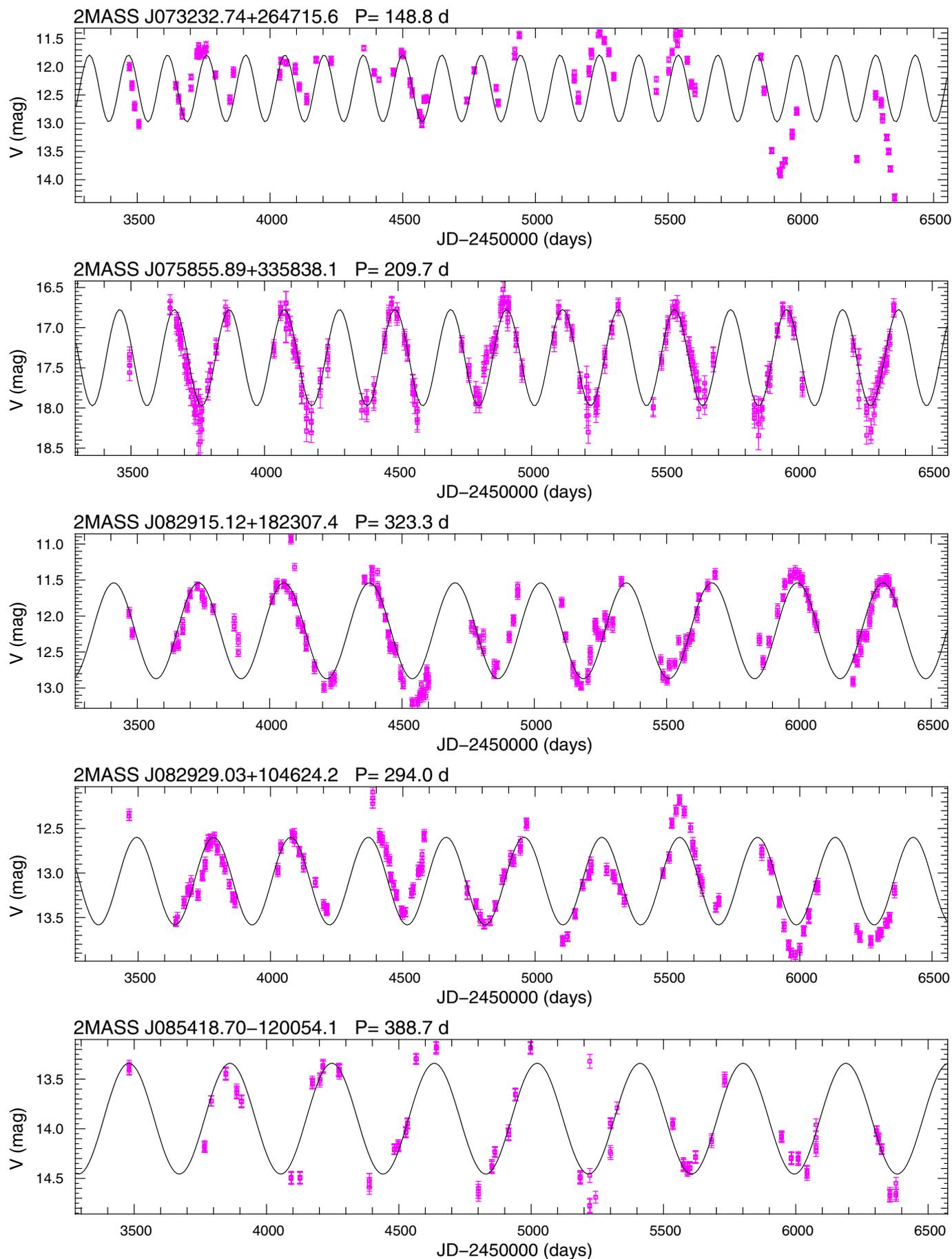


Fig. A.6. continued.

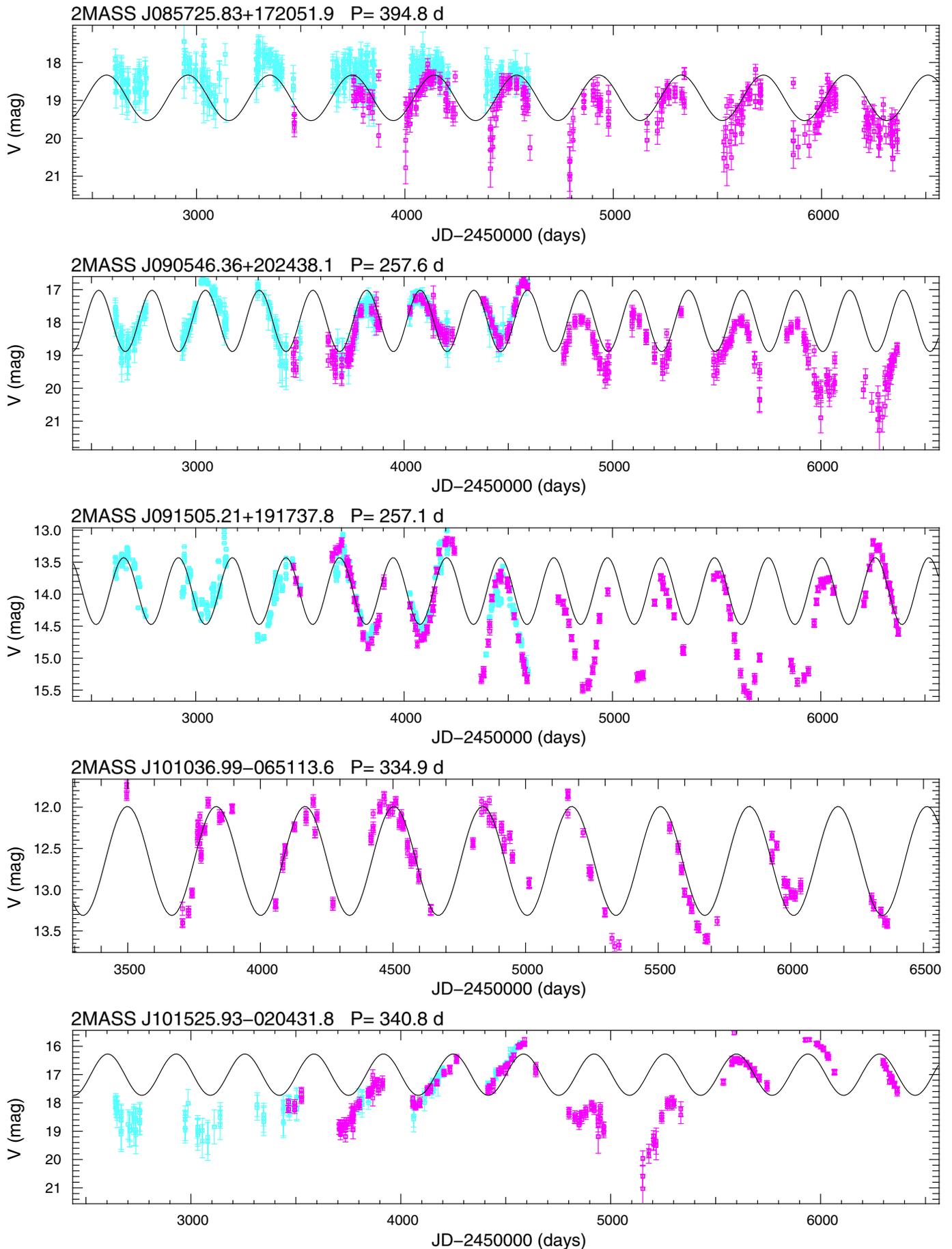


Fig. A.6. continued.

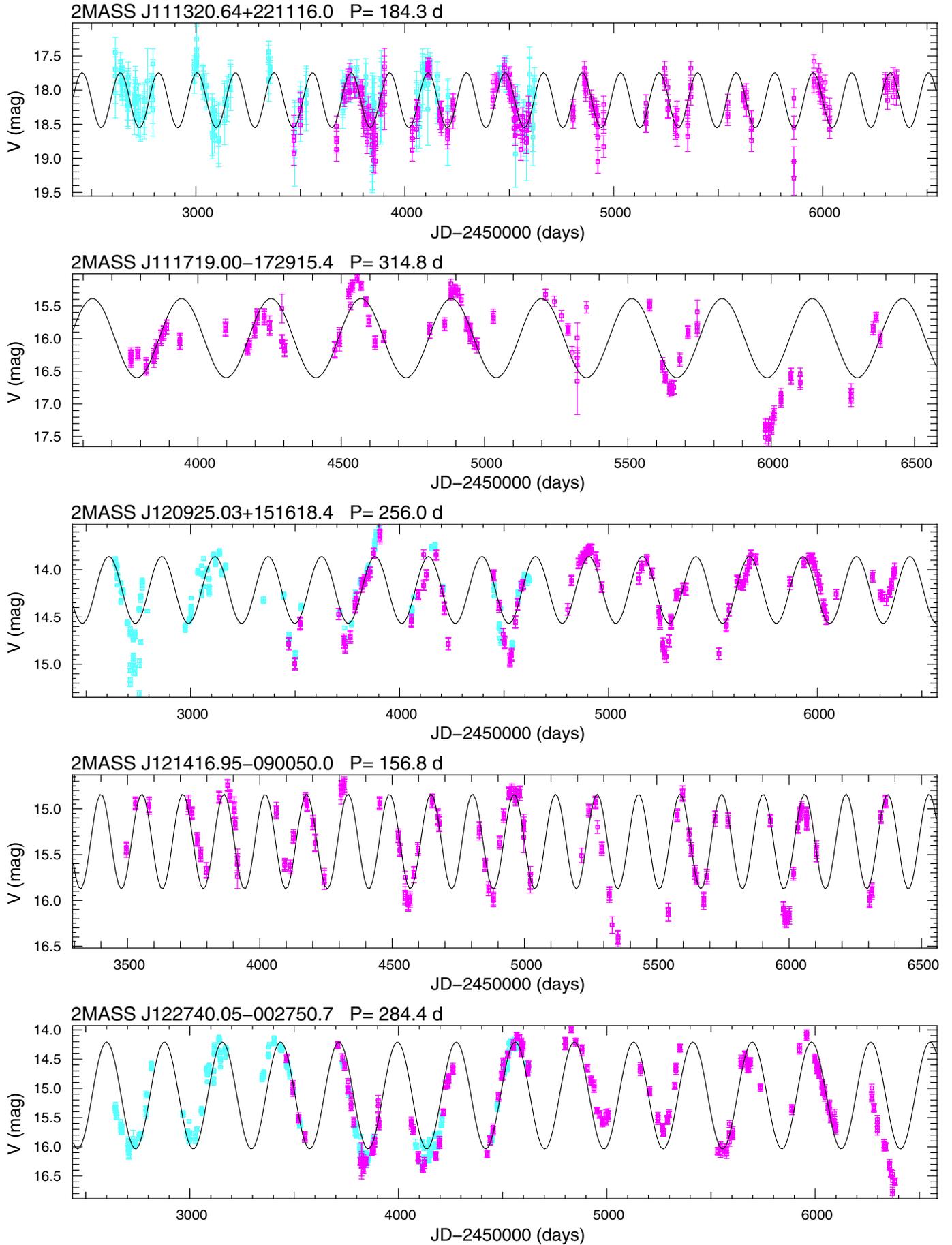


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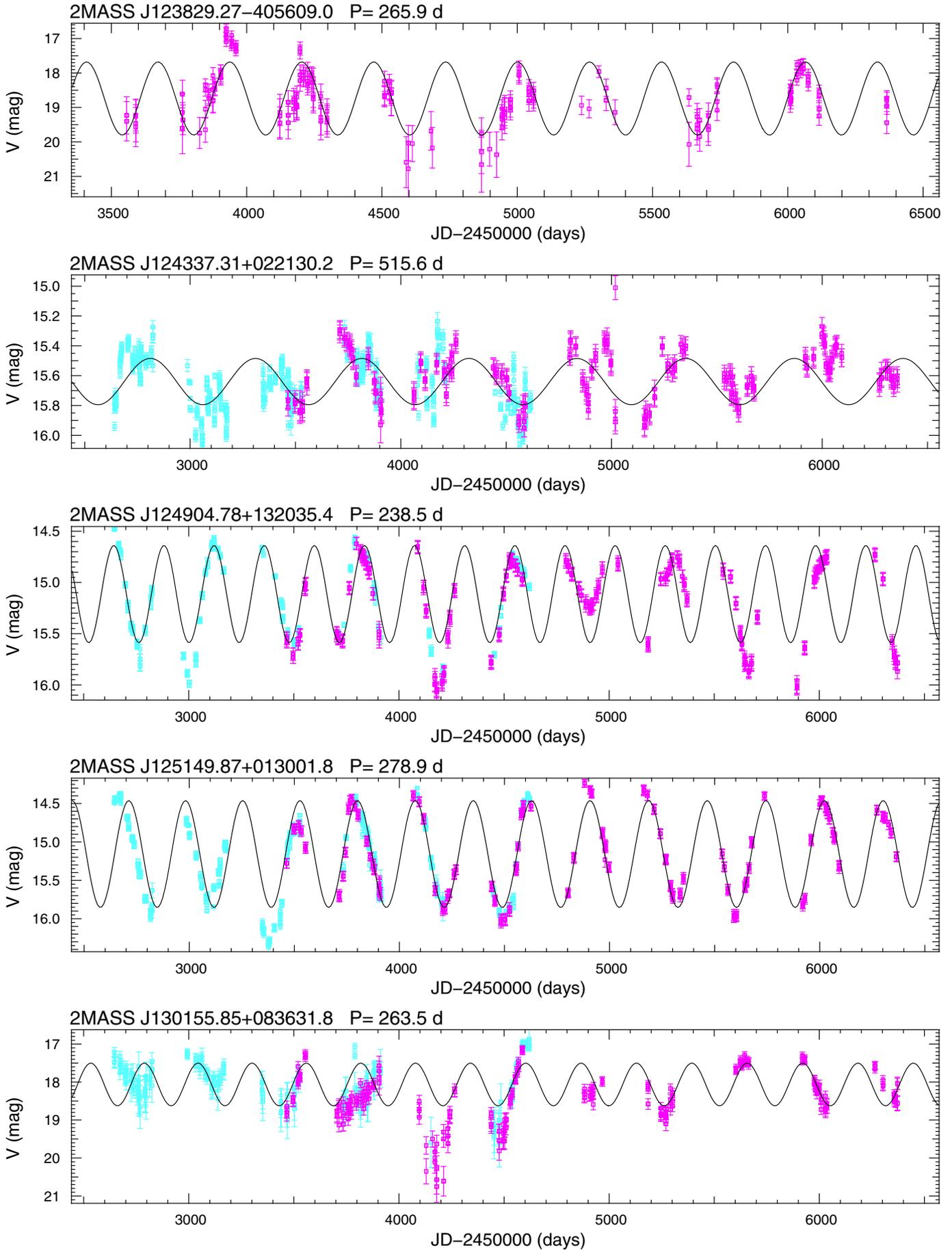


Fig. A.6. continued.

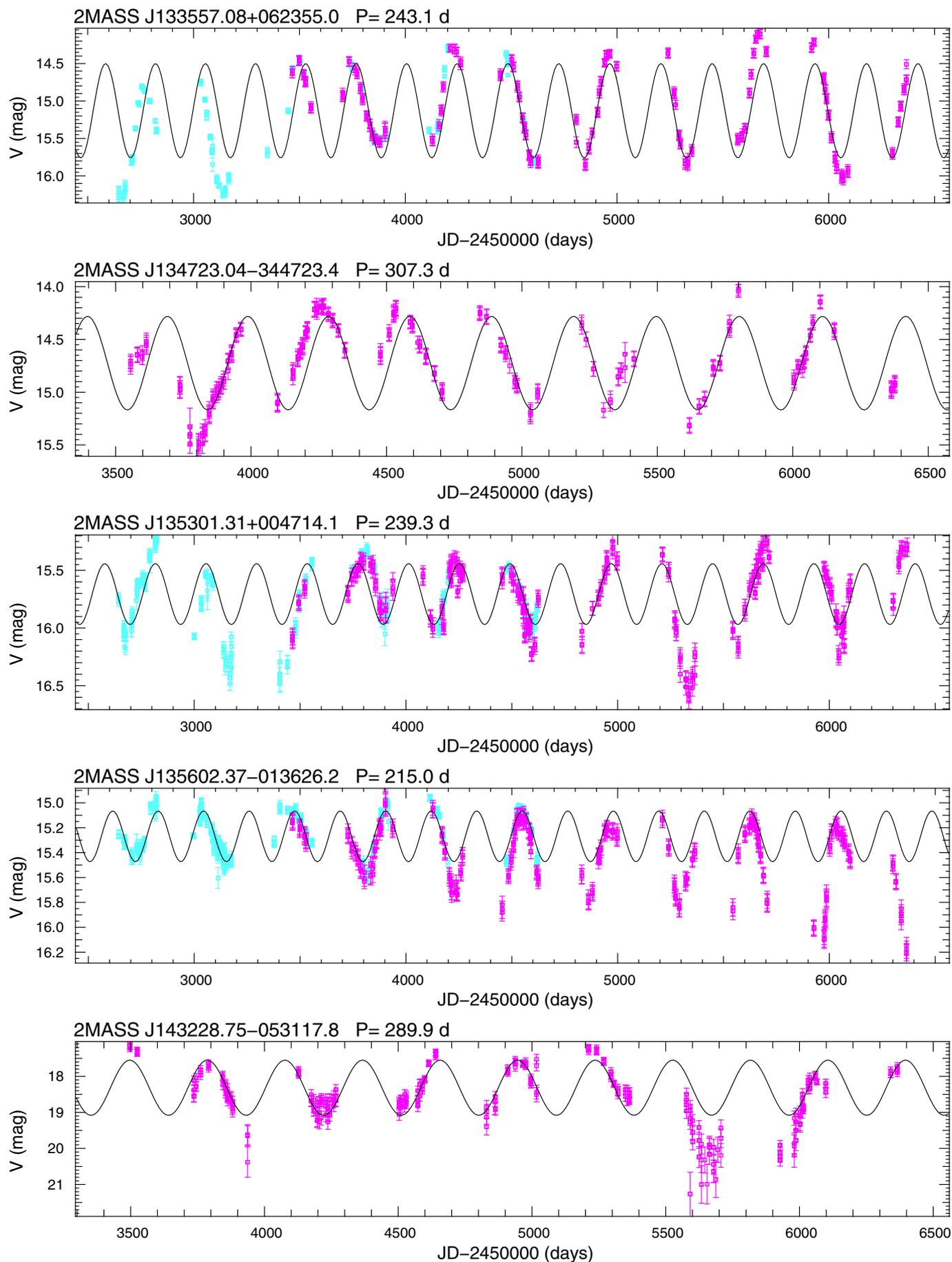


Fig. A.6. continued.

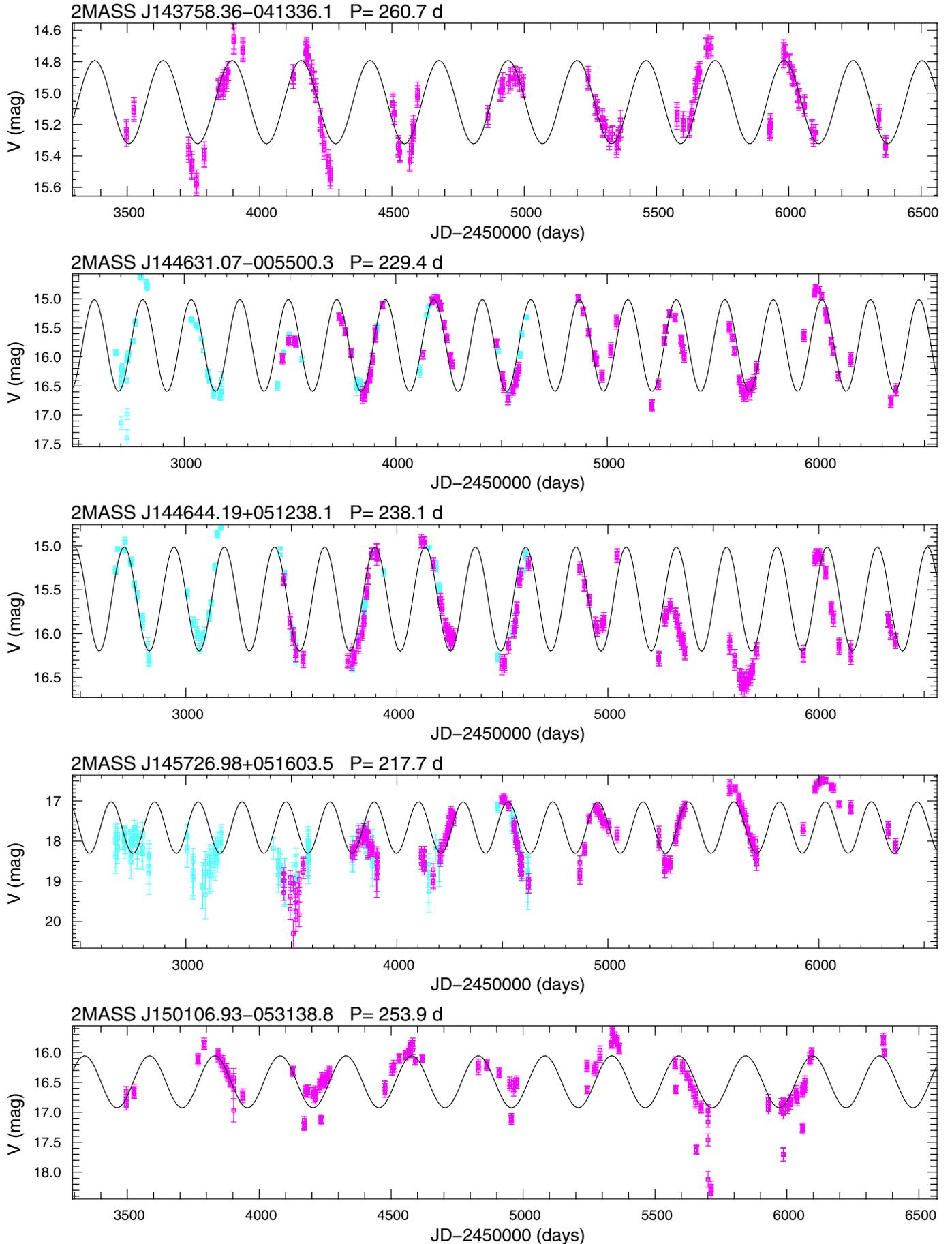


Fig. A.6. continued.

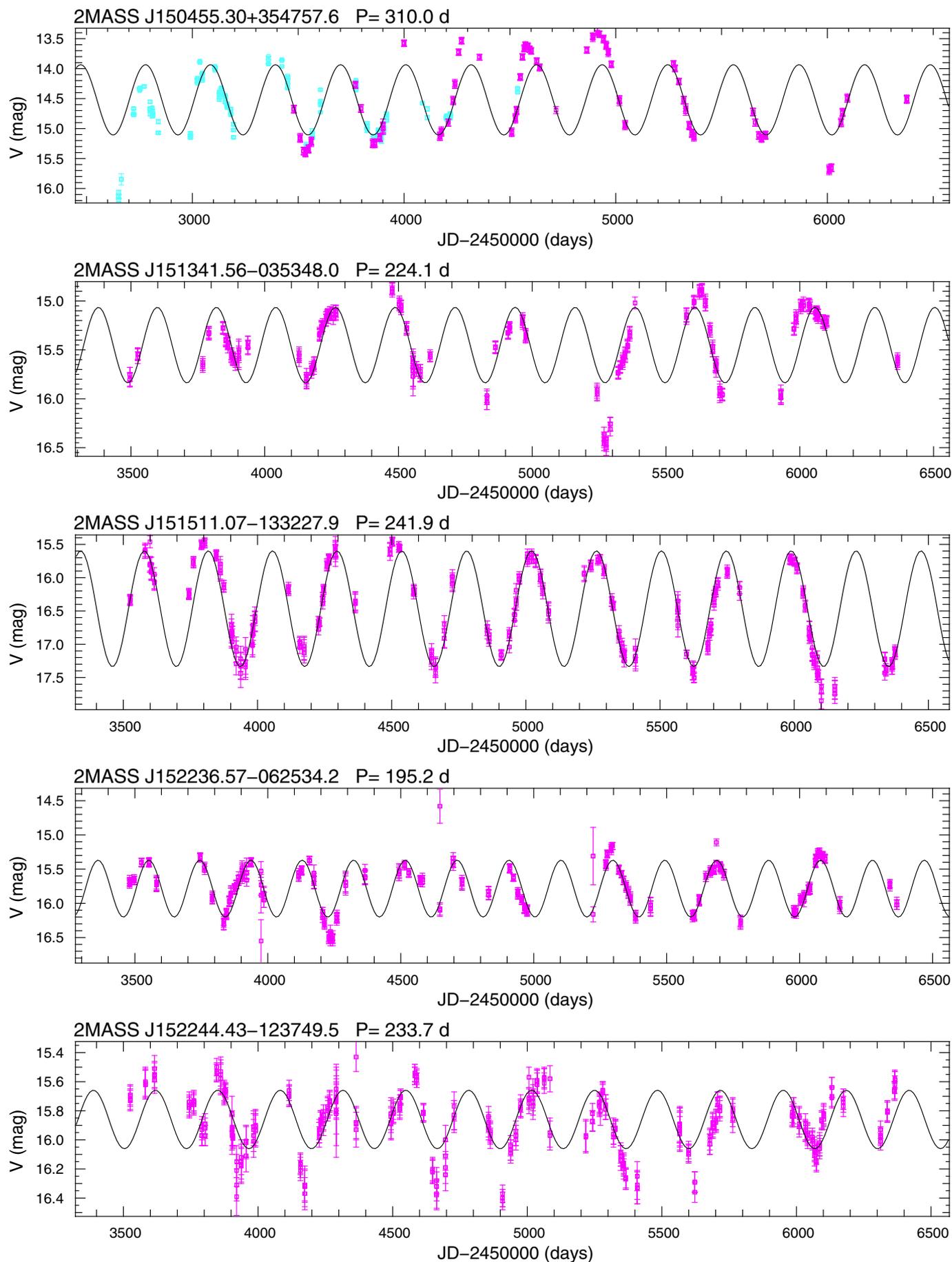


Fig. A.6. continued.

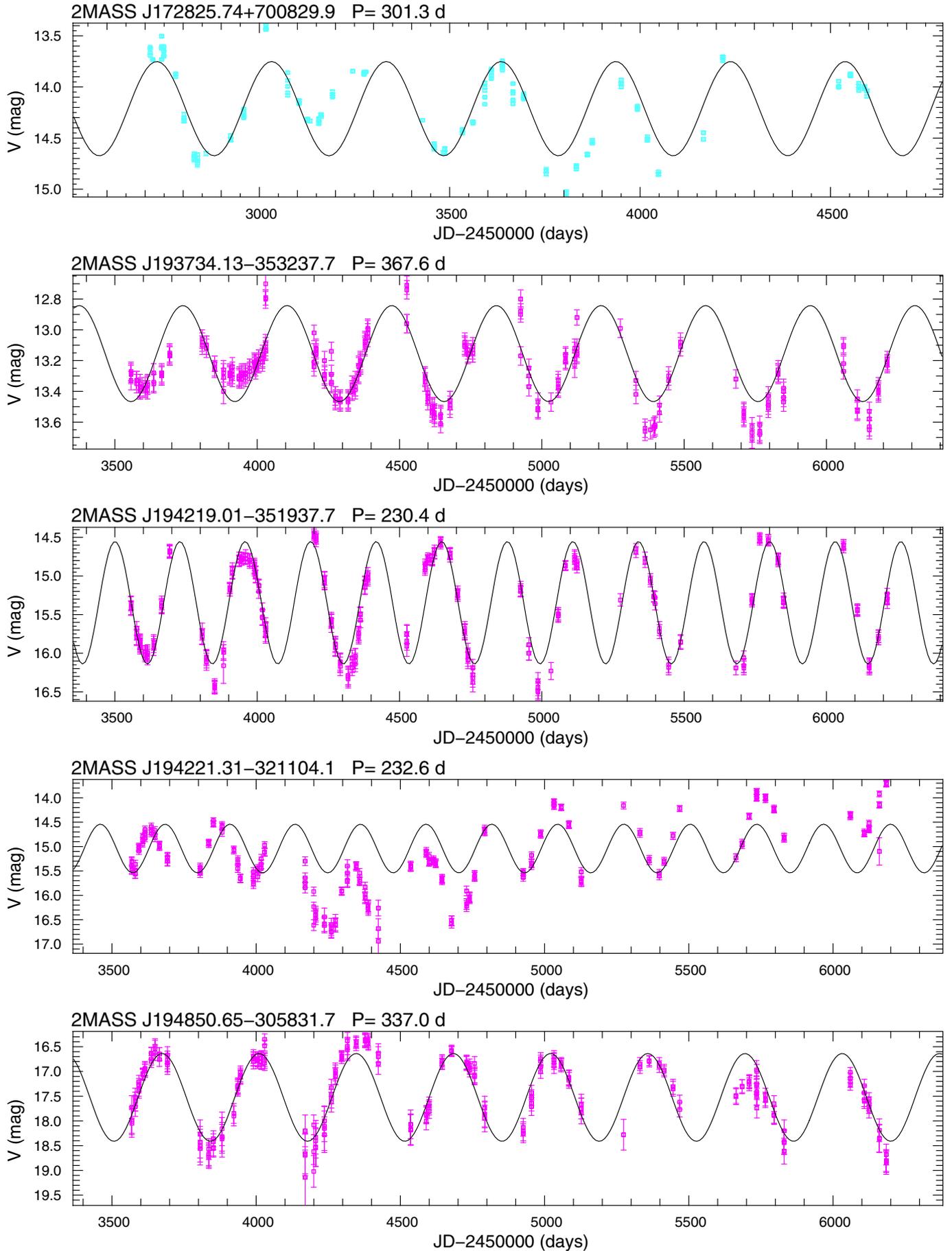


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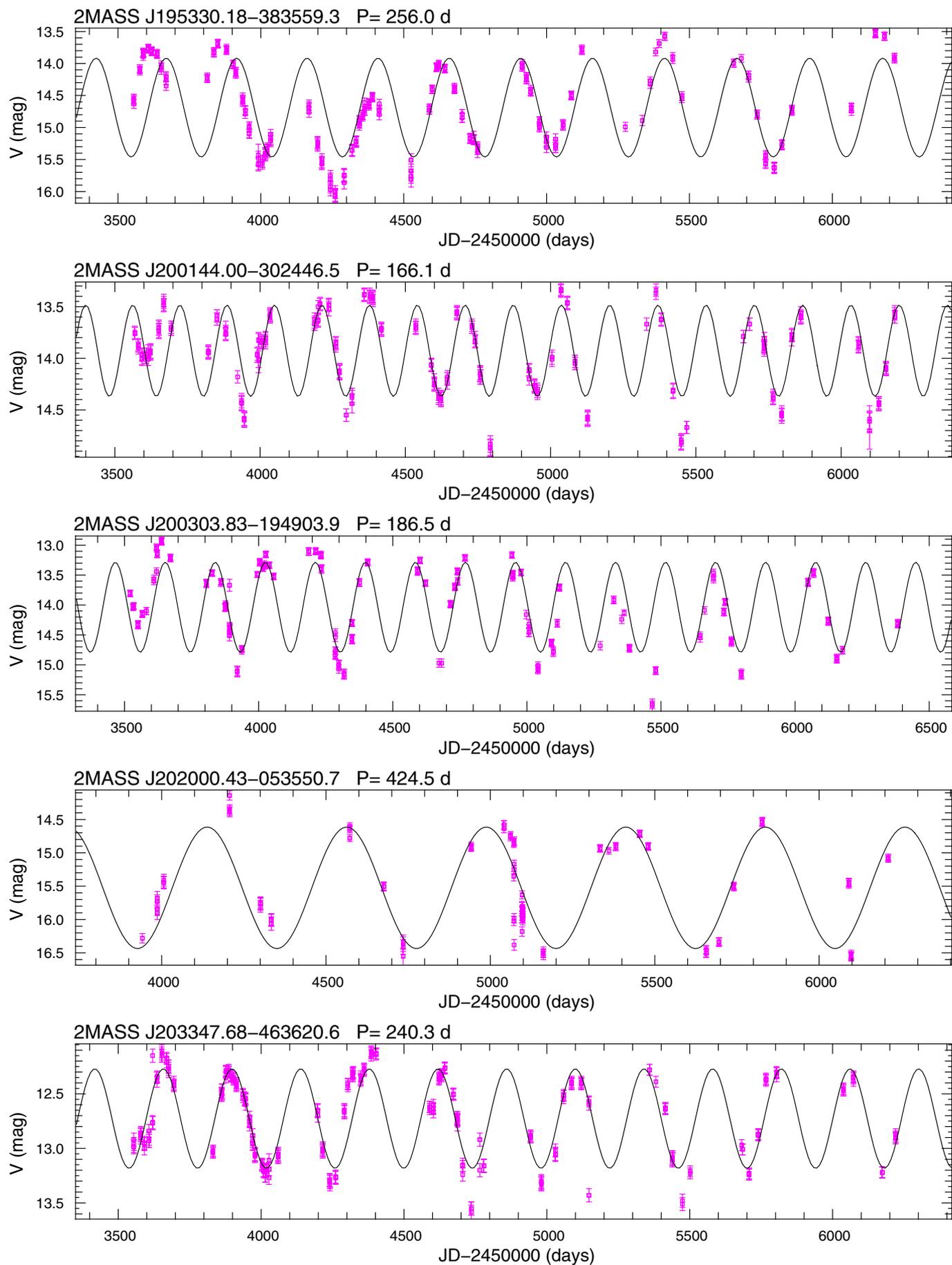


Fig. A.6. continued.

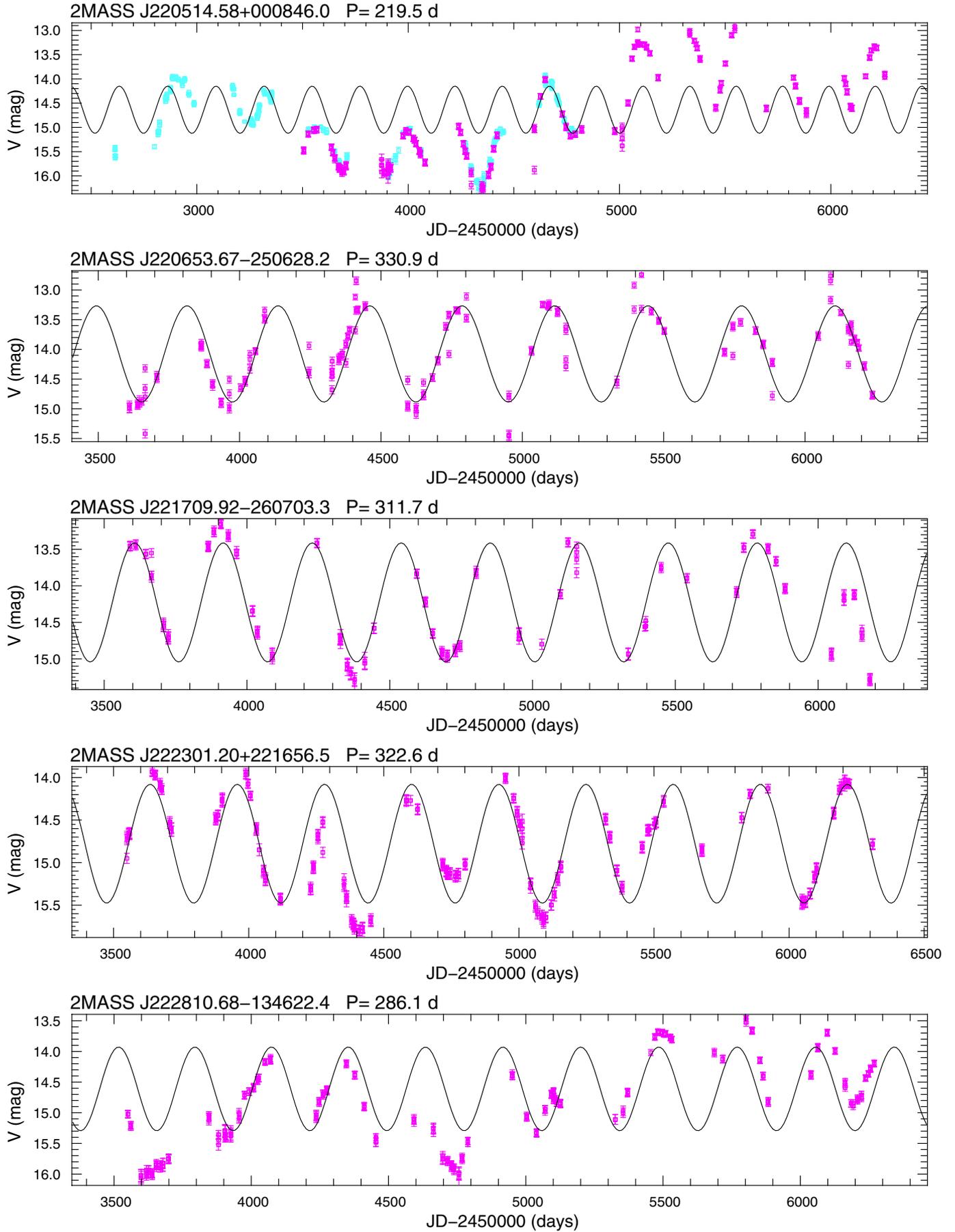


Fig. A.6. continued.

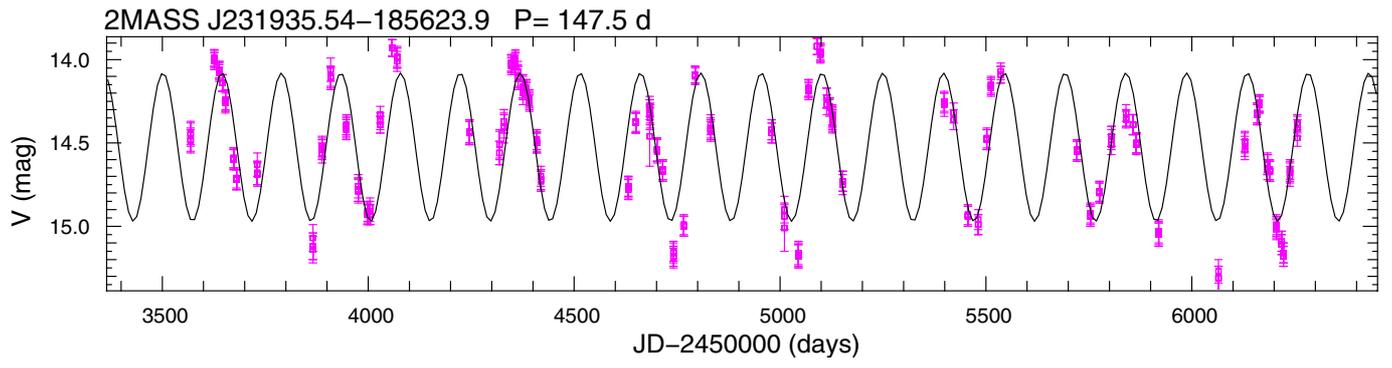


Fig. A.6. continued.

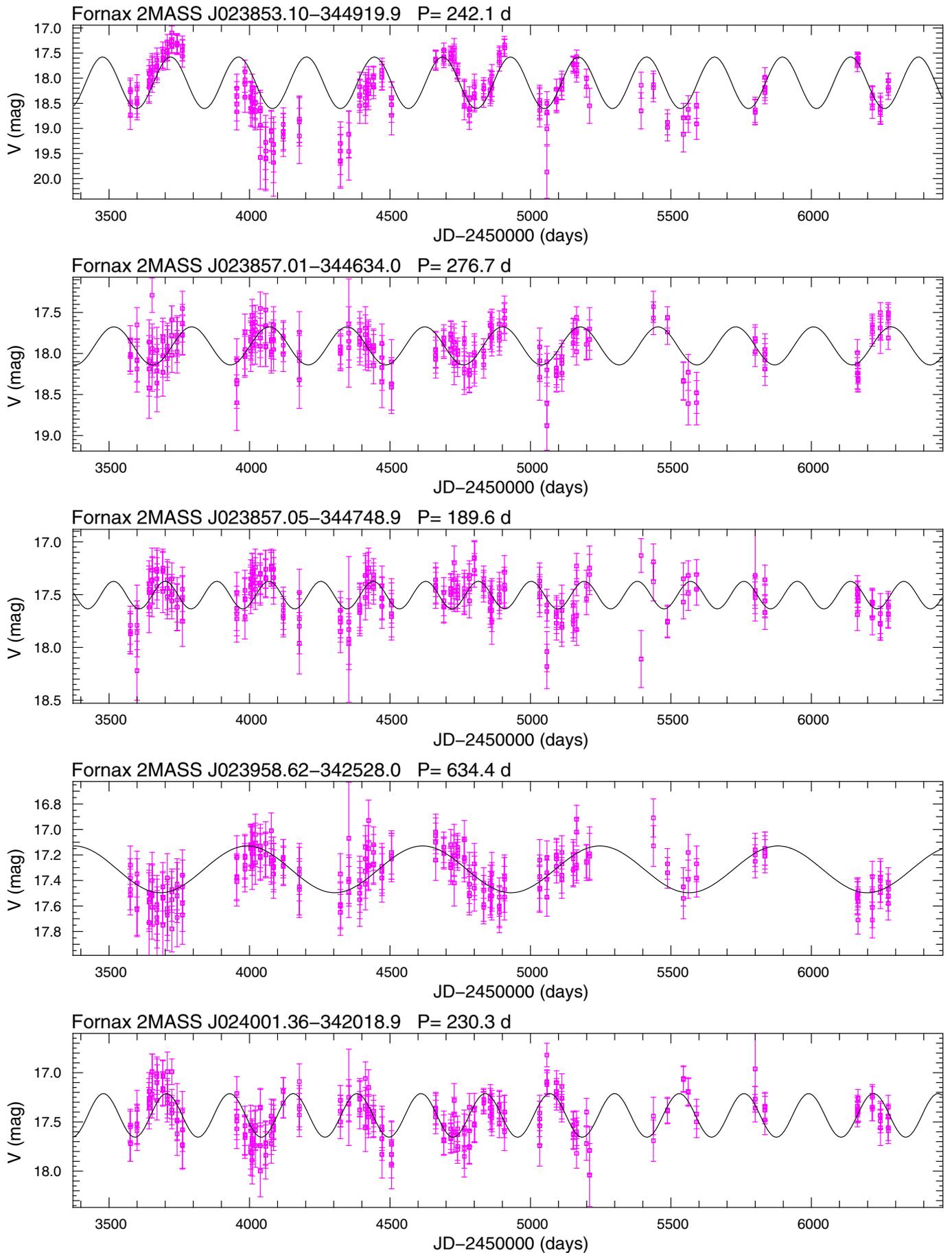


Fig. A.7. Light curves of Fornax C stars and fitted sinusoids.

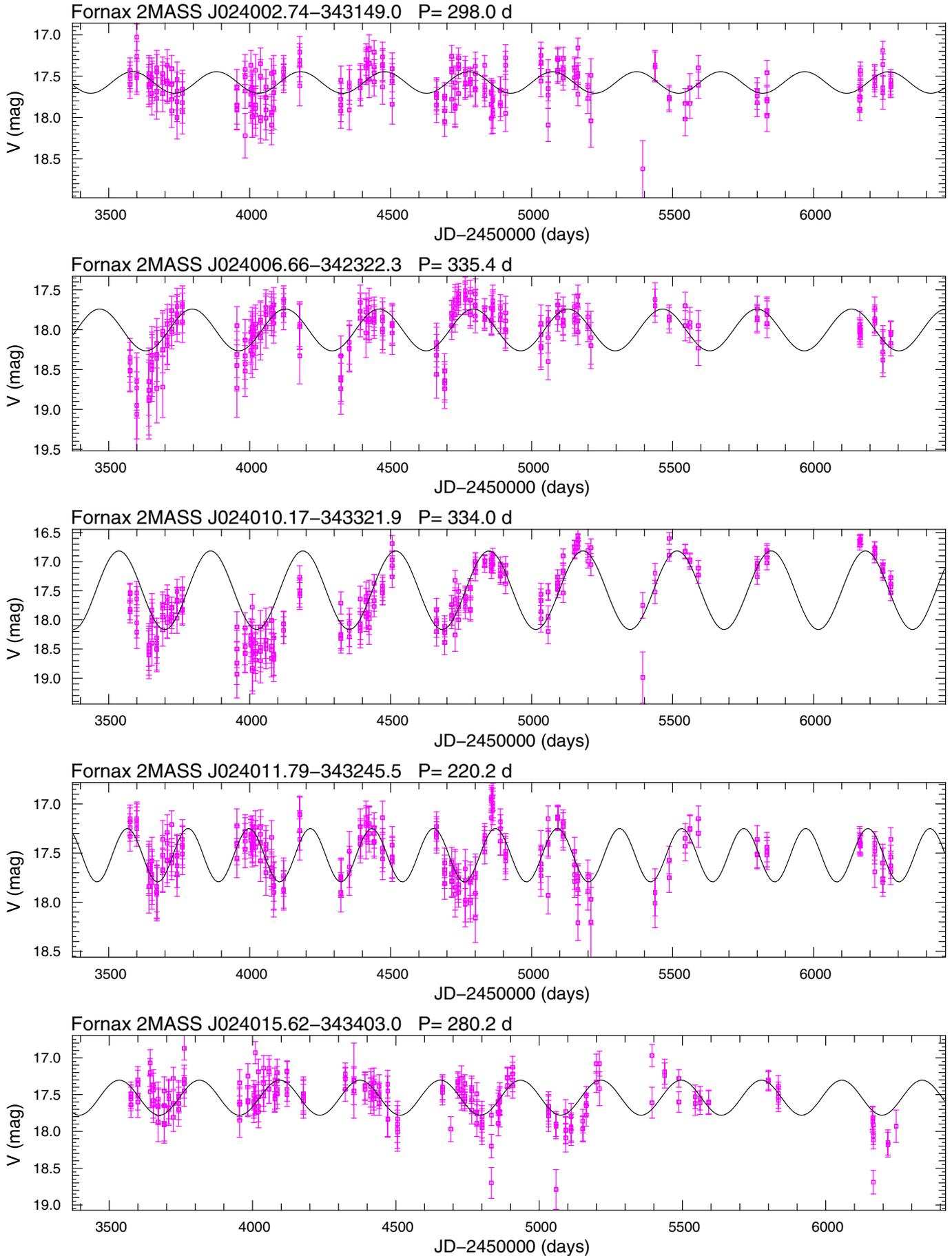


Fig. A.7. continued.

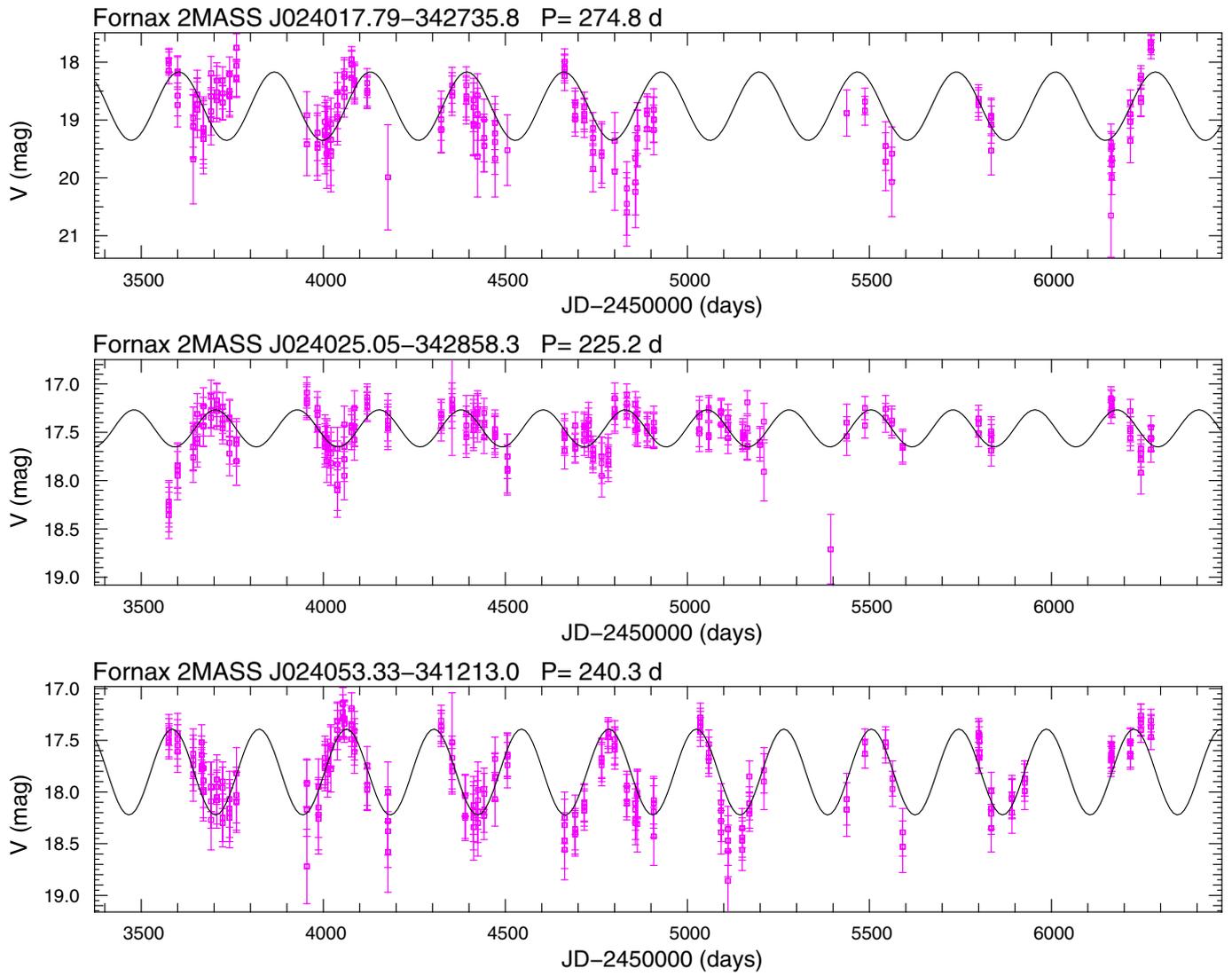


Fig. A.7. continued.