The Astronomical Journal, 125:3165–3174, 2003 June

NEW SX PHOENICIS STARS IN THE GLOBULAR CLUSTER M53

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Received 2002 October 7; accepted 2003 March 13

ABSTRACT

Through time-series CCD photometry of the metal-poor globular cluster M53 we have discovered eight new SX Phoenicis–type stars (labeled "SXP1" to "SXP8"). All the new SX Phoenicis stars are located in the blue straggler star region of the color-magnitude diagram of M53. One of these stars (SXP2) is found to have very closely separated pulsation frequencies: $f_1/f_2 = 0.9595$, where f_1 and f_2 are the primary and secondary frequencies, respectively. This may be due to excitation of nonradial modes. Six of these SX Phoenicis stars are considered to be pulsating in the fundamental mode. They show a tight linear correlation between the period and luminosity. We derive a period-luminosity relation for the fundamental mode for the period range of $-1.36 < \log P(\text{days}) < -1.15$: $\langle V \rangle = -3.010(\pm 0.262) \log P + 15.310(\pm 0.048)$ with an rms scatter of 0.038, corresponding to $\langle M_V \rangle = -3.010 \log P - 1.070$ for an adopted distance modulus of $(m - M)_V = 16.38$.

Key words: blue stragglers — globular clusters: individual (M53) — stars: oscillations — stars: variables: other

1. INTRODUCTION

SX Phoenicis stars are Population II pulsating variable stars, with shorter periods (<0.1 days) and larger amplitudes of variability than δ Scuti stars, which are short-period pulsating variable stars belonging to Population I. Interestingly, most of known SX Phoenicis stars in globular clusters are located in the blue straggler star (BSS) region in the color-magnitude diagram (CMD). It has been a long time since the presence of the BSS in the globular cluster M3 was made known by Sandage (1953). Now many BSSs have been discovered in the globular clusters and open clusters in our Galaxy and in the fields of nearby galaxies. However, the origin of the BSSs is still controversial. The BSSs are hotter and brighter than the main-sequence turnoff stars, so that it is necessary to identify some mechanisms that makes the stars hotter and brighter (more massive) to explain the origin of the BSS. Two classes of mechanisms have been suggested. One class involves a single star, where mixing in the atmosphere can increase the lifetime of the main sequence. The other class is based on merger process, where two low-mass stars merge to form a more massive unevolved star via mass transfer or direct collisions between stars. These days the latter is preferred (Bailyn 1995). Recently, a significant fraction of the BSS in globular clusters are known to be SX Phoenicis stars. The presence of these pulsating variable stars (as well as eclipsing variables) among the BSSs provides an excellent opportunity to understand the origin of the BSSs, because we can investigate physical properties and processes of the stars in more detail compared with the case of nonvariable stars. Therefore, the study of SX Phoenicis stars can provide us with important clues on the origin of the BSSs.

It is only since the 1980s that SX Phoenicis stars have been discovered in globular clusters. Since the first discovery of SX Phoenicis stars in the globular cluster ω Centauri (Niss 1981), the discovery rate of these stars in the globular clusters has increased rapidly, in particular during the last decade using the intermediate to large telescopes. Recently, many SX Phoenicis stars have been discovered in several globular clusters and nearby galaxies. Some examples are ω Centauri (Kaluzny et al. 1997), M5 (Kaluzny et al. 1999), M15 (Jeon et al. 2001b), M22 (Kaluzny & Thompson 2001), 47 Tuc (Gilliland et al. 1998; Bruntt et al. 2001), and M55 (Pych et al. 2001). Rodríguez & Lopéz-González (2000) listed a total of 122 SX Phoenicis stars belonging to 18 globular clusters and 27 stars in two external galaxies, covering information published up to 2000 January. However, the characteristics of the SX Phoenicis stars have not yet been fully explained by the present stellar evolution theories, requiring further investigation in observation and theory.

In addition, SX Phoenicis stars are known to show a period-luminosity (P-L) or period-metallicity-luminosity (P-[Fe/H]-L) relation, which can be a very useful distance indicator for globular clusters and nearby galaxies (McNamara 1997; Nemec et al. 1994). However, the

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number of known SX Phoenicis stars in a given globular cluster is small and most studies use an inhomogeneous sample based on different sources. Therefore, a large variation is seen among these relations. For example, McNamara (1997) derived a slope of −3.7, while Pych et al. (2001) obtained a much flatter slope of −2.9.

In 1999 we began time series CCD photometry to search for variable BSSs in globular clusters using the 1.8 m telescope at the Bohyunsan Optical Astronomy Observatory (BOAO) in Korea. Generally we can detect SX Phoenicis–type stars brighter than $V = 19.5$ mag for 200 s exposures, depending on the seeing condition. For larger amplitude variable stars, such as W UMa–type eclipsing binaries, the detecting magnitude reaches 20.2 mag for the same exposures. The first result of our survey was the discovery of an SX Phoenicis star (Jeon et al. 2001b) and two W UMa–type variable stars (Jeon et al. 2001a) in the globular cluster M15.

In this paper we present the result of our survey for short-period variable stars in the metal-poor globular cluster M53. M53 (R.A. $= 13^h12^m55^s.3$, decl. $= +18°10'09''$, J2000.0; Harris 1996[3]) has a very low metallicity, [Fe/H] $=$ -1.99, a low interstellar reddening, $E(B-V) = 0.02$, and an apparent V distance modulus $(m - M)_V = 16.38$ (Harris 1996). Many blue straggler stars are known to exist in M53 (Rey et al. 1998). Some of these blue stragglers are expected to be SX Phoenicis stars, but no SX Phoenicis stars have been reported yet (Rodríguez & Lopéz-González 2000; Clement 2001). Here we report a discovery of eight SX Phoenicis stars in this cluster.

This paper is composed as follows. Observations and data reduction are described in § 2. Section 3 presents the light curves of the new SX Phoenicis stars in M53, and § 4 discusses the characteristics of these stars, including the pulsation modes and the period-luminosity relation. Finally, primary results are summarized in § 5.

[3] Available at http://physun.physics.mcmaster.ca/Globular.html; revised 1999 June 22.

2. OBSERVATIONS AND DATA REDUCTION

2.1. *Observations*

We obtained time series CCD images of M53 for 11 nights from 1999 March 12 to 2001 April 1. A total of 45 and 381 frames were obtained for the B and V bands, respectively. Because the observations were performed under various seeing conditions, we adjusted exposure times depending on the seeing. The observation log is listed in Table 1.

The CCD images were obtained with a thinned SITe 2k CCD camera attached to the BOAO 1.8 m telescope. The field of view of a CCD image is $11'.6 \times 11'.6$ ($0''.3438$ pixel^{-1}) at the f/8 Cassegrain focus of the telescope. The readout noise, gain, and readout time of the CCD are 7.0 e^-, 1.8 e^- ADU^{-1}, and 100 s, respectively.

A gray-scale map of a V-band CCD image is shown in Figure 1. It shows only the southeast region ($7'.6 \times 6'.7$) of the cluster, out of the total observed field of $11'.6 \times 11'.6$. Eight new SX Phoenicis stars are represented by circles and labeled from SXP1 to SXP8.

2.2. *Data Reduction*

Using the IRAF/CCDRED package, we processed the CCD images to correct overscan regions, trim unreliable subsections, subtract bias frames and correct flat-field images. Instrumental magnitudes were obtained using the point-spread function– (PSF-) fitting photometry routine in the IRAF/DAOPHOT package (Massey & Davis 1992). The instrumental magnitudes of the stars in M53 were transformed to the standard system using the BVI standard stars (Landolt 1992) observed on the photometric night of 2000 March 30. In Figure 2 we plotted CMDs for a total of about 18,000 stars on the (V, $B-V$) plane. The left panel in Figure 2 shows the CMD for a central region at $r < 1'.0$, and the right panel shows the CMD for an outer region at $r \geq 1'.0$. On the right panel the main sequence (MS), the red giant branch (RGB), and the horizontal branch (HB) are clearly seen. In addition, there are about 100 stars at the brighter

TABLE 1
Observation Log

Date (UT)	Start HJD 2,450,000+	Duration (hr)	N_{obs}	Seeing (arcsec)	Exposure Time (s)	Remarks
1999 Mar 12	1250.173(V)	4.7	30(V)	~1.2–2.4(V)	300(V)	
2000 Mar 30	1634.007(V)	5.1	38(V)	~1.2–2.3(V)	180, 240(V)	Standard stars
	1634.022(B)		12(B)	~1.3–2.0(B)	300, 450(B)	
2000 Mar 31	1635.018(V)	7.6	46(V)	~2.1–3.4(V)	210, 180(V)	
	1635.029(B)		14(B)	~2.3–3.1(B)	300(B)	
2000 Apr 1	1636.153(V)	2.3	16(V)	~2.2–2.4(V)	420, 210(V)	Thin cloud
	1636.165(B)		1(B)	2.6(B)	300(B)	
2000 Apr 4	1639.196(V)	1.0	6(V)	~2.2–2.4(V)	210(V)	
	1639.201(B)		3(B)	~2.3–3.0(B)	300(B)	
2000 Apr 5	1640.010(V)	5.2	38(V)	~2.8–3.6(V)	210, 300(V)	
	1640.025(B)		11(B)	~3.0–3.7(B)	300(B)	
2000 Apr 6	1641.103(V)	4.3	34(V)	~1.6–2.1(V)	210, 180(V)	Thin cloud
	1641.133(B)		4(B)	~1.8–1.9(B)	300(B)	
2001Mar 26	1995.085(V)	6.4	42(V)	~3.1–4.0(V)	400(V)	Bad seeing
2001 Mar 29	1998.058(V)	5.9	34(V)	~1.9–2.8(V)	~350–500(V)	
2001Mar31	2000.000(V)	7.5	42(V)	~1.8–2.7(V)	500(V)	
2001 Apr 1	2000.988(V)	8.1	53(V)	~1.2–2.3(V)	~300–600(V)	

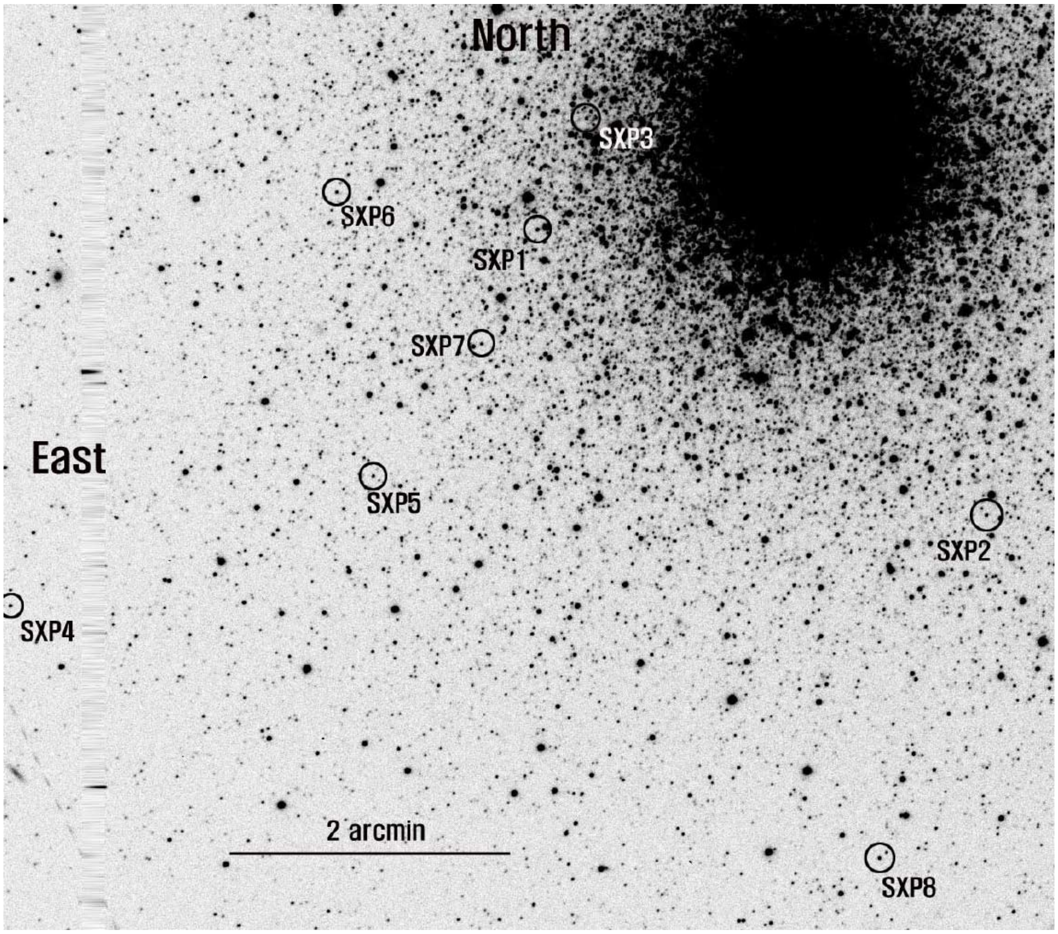

FIG. 1.—Gray-scale map of a *V*-band CCD image of the globular cluster M53. This image shows a 7.′6 × 6.′7 field in the southeast region of the cluster, out of the observed field of 11.′6 × 11.′6. Eight new SX Phoenicis stars are labeled "SXP1" to "SXP8."

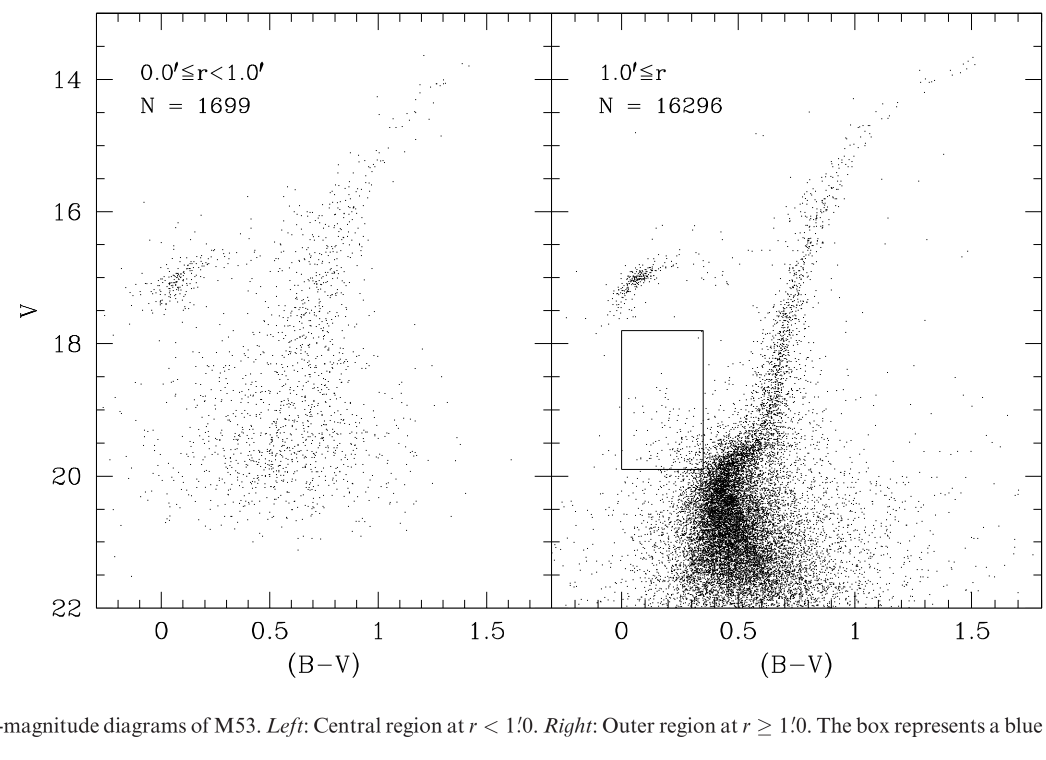

FIG. 2.—Color-magnitude diagrams of M53. *Left*: Central region at $r < 1.'0$. *Right*: Outer region at $r \geq 1.'0$. The box represents a blue straggler region.

and bluer region above the MS turnoff (represented by a box), which are blue stragglers. Large scatters shown in the left panel CMD for $r < 1'.0$ are due to crowding, so that we could not find any variable stars at $r < 1'.0$.

We applied the ensemble normalization technique (Gilliland & Brown 1988; Jeon et al. 2001b) to normalize instrumental magnitudes between time-series CCD frames. We used about a hundred normalizing stars ranging from 13.7 to 17.8 mag for the V-band and from 13.7 to 18.5 mag for the B-band, except for variable stars and central stars at $r < 1'.0$, where the crowding is severe. For B-band data, we use them only for obtaining mean magnitudes, because the data quality was not good enough to apply frequency analysis. The normalization equation is

$$B \text{ or } V = m + c_1 + c_2(B - V) + c_3P_x + c_4P_y \ , \qquad (1)$$

where B, V, and m are the standard and instrumental magnitudes of the normalizing stars, respectively. The value c_1 is the zero point and c_2 is the color coefficient. The values c_3 and c_4 are used to correct position-dependent terms such as atmospheric differential extinction and variable PSF.

3. LIGHT CURVES AND FREQUENCY ANALYSIS

After photometric reduction of the time-series frames we inspected luminosity variations for about 18,000 stars to search for variable stars. From the variable star search we discovered eight new SX Phoenicis stars and recovered about a tenth of previously known RR Lyrae stars. Here we report only the results on the SX Phoenicis stars. Detailed results on the RR Lyrae stars will be presented in a separate paper (Jeon et al. 2003).

The mean magnitudes and color indices of the SX Phoenicis stars are listed in Table 2. The right ascension and declination coordinates (J2000.0) of the stars in Table 2 were obtained from the astrometry using the Guide Star Catalog (version 1.1). Interestingly, all the new SX Phoenicis stars are located in the southeast direction from the center of M53. We checked any possible systematic errors preventing us from finding variable stars in other regions of the field but found none. The coordinates, mean magnitudes, and color indices of the eight new SX Phoenicis stars are listed in Table 2.

Figure 3 displays V-band light curves of eight new SX Phoenicis stars. Because SXP3 is located near the cluster center and SXP4 close to the CCD edge, some data of SXP3 were lost because of poor seeing and some data of SXP4 by the daily variation of the observing field center. The light curves in Figure 3 show typical characteristics of SX Phoenicis stars, i.e., short periods and low amplitudes.

We have performed multiple-frequency analyses to derive the pulsation frequencies of the eight SX Phoenicis stars using the discrete Fourier transform and linear least-squares fitting methods (Kim & Lee 1996). Figure 4 displays the power spectra the eight SX Phoenicis stars we derived. The small inset panels in Figure 4 represent the prewhitening processes. We searched for one to three pulsation frequencies for each star in the frequency region from 5 to 70 cycles per day. Low frequencies detected for the SXP1, SXP3, SXP4, and SXP8 might have resulted from variable seeing conditions and/or drift during long observing runs from 1999 to 2001. The synthetic light curves obtained from these analyses are superposed on the data in Figure 3, fitting the data well.

The results of the multiple-frequency analyses for the eight SX Phoenicis stars are summarized in Table 3. In this table we accepted as intrinsic pulsation frequencies with amplitude signal-to-noise ratios (S/Ns) larger than 4 (Breger et al. 1993), except for a frequency f_3 of SXP2. Although the amplitude S/N of SXP2, 3.8, is slightly smaller than 4, its f_3 seems to be a harmonic frequency of f_1. The periods of the primary modes for these SX Phoenicis stars range from 0.0385 days to 0.0701 days, and the semi-amplitudes of the variability range from 0.030 to 0.118 mag.

3.1. *The Characteristics of the Individual SX Phoenicis Star*

SXP1: SXP1 has the longest primary period of 0.0701 days among the eight new SX Phoenicis type stars of M53. This star has two frequencies, $f_1 = 14.2600$ cycles day^{-1} and $f_2 = 27.5256$ cycles day^{-1}. This star might be a monoperiodic pulsator, because the second frequency f_2 seems to be caused by 1 cycle day^{-1} alias effect of a harmonic frequency of f_1, $2f_1 = 28.5200$ cycles day^{-1}, In Figure 3 the light curves of SXP1 shows an asymmetric sinusoidal feature, which is the characteristic of harmonic frequencies. The maximum amplitude of SXP1 is estimated to be $\Delta V = 0.292$ mag.

SXP2: Light curves of this star in Figure 3 show an amplitudes change from day to day, implying the excitation of multiple pulsation frequencies. We derived two closely separated frequencies of $f_1 = 22.0450$ cycles day^{-1} and $f_2 = 22.9750$ cycles day^{-1}, with a ratio of $f_1/f_2 = 0.9595$. These frequencies can be explained by the excitation of nonradial modes. Pulsations with nonradial modes were found in several recent observational results of the SX Phoenicis stars: SX Phoenicis itself (Garrido & Rodríguez 1996), BL Cam (Zhou et al. 1999), V3 in 47 Tuc (Gilliland et al. 1998), SXP1 in M15 (Jeon et al. 2001b), and 10 SX Phoenicis stars in M55 (Pych et al. 2001). After these two frequencies are prewhitened, the third frequency is detected at $f_3 = 43.0190$ cycles day^{-1}, which might have resulted from 1 cycle day^{-1} alias effect of $2f_1 = 44.0900$ cycles day^{-1}. Even if the amplitude S/N for the third frequency is only 3.8, the light curves of SXP2 show an asymmetric sinusoidal feature, supporting the existence of harmonic frequencies. The maximum amplitude of SXP2 is estimated to be $\Delta V = 0.372$ mag, which is the largest value among the eight SX Phoenicis stars in M53.

SXP3, SXP4, SXP5, SXP6, SXP7: We could detect only a primary frequency for these five stars. Primary frequencies and the maximum amplitudes of SXP3, SXP4, SXP5, SXP6, and SXP7 are $f_1 = 20.8796$, 20.0114, 22.9880,

TABLE 2
Observational Parameters of the Eight SX Phoenicis Stars

Name	R.A. (J2000.0)	Decl. (J2000.0)	$\langle V \rangle$	$\langle B \rangle - \langle V \rangle$
SXP1.......	13 13 03.38	18 09 25.3	18.814	0.284
SXP2.......	13 12 49.71	18 07 26.0	18.915	0.310
SXP3.......	13 13 01.95	18 10 13.4	19.248	0.261
SXP4.......	13 13 19.09	18 06 40.7	19.171	0.337
SXP5.......	13 13 08.21	18 07 38.7	19.441	0.252
SXP6.......	13 13 09.44	18 09 40.1	19.366	0.301
SXP7.......	13 13 05.01	18 08 36.1	19.522	0.223
SXP8.......	13 12 52.77	18 04 58.4	18.959	0.264

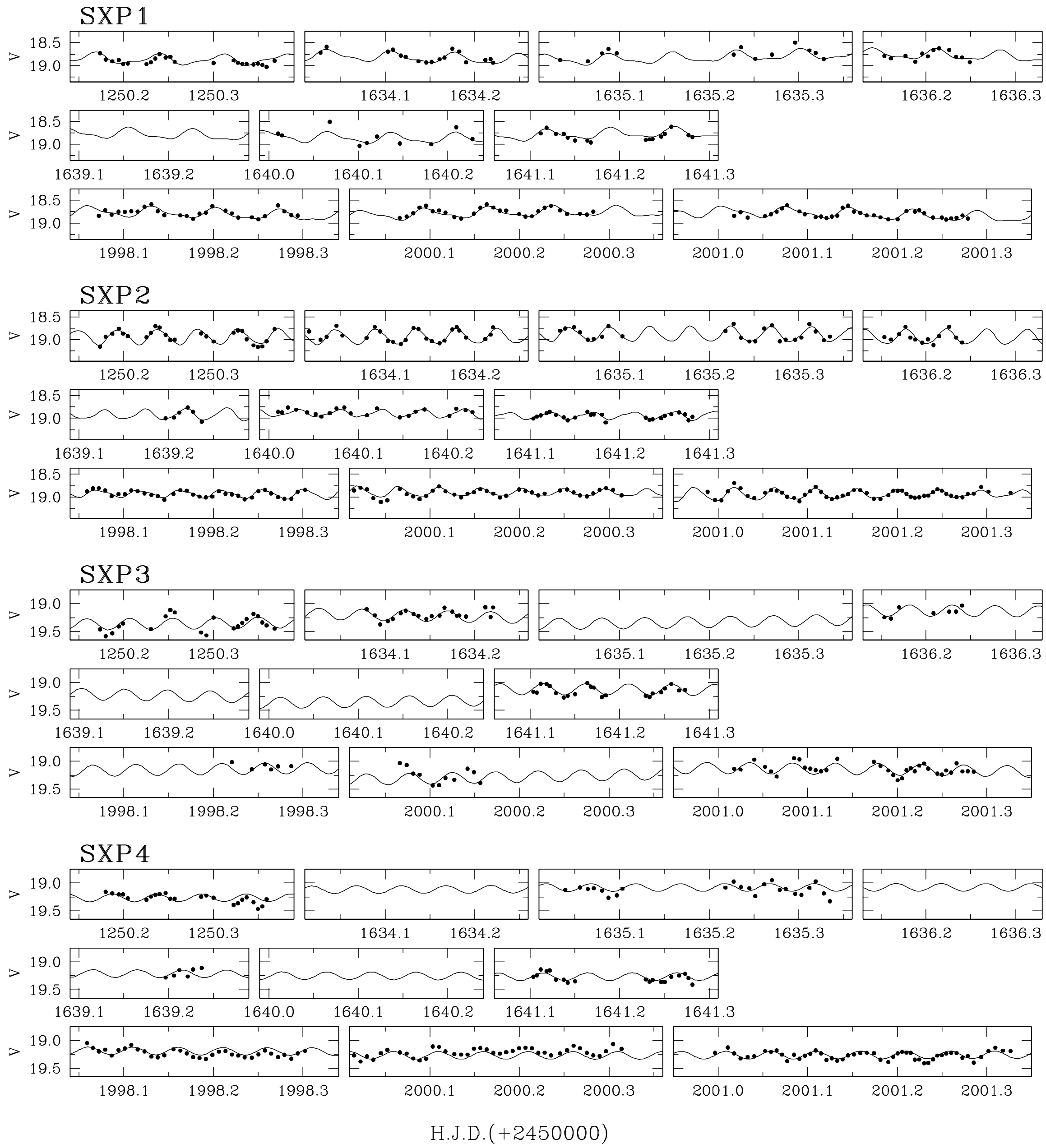

FIG. 3.—Observed light curves (*dots*) for eight new SX Phoenicis stars. Synthetic light curves (*solid lines*) obtained from the multiple-frequency analysis (see Table 3) are superposed on the data.

22.6000, and 24.1024 cycles day^{-1} and $\Delta V = 0.204$, 0.138, 0.082, 0.200, and 0.194 mag, respectively. In Figure 4 SXP4 and SXP5 show some hints of the existence of harmonic frequencies above 40 cycles day^{-1}, but they are not conclusive.

SXP8: SXP8 has the shortest primary period, of 0.0385 days, and the smallest semiamplitude, 0.030 mag, among the eight SX Phoenicis stars of M53. SXP8 shows a typical feature of low-amplitude δ Scuti stars, i.e., a complicated oscillation pattern and several frequencies compared with the one or two stable frequencies of high-amplitude δ Scuti stars. We could detect three frequencies with amplitude S/Ns over 4.0, although the data are not excellent. The primary, secondary, and third frequencies are $f_1 = 25.9800$, $f_2 = 38.1942$, and $f_3 = 8.2322$ cycles day^{-1}, respectively.

4. DISCUSSION

4.1. *Characteristics of the New SX Phoenicis Stars*

In Figure 5 we show the position of the eight new SX Phoenicis stars in the color-magnitude diagram of M53. All the SX Phoenicis stars discovered in M53 are found to be located in the blue straggler region, brighter and bluer than the main-sequence turnoff point. It is interesting that all of them are located in the red side in the BSS region of M53. This indicates that the pulsational instability strip may cover only a part of the BSS region (a hotter region in this case) and that only those in this region (or some of them) can start pulsation. It is not yet known why some BSSs pulsate and some do not in the same pulsational instability region. It needs further study using several globular clusters with SX Phoenicis stars.

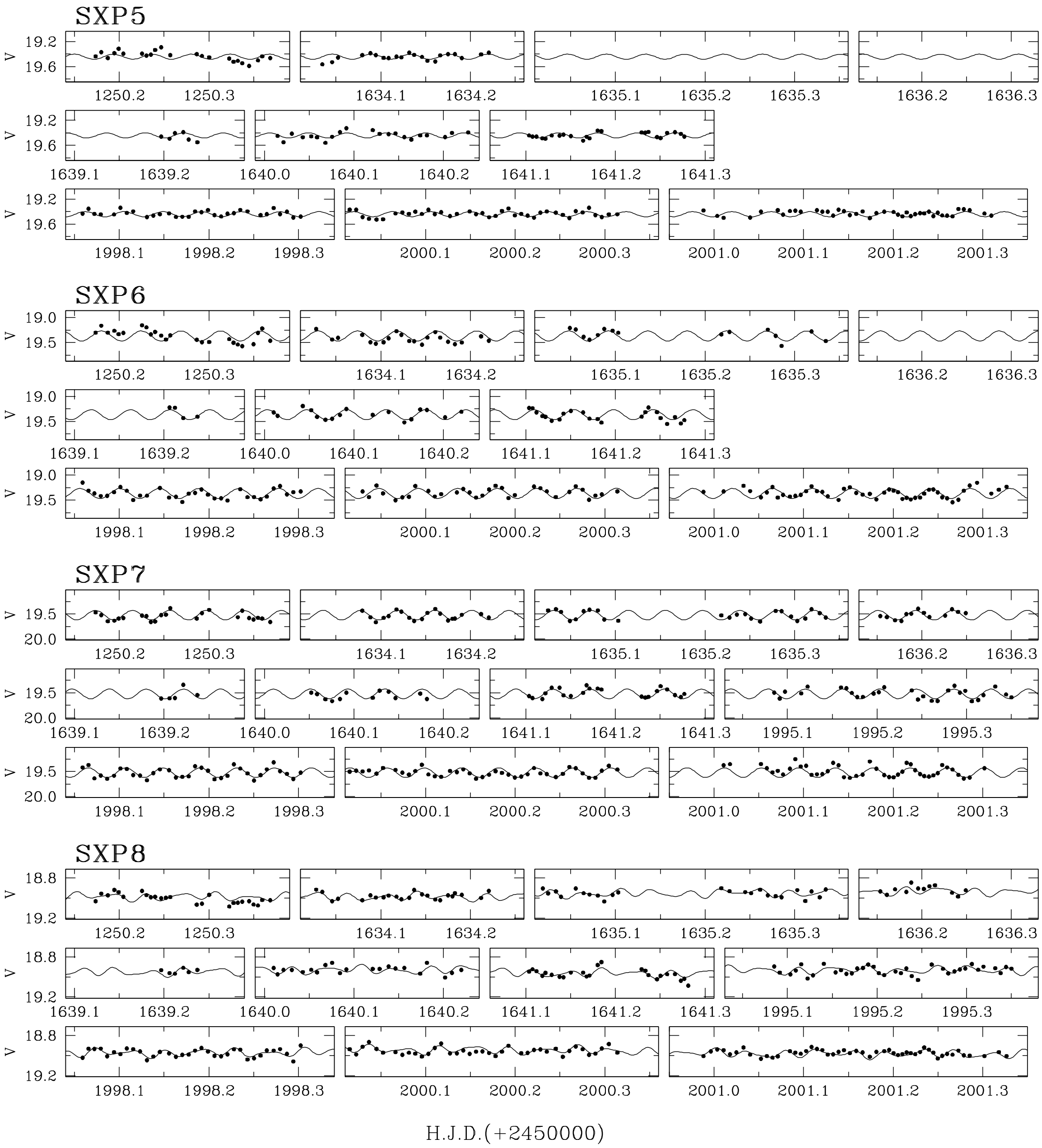

FIG. 3.—*Continued*

In Figure 6 we have compared the *V* amplitudes and periods of the SX Phoenicis stars in M53 with those of SX Phoenicis stars and δ Scuti stars in other globular clusters and field SX Phoenicis stars. The sources of the data in Figure 6 are Rodríguez et al. (2000) for field SX Phoenicis stars and δ Scuti stars, and Rodríguez & Lopéz-González (2000) for SX Phoenicis stars in Galactic globular clusters. Figure 6 shows that the *V* amplitudes and periods of the eight SX Phoenicis stars (*star symbols*) are consistent with those for other SX Phoenicis stars in globular clusters. The *V* amplitudes of the SX Phoenicis stars are much larger than those of δ Scuti stars with the same period, and the periods of the SX Phoenicis stars are at the shortest end.

4.2. *Mode Identification and Period-Luminosity Relation*

The *P-L* relation of SX Phoenicis stars in the globular clusters can be very useful for estimating the distances to the clusters and nearby galaxies. However, it is not easy to derive the *P-L* relation from the observations, because a mixture of different pulsation modes is often seen in SX Phoenicis stars. The different pulsation modes of the SX Phoenicis stars follow different *P-L* relation (offsets in the zero points).

It is well known that observational identification of the pulsation modes of the SX Phoenicis star is difficult in general. McNamara (1997, 2000, 2001) suggested that the light amplitude and the degree of asymmetry of the light curves might be useful parameters in deciding the pulsation modes of the high-amplitude stars. McNamara (2000) showed that most of the known SX Phoenicis stars at the fundamental mode show large amplitude (for example, larger than 0.15 mag in the case of SX Phoenicis stars in ω Centauri) and asymmetric light curve. However, not all of the SX Phoenicis stars with large amplitudes are at the fundamental mode,

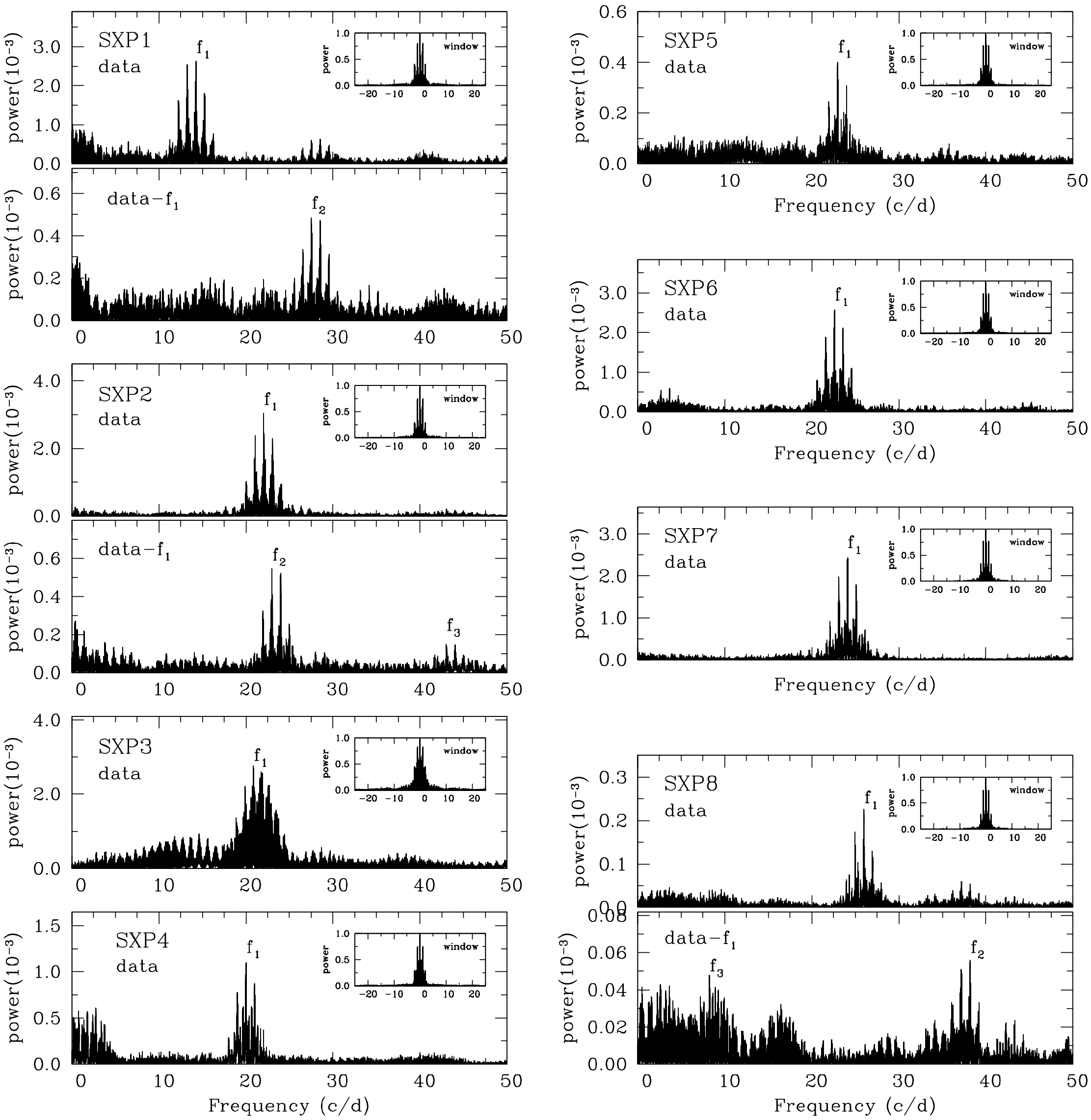

FIG. 4.—Power spectra of eight new SX Phoenicis stars. Window spectra are shown in the insets in each panel.

TABLE 3
PULSATION PROPERTIES OF THE EIGHT SX PHOENICIS STARS

Name	Value	Frequency[a,b]	Amp.[b] (mag)	Phase[b]	S/N[c]	Mode	Remarks
SXP1...............	f_1	14.2600	0.103	0.6873	9.0	F	
	f_2	27.5256	0.043	−1.1868	5.1	$2f_1$	$f_2 - 2f_1 = -0.9944$
SXP2...............	f_1	22.0450	0.118	−0.0736	14.4	1H	Highest amp.
	f_2	22.9750	0.047	1.5520	7.2	Nonradial	$f_1/f_2 = 0.9595$
	f_3	43.0190	0.021	−1.3179	3.8	$2f_1$	$f_3 - 2f_1 = -1.0630$
SXP3...............	f_1	20.8796	0.102	4.2981	7.0	F	
SXP4...............	f_1	20.0114	0.069	3.1873	7.9	F	
SXP5...............	f_1	22.9880	0.041	0.3222	6.0	F	
SXP6...............	f_1	22.6000	0.100	2.6747	12.1	F	
SXP7...............	f_1	24.1024	0.097	2.0239	14.4	F	
SXP8...............	f_1	25.9800	0.030	3.1414	8.2	2H	
	f_2	38.1912	0.015	−1.5238	4.4	Nonradial?	
	f_3	8.2322	0.014	−0.7535	4.3	Nonradial?	

[a] In cycles per day.
[b] $V = \text{Const} + \Sigma_j A_j \cos\{2\pi f_j(t - t_0) + \phi_j\}$, t_0 = HJD 2,450,000.00.
[c] Amplitude S/N introduced by Breger et al. 1993.

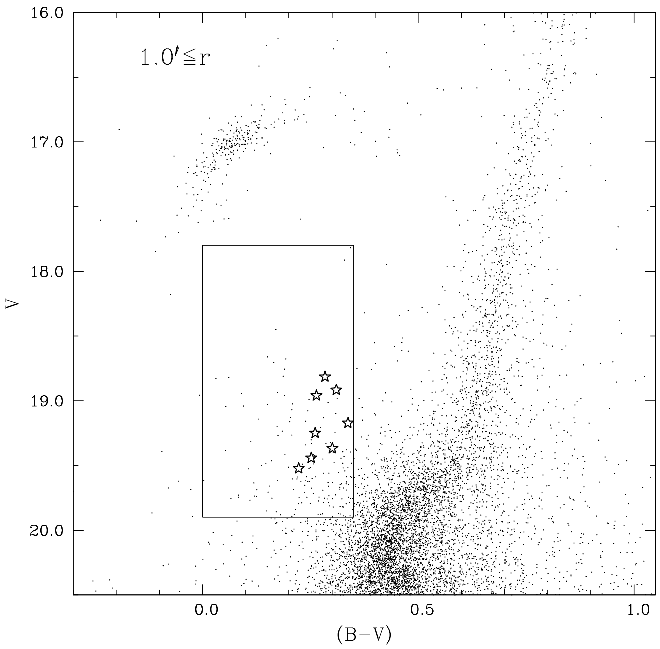

FIG. 5.—Positions of eight new SX Phoenicis stars in the color-magnitude diagram of M53. Note that all they are located in the blue straggler region.

as shown by McNamara (2000). On the other hand, as Pych et al. (2001) pointed out, "Amplitudes generally yield no definitive clues for the identification of modes, except that large amplitudes are more likely to occur in radial pulsations." Another possible way of identifying the pulsation modes is to use the period-luminosity relations and the period ratios of the SX Phoenicis stars in globular clusters being applied in this study.

In Figure 7 we display the period and mean V magnitude relation for the SX Phoenicis stars in M53 in comparison

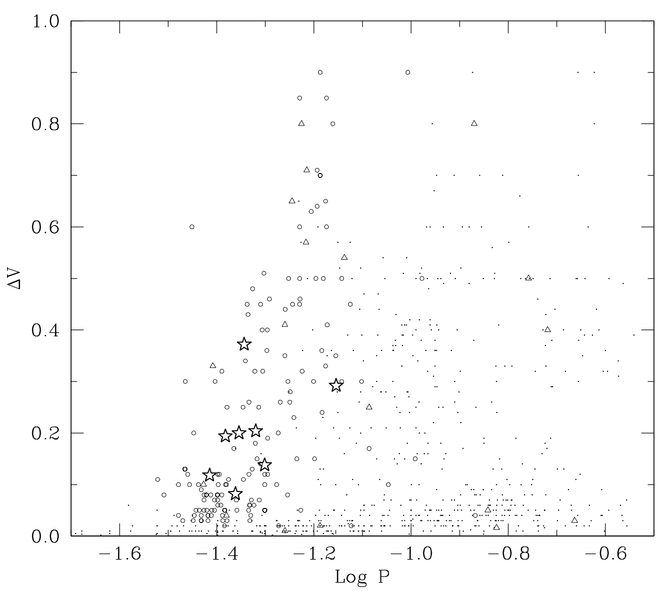

FIG. 6.—V amplitude vs. period diagram. Star symbols denote eight new SX Phoenicis stars in M53, triangles represent field SX Phoenicis stars, open circles indicate SX Phoenicis stars in other globular clusters, and dots denote δ Scuti stars.

with other globular clusters and theoretical models. Several interesting features are seen in Figure 7. Figure 7*a* illustrates that six SX Phoenicis stars in M53 show a very good correlation between the period and mean V magnitude, while the other two stars (SXP2 and SXP8) are in the higher mode than the others. SXP1, the brightest in the sample, has a period much longer than the rest of the SX Phoenicis stars. This star is considered to be a member of M53 for three reasons. First, it is seen inside the blue straggler region in the color-magnitude diagram. Second, it is located closer to the center of M53 in the sky than SXP4, which is clearly a member of M53. And, third, it has a period and V magnitude consistent with those of other SX Phoenicis stars in M53. We derive a period-luminosity relation using these six stars with $-1.36 < \log P(\mathrm{days}) < -1.15$:

$$\langle V \rangle = -3.010(\pm 0.262) \log P + 15.310(\pm 0.048) , \quad (2)$$

with an rms scatter of 0.038. This result corresponds to $\langle M_V \rangle = -3.010 \log P - 1.070$ for an adopted distance modulus of $(m - M)_V = 16.38$ (Harris 1996).

In Figure 7*a* we compare the SX Phoenicis stars in M53 and NGC 5466. The results for NGC 5466 were also obtained using the same procedures as for M53 from the similar data so that they can be compared directly with those of M53 (Jeon et al. 2003). We adopted a distance modulus of $(m - V)_0 = 16.15$ and zero foreground reddening for NGC 5466 (Harris 1996). It is shown clearly that the *P-L* relation of the SX Phoenicis stars in NGC 5466 agrees very well with that of M53. The *P-L* relation for NGC5466 has a slope very similar to that for M53 and a zero point slightly brighter than that for M53. Most of the SX Phoenicis stars in NGC 5466 are considered to be in the fundamental pulsation mode (see Jeon et al. 2003 for details). Therefore, it is concluded that all SX Phoenicis stars (except for SXP2 and SXP8) in M53 are probably in the fundamental pulsation mode. Then SXP2 and SXP8 are probably in the first- and second-overtone mode, respectively. Interestingly, the amplitudes of SX Phoenicis stars in NGC 5466 are much larger than those of M53 stars. This will be discussed in detail in Jeon et al. (2003).

In Figure 7*b* we compare the SX Phoenicis stars in M53 and M55, where as many as 24 SX Phoenicis stars were discovered recently by Pych et al. (2001). We adopted a distance modulus of $(m - V)_V = 13.86$ (Pych et al. 2001) and foreground reddening of $E(B-V) = 0.07$ for M55 (Harris 1996). Note that Pych et al. (2001), using the *Hipparcos* data for SX Phoenicis star itself, derived a distance modulus, $(m - V)_V = 13.86 \pm 0.25$, which is very similar to the value given by Harris (1996), $(m - V)_V = 13.87$. Pych et al. (2001) used SX Phoenicis stars in M55 to estimate the slope of the *P-L* relation and used *Hipparcos* data for SX Phoenicis star itself to calibrate the zero point, deriving a *P-L* relation for the fundamental mode: $\langle M_V \rangle = -2.88 \log P - 0.77$. Figure 7*b* shows that the *P-L* relation for M53 agrees approximately with that for the fundamental mode of SX Phoenicis stars in M55 and that the scatter of the *P-L* relation for M53 is much smaller than that for M55.

In Figure 7*c* we compare the SX Phoenicis stars in M53 and ω Centauri, where as many as 34 SX Phoenicis stars, were discovered by Kaluzny et al. (1996, 1997). Using the data for ω Centauri, McNamara (2000) derived steep *P-L* relations for the fundamental mode and first-overtone

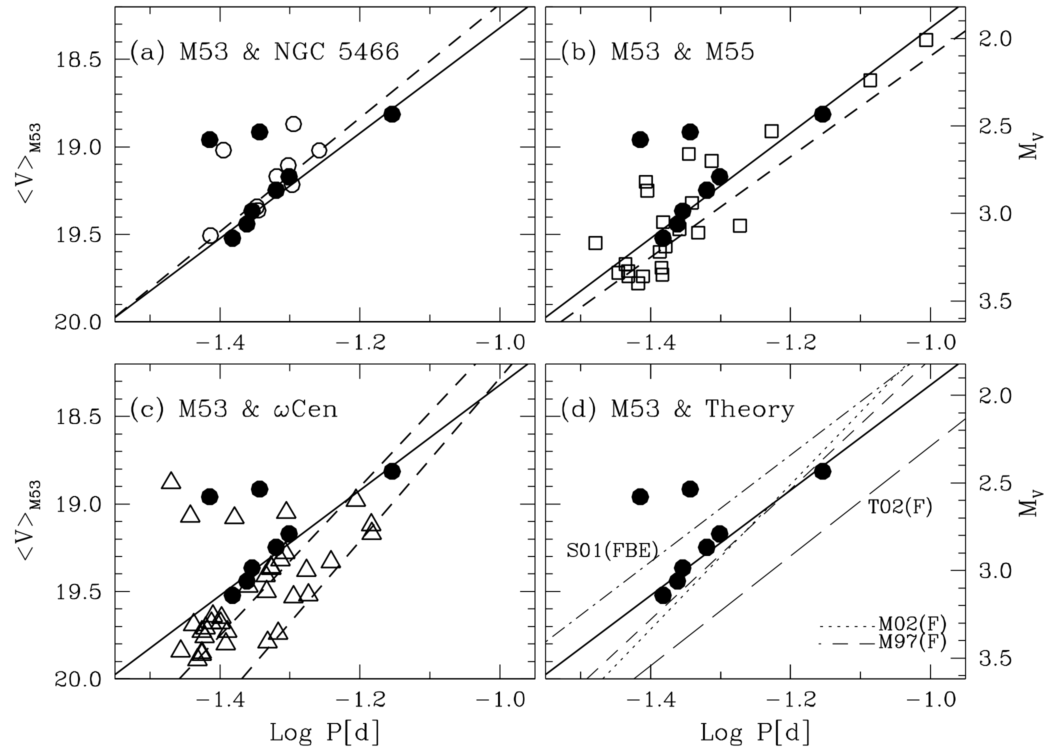

FIG. 7.—Mean magnitude $\langle V \rangle$ vs. period diagram. Filled circles represent the SX Phoenicis stars in M53. The solid line represent a linear fit to the data for the fundamental mode of M53. (*a*) Comparison with the SX Phoenicis stars in NGC 5466 (*open circles*). The dashed line represents a linear fit to the data of the fundamental mode of NGC 5466 (Jeon et al. 2003). (*b*) Comparison with the SX Phoenicis stars in M55 (*open squares*). The dashed line represents a linear fit to the data for the fundamental mode of M55 (Pych et al 2001). (*c*) Comparison with the SX Phoenicis stars in ω Centauri (*open triangles*). The two dashed lines represent linear fits to the data for the A sequence (*left*) and the B sequence (*right*) of ω Centauri. (*d*) Comparison with empirical *P-L* relations (*short dashed lines*) given by McNamara (1997, 2002) and with theoretical *P-L* relations. The long dashed line represents a theoretical relation for the fundamental mode given by Templeton et al. (2002). The dot-dashed lines, respectively, represent the blue edge of the fundamental mode, the first-overtone mode, and the second-overtone mode (*bottom to top*) given by Santolamazza et al. (2001).

mode, $\langle V \rangle = -4.66 \log P + 11.21$ and $\langle V \rangle = -4.26 \log P + 11.38$, respectively. We adopted a distance modulus of $(m - V)_V = 14.05 \pm 0.11$ and foreground reddening of $E(B-V) = 0.13$ for ω Centauri, given recently by Thompson et al. (2001), who used a detached eclipsing binary in ω Centauri. These values are very similar to those in Harris (1996), $(m - V)_V = 13.97$ and $E(B-V) = 0.12$.

Figure 7*c* shows that the *P-L* relation for M53 agrees approximately with that for the SX Phoenicis stars in ω Centauri, which were considered to be in the first-overtone mode by McNamara (2000) (hereafter "A-sequence"). Note that the steep slope for the first-overtone mode in ω Centauri is based on the data for the period range of $\log P < -1.3$, where five stars at the fundamental mode in M53 show a similar behavior. The SX Phoenicis stars in the fundamental mode in ω Centauri (hereafter "B-sequence") are ~0.4–0.5 mag fainter than those in M53.

This result is very intriguing, and the reasons for this discrepancy are not clear. ω Centauri has been known to be a very unique globular cluster among the Galactic globular clusters in several aspects: it is the most massive globular cluster in the Milky Way; it has multiple stellar populations with a wide spread in metallicity, from $[Fe/H] = -2.0$ to -0.6 dex (the metallicity of the main population is $[Fe/H] \sim -1.6$ dex), and it has a very elongated structure. These features lead to a suggestion that it may be a remnant core of dwarf spheroidal galaxy that formed via the merging of several components (Gnedin et al. 2002; Ferraro et al. 2002 and references therein). This peculiarity of ω Centauri may be related to the fact that it is the only cluster where more first-overtone mode SX Phoenicis stars were found than fundamental-mode stars (or a comparable number). Note that many fewer first-overtone mode stars were found than fundamental-mode stars in globular clusters.

We checked several possibilities for understanding this puzzling result: (1) If the A-sequence and the B-sequence are, respectively, indeed in the first-overtone and fundamental mode, as considered by McNamara (2000) (and if the *P-L* relation of SX Phoenicis stars is universal), then the distance modulus of either ω Centauri or M53 must be wrong by as much as ~0.4–0.5 mag. This is very unlikely, considering the good agreement among the different estimates of the distance to these objects; (2) the A-sequence may be the fundamental rather than first-overtone mode. Then it is not possible to explain the existence of the B-sequence without assuming that the B-sequence is another fundamental mode behind the A-sequence. This is also unlikely for the same reason as (1). (3) The A-sequence and the B-sequence may not be two independent modes. Instead, both may belong to the same fundamental mode with a large dispersion. This is contrary to the result given by McNamara (2000). However, it happens to be consistent with the theoretical *P-L* relation for the fundamental mode given by Templeton, Basu, & Demarque (2002), as shown in Figure 7*d*. Therefore, this problem remains to be explained by further studies.

In Figure 7*d* we compare the *P-L* relation for M53 with empirical relations given by McNamara (1997, 2002) and with theoretical relations given by Santolamazza et al.

(2001) and Templeton et al. (2002). The slope of the *P-L* relation for the fundamental mode of M53 is very similar to those in theoretical ones (−3.05, Santolamazza et al. 2001; and −3.14, Templeton et al. 2002). The six SX Phoenicis stars in M53 are located at the right side of the blue edge of the fundamental-mode relation given by Santolamazza et al. (2001), consistent with the conclusion that these stars are indeed the fundamental modes. On the other hand, the zero point of the M53 relation is about 0.4 mag brighter than that of the theoretical relation given by Templeton et al. (2002). The reason for this discrepancy is not known at this moment. The empirical *P-L* relations given by McNamara (1997, 2002) ($\langle M_V \rangle = -3.725 \log P - 1.933 \langle M_V \rangle = -4.14 \log P - 2.46$) are steeper than those for M53 and the theoretical relations given by Santolamazza et al. (2001) and Templeton et al. (2002).

5. SUMMARY

We present time-series *BV* CCD photometry of the metal-poor globular cluster M53. We have discovered eight new SX Phoenicis–type stars (labeled "SXP1" to "SXP8"). Physical parameters of these stars are summarized in Tables 2 and 3. All the new SX Phoenicis stars are located in the blue straggler star region of the color-magnitude diagram of M53. One of these stars (SXP2) is found to have very closely separated pulsation frequencies: $f_1/f_2 = 0.9595$, where f_1 and f_2 are the primary and secondary frequencies. This may be due to the excitation of nonradial modes.

Considering the position in the period-*V* magnitude diagram, six of these SX Phoenicis stars are identified to be pulsating in the fundamental mode, and SXP2 and SXP3 are probably in the first- and second-overtone modes. We derive a period-luminosity relation for the fundamental mode for the period range of $-1.36 < \log P(\text{days}) < -1.15$: $\langle V \rangle = -3.010(\pm 0.262) \log P + 15.310(\pm 0.048)$, with an rms scatter of 0.038, corresponding to $\langle M_V \rangle = -3.010 \log P - 1.070$, for an adopted distance modulus of $(m - M)_V = 16.38$ (Harris 1996).

The authors are very grateful to Dr. D. H. McNamara, the referee, who provided very useful comments helping to improve this paper. M. G. L. thanks the director and staff of the Department of Terrestrial Magnetism, the Carnegie Institution of Washington, for their kind hospitality. M. G. L. was supported in part by the Korean Research Foundation Grant (KRF-2000-DP0450).

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