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A NEW SX PHOENICIS STAR IN THE GLOBULAR CLUSTER M15

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ABSTRACT

A new SX Phoenicis star (labeled SXP 1) found from BV CCD photometry is the first to be discovered in the globular cluster M15. It is a blue straggler and is located 102″.8 north and 285″.6 west of the center of M15. The mean magnitudes of SXP 1 are $\langle B \rangle = 18.671$ and $\langle V \rangle = 18.445$. The amplitude of variability of SXP 1 is measured to be $\Delta V \approx 0.15$. From multiple-frequency analysis based on the Fourier decomposition method, we detect two very closely separated pulsation frequencies: the primary frequency at $f_1 = 24.630$ cycles day^{-1} for both B and V bands, and the secondary frequency at $f_2 = 24.338$ cycles day^{-1} for the B band and 24.343 cycles day^{-1} for the V band. This star is the second among known SX Phoenicis stars found to pulsate with very closely separated frequencies ($f_2/f_1 \geq 0.95$). These frequencies may be explained by excitation of nonradial modes; however, we have an incomplete understanding of this phenomenon in the case of SX Phoenicis stars with relatively high amplitudes. The relations between metallicity and period and between the variability amplitude and period for SXP 1 are found to be consistent with those for SX Phoenicis stars in other globular clusters.

Key words: blue stragglers — globular clusters: individual (M15 = NGC 7078) — stars: oscillations — stars: variables: general

1. INTRODUCTION

SX Phoenicis stars are short-period (<0.1 day) pulsating variable stars. They have low metallicities and high spatial motions typical of Population II (Rodríguez & Lopéz-González 2000). They are located in the blue straggler region in the H-R diagram and within the lowest section of the classical Cepheid instability strip. The characteristics of these stars are not yet fully explained by current stellar theories.

Only a few field SX Phoenicis stars are known at present; most of the known SX Phoenicis stars were discovered in Galactic globular clusters and in two dwarf spheroidal galaxies, Carina and Sagittarius. Recently, Rodríguez & Lopéz-González (2000) published a catalog of SX Phoenicis stars in Galactic globular clusters including those in the two dwarf spheroidal galaxies. They listed a total of 122 SX Phoenicis stars belonging to 18 globular clusters and 27 belonging to the two galaxies, covering information published through 2000 January. Since the initial discovery of SX Phoenicis stars in the globular cluster ω Cen (Niss 1981), the identification rate of these stars in globular clusters has increased rapidly over the last decade (see Fig. 1 in Rodríguez & Lopéz-González 2000).

In this paper, we report the first discovery of an SX Phoenicis star (hereafter SXP 1) in the globular cluster M15 (R.A. = $21^h29^m58^s.3$, decl. = $+12°10'01''$, J2000.0; Harris 1996).[2] M15 has an extremely low metallicity, [Fe/H] $= -2.25$, an interstellar reddening of $E(B-V) = 0.10$, and a distance modulus $(m - M)_V = 15.37$ (Harris 1996). There are 126 known variable stars in M15, but no SX Phoenicis star had yet been discovered in this cluster (Clement 2000).[3] Preliminary results from this study were presented in Jeon et al. (2000).

2. OBSERVATIONS AND DATA REDUCTION

2.1. *Observations*

We obtained $UBVI$ CCD images of M15 on the photometric night of 1998 September 13, and a series of BV CCD images of M15 on four nights from 1999 August 12 to 16 and over two nights from 2000 September 25 to 26. A total of 194 (over $\sim$29.7 hr) and 232 (over $\sim$32.1 hr) frames were obtained for the B and V bands, respectively. The observation log is given in Table 1.

The CCD images were obtained with a thinned SITe 2K CCD camera (2048 × 2048 pixels) attached to the 1.8 m telescope at the Bohyunsan Optical Astronomy Observatory. The size of the field of view of a CCD image is 11′.6 × 11′.6 at the f/8 Cassegrain focus of the telescope. The readout noise and gain of the CCD are 7.0 e^- and 1.8 e^- ADU^{-1}, respectively. We used the 2 × 2 binning mode, resulting in a scale of 0″.6876 pixel^{-1}. A gray-scale map of a V CCD image of M15 is shown in Figure 1.

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

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[2] See http://www.astro.utoronto.ca/~cclement/read.html.
[3] See http://physun.physics.mcmaster.ca/Globular.html.

TABLE 1

OBSERVATION LOG

Date	Start HJD (2,451,000+)	Duration (hr)	N_{obs}	Seeing (arcsec)	Exposure Time (s)	Comment
1999 Aug 12......	403.03	6.0	46 (*V*), 43 (*B*)	2.4	100 (*V*), 200 (*B*)	Nonphotometric
1999 Aug 13......	404.00	7.9	56 (*V*), 53 (*B*)	2.2	100 (*V*), 200 (*B*)	Nonphotometric
1999 Aug 14......	404.99	5.5	47 (*V*), 43 (*B*)	2.0	100 (*V*), 200 (*B*)	Nonphotometric
1999 Aug 16......	407.04	4.1	36 (*V*), 36 (*B*)	2.2	100 (*V*), 200 (*B*)	Nonphotometric
2000 Sep 24	811.95	2.4	21 (*V*)	2.8	200 (*V*)	Cirrus
2000 Sep 26	813.93	6.2	26 (*V*), 19 (*B*)	2.2	200 (*V*), 360 (*B*)	Nonphotometric

point-spread function (PSF) fitting photometry routine in the IRAF DAOPHOT package (Massey & Davis 1992).

The instrumental magnitudes of the stars in M15 observed on 1998 September 13 were transformed to the standard system using photometry of Landolt standard stars obtained on the same night as M15 (Landolt 1992). Then the time-series *BV* data were calibrated using these data. Detailed analysis and results of the *UBVI* photometry of M15 will be presented elsewhere (Jeon, Lee, & Lee 2001b).

We applied the ensemble normalization technique (Gilliland & Brown 1988; Kim, Park, & Chun 1999) to normalize instrumental magnitudes between time-series CCD frames. We used about a hundred normalizing stars ranging from 14.0 to 17.5 mag for the *V* band and from 13.5 to 17.3 mag for the *B* band, except for variable stars and central stars within $r < 1'.5$. The normalization equation is

$$B \text{ or } V = m + c_1 + c_2(B - V) + c_3 P_x + c_4 P_y \,, \quad (1)$$

where *B*, *V*, and *m* are the standard and instrumental magnitudes of the normalizing stars, respectively, c_1 is the zero point, and c_2 is the color coefficient; 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 21,000 stars to search for variable stars. We confirmed 86 previously known RR Lyrae stars and one Cepheid variable, and we

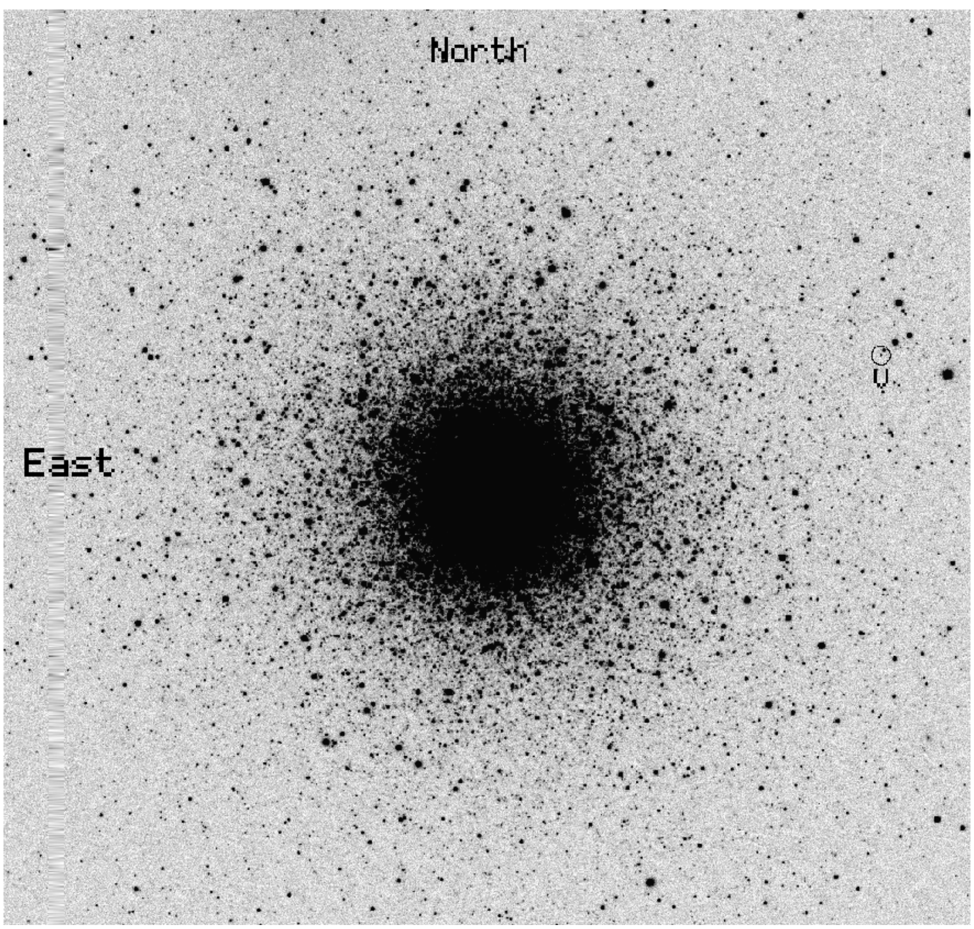

FIG. 1.—Gray-scale map of a *V*-band CCD image of the globular cluster M15. A new SX Phoenicis star (SXP 1, *circled*) is indicated by a "V." SXP 1 is located 102''.8 north and 285''.6 west of the center of M15.

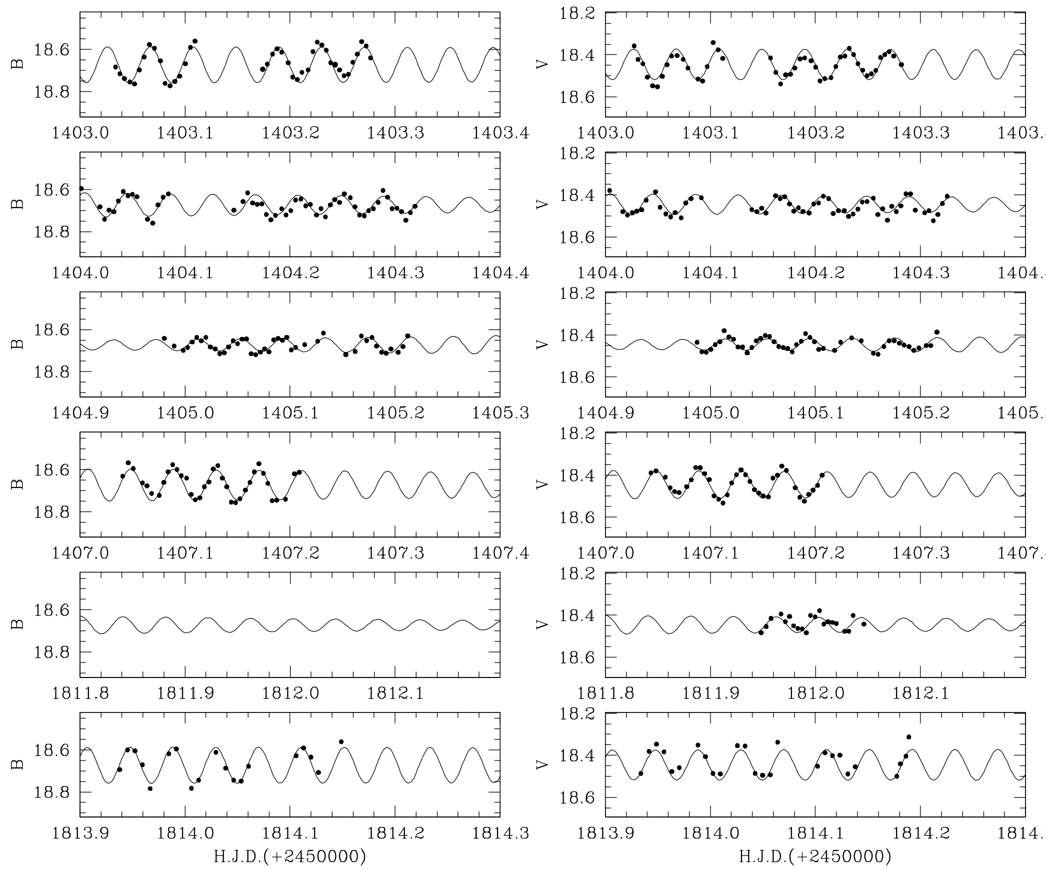

FIG. 2.—Observed light curves (*circles*) for SXP 1 for the *B* band (*left*) and *V* band (*right*). Synthetic light curves (*solid lines*) obtained from the multiple-frequency analysis (see Table 2) are superposed.

discovered 16 new variable stars in the cluster: two faint eclipsing binaries, two long-period variable stars, three RR Lyrae stars, eight variable candidates, and one SX Phoenicis star (SXP 1). Here we report only the results for the SX Phoenicis star; detailed results on the other variable stars will be published elsewhere (Jeon et al. 2001a).

There had hitherto been no known eclipsing binaries or SX Phoenicis stars in M15 (Rodríguez & Lopéz-González 2000; Clement 2000), making SXP 1 the first SX Phoenicis star discovered in the cluster. SXP 1 is located 102''.8 north and 285''.6 west of the center of M15, as marked by the "V" in Figure 1. The coordinates of SXP 1 are R.A. $= 21^h29^m39^s.4$, decl. $= +12°11'43''.4$ (J2000.0).

BV light curves of SXP 1 that we obtained are displayed in Figure 2 (*circles*). The curves are sinusoidal with short periods and low amplitudes, showing that SXP 1 is a pulsating variable star. The maximum amplitudes of SXP 1 in the *B* and *V* bands are estimated to be 0.17 and 0.15 mag, respectively. It should be noted that there are amplitude-modulating features in the light curves of SXP 1, implying the excitation of closely separated pulsation frequencies.

We have performed a multiple-frequency analysis to find the pulsation frequencies of SXP 1 using the discrete Fourier transform method and linear least-squares fitting (Kim & Lee 1996). Figure 3 displays the power spectra of SXP 1 for the *B* and *V* bands. The top panels in Figure 3 show the spectral window, and the other panels represent the prewhitening processes. A primary frequency at $f_1 =$ 24.630 cycles day^{-1} for both bands is evident. After the primary frequency f_1 is prewhitened (Fig. 3, *third from top*), the secondary frequency is detected at $f_2 = 24.338$ cycles day^{-1} for the *B* band and at 24.343 cycles day^{-1} for the *V*

TABLE 2

RESULTS OF THE MULTIPLE-FREQUENCY ANALYSIS

	B BAND				*V* BAND			
VALUE	Frequency[a]	Amp.[b]	Phase[b]	S/N[c]	Frequency[a]	Amp.[b]	Phase[b]	S/N[c]
f_1	24.630	0.054	−0.240	9.2	24.630	0.048	−0.324	10.4
f_2	24.338	0.032	4.117	7.2	24.343	0.025	3.919	6.9
s.d.[d]		0.022				0.022		

[a] In cycles per day.
[b] *B* or $V = \text{const} + \sum_j A_j \cos[2\pi f_j(t - t_0) + \phi_j]$, t_0 = HJD 2,451,400.00.
[c] Amplitude signal-to-noise ratio, introduced by Breger et al. 1993.
[d] Standard deviation after fitting synthetic curves to the data.

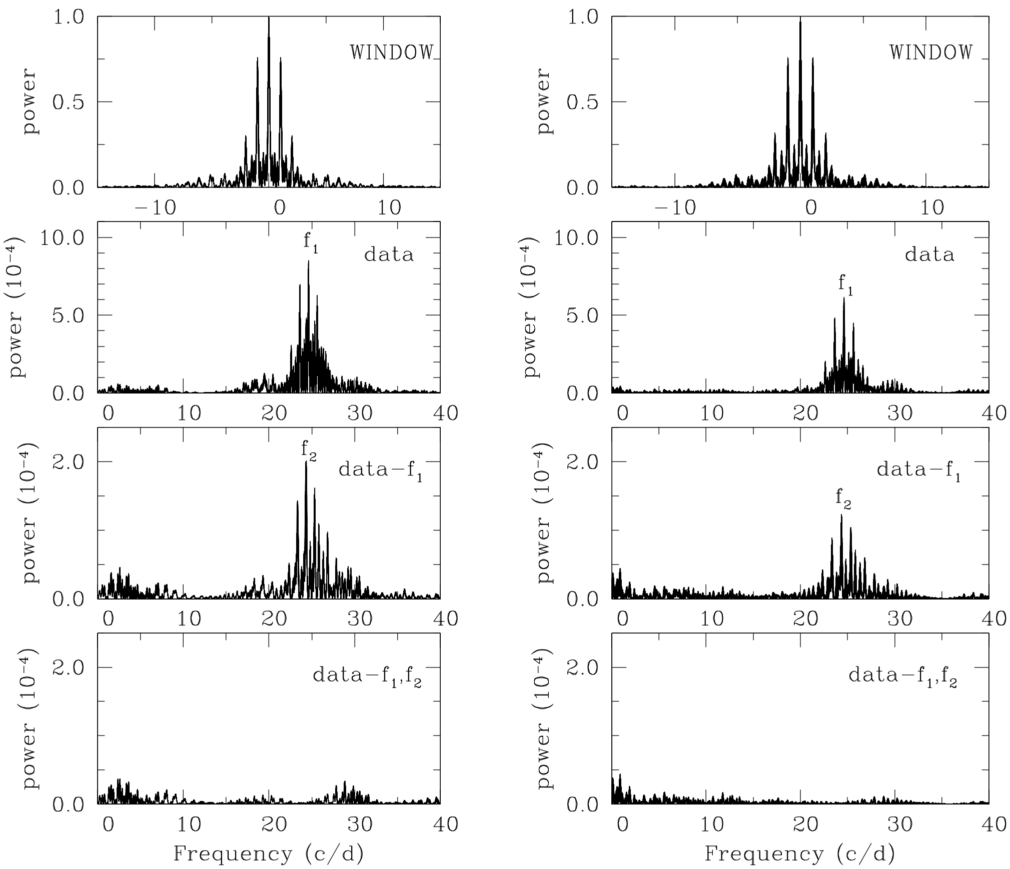

FIG. 3.—Power spectra of SXP 1 for the *B* band (*left*) and *V* band (*right*). Window spectra are in the top panels. Two closely separated frequencies, f_1 and f_2, are clearly found.

band. Since the amplitude signal-to-noise ratios are larger than 4, the secondary frequencies can be accepted as intrinsic frequencies (Breger et al. 1993). After removing synthetic curves with the two frequencies from the data, the residual light curves indicate that there are no more frequencies detectable in the data (see Fig. 3, *bottom*). The results of the multiple-frequency analysis for SXP 1 are summarized in Table 2. Synthetic light curves obtained from this analysis are superposed on the data in Figure 2 and show good agreement.

4. DISCUSSION

4.1. *SXP 1: An SX Phoenicis Star or a δ Scuti Star?*

In Figure 4, we show the position of SXP 1 in the color-magnitude diagram (CMD) of M15. SXP 1 is found to be located in the blue straggler region along an extension of the main sequence, in a region brighter and bluer than the main-sequence turnoff point. The mean magnitudes of SXP 1 are $\langle B \rangle = 18.671$ and $\langle V \rangle = 18.445$. Based on the position of SXP 1 in the CMD, in conjunction with its pulsation period and amplitude, it could be either an SX Phoenicis star in the globular cluster or a field δ Scuti star. In order to define the pulsation type of SXP 1 more clearly, we examine the *V*-amplitude versus period diagram for SX Phoenicis stars and δ Scuti stars in Figure 5. The sources of the data are Rodríguez, Lopéz-González, & López de Coca (2000) for field SX Phoenicis stars and δ Scuti stars, and Rodríguez & Lopéz-González (2000) for SX Phoenicis stars in Galactic globular clusters. Figure 5 shows that the *V* amplitude and period of SXP 1 are consistent with those for other SX Phoenicis stars in globular clusters and that the *V* amplitude of SXP 1 is much larger than those of δ Scuti stars with the same period. This shows that SXP 1 is an SX Phoenicis star, not a δ Scuti star.

4.2. *Membership of SXP 1*

Following the suggestion of McNamara (1997) that SX Phoenicis stars with $\Delta V \leq 0.20$ mag can be classified as first-overtone pulsators, we assume that SXP 1 is a first-overtone pulsator. After fundamentalizing the dominant frequency f_1 by assuming a fundamental–to–first-overtone period ratio $P_1/P_0 = 0.778$, we obtain the absolute magnitude of SXP 1, $M_V = 2.84$, and the distance modulus, $(m - M)_V = 15.61$, using the period-luminosity (P-L) relation given by McNamara (1997; his eq. [4], $M_V = -3.725 \log P_0 - 1.930$).

Recently, McNamara (2001) established equations for the magnitudes of the horizontal branch and the main-sequence turnoff: $M_V(\mathrm{HB}) = 0.30[\mathrm{Fe/H}] + 0.92$ and $M_V(\mathrm{TO}) = 0.34[\mathrm{Fe/H}] + 4.48$. Using these equations, we obtain $M_V(\mathrm{HB}) = 0.24$ and $M_V(\mathrm{TO}) = 3.71$ for $[\mathrm{Fe/H}] = -2.25$, the metallicity of M15. From the CMD of M15 (see Fig. 4), the magnitudes of the horizontal branch and the main-sequence turnoff are respectively $V(\mathrm{HB}) = 15.80$ and $V(\mathrm{TO}) = 19.30$. Therefore, the corresponding absolute

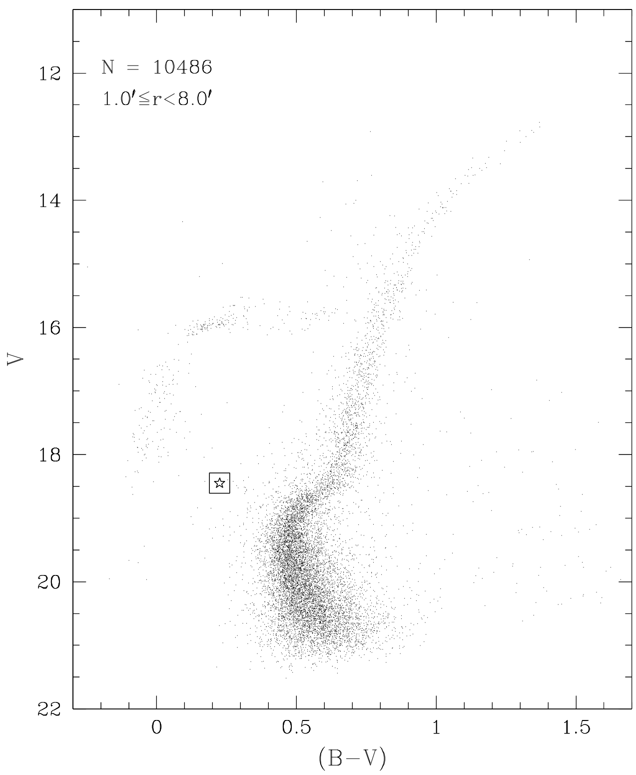

FIG. 4.—Position of SXP 1 in the CMD of M15. Note that it is located in the blue straggler region.

magnitudes of SXP 1 are $M_V = 2.88$ from M_V(HB) and $M_V = 2.85$ from M_V(TO). These are in good agreement with the absolute magnitude of SXP 1, $M_V = 2.84$, derived from the P-L relation.

If we use the period-luminosity-metallicity (P-L-[Fe/H]) relation given by Nemec, Nemec, & Lutz (1994), $M_V = -2.56 \log P_0 + 0.32[\mathrm{Fe/H}] + 0.36$, we obtain a distance modulus of $(m - M)_V = 15.49$, adopting the cluster metallicity $[\mathrm{Fe/H}] = -2.25$ (Harris 1996). These two results are

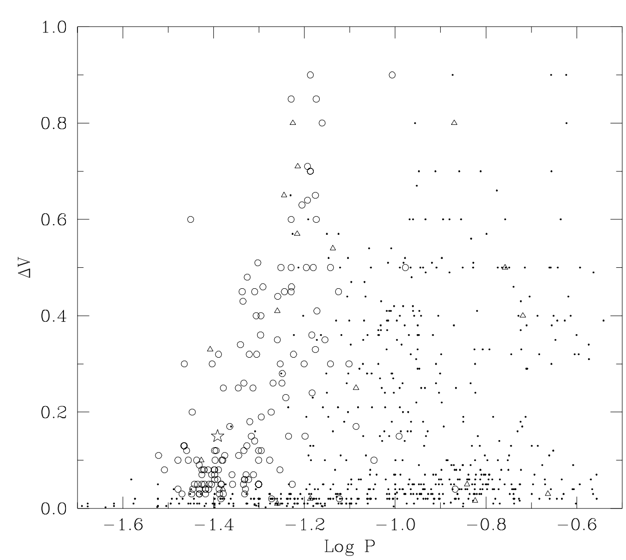

FIG. 5.—V-amplitude vs. period diagram. A five-pointed star denotes SXP 1, in M15, dots denote δ Scuti stars, triangles represent field SX Phoenicis stars, and open circles indicate SX Phoenicis stars in other globular clusters.

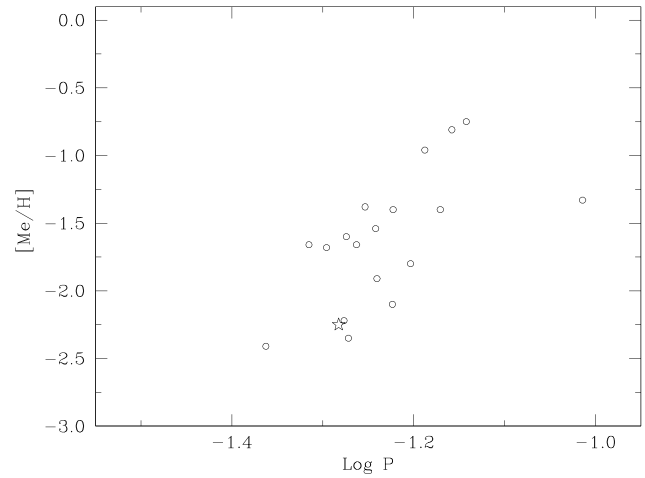

FIG. 6.—[Me/H] vs. fundamentalized period diagram for SX Phoenicis stars in Galactic globular clusters. The star represents SXP 1.

consistent within 2 σ (for the P-L relation) or 1 σ (for P-L-[Fe/H]) error with the distance modulus of M15, $(m - M)_V = 15.37 \pm 0.15$ (Harris 1996). The fundamentalized f_1 period and [Fe/H] relation of SXP 1 is also consistent with the metallicity-period relation of other SX Phoenicis stars in Galactic globular clusters (Rodríguez & Lopéz-González 2000), as shown in Figure 6. All these facts support the contention that SXP 1 is a member of M15, as well as an SX Phoenicis star in the cluster.

4.3. *Two Close Frequencies of SXP 1*

It should be noted that the two detected frequencies of SXP 1 are very closely separated (frequency ratio 0.988). This is often seen in the case of low-amplitude δ Scuti stars, but it is very rare for SX Phoenicis stars. Up to now, only one SX Phoenicis star, BL Cam (Zhou et al. 1999), was known to have very closely separated frequencies (frequency ratio ≥ 0.95). These frequencies can be explained by excitation of a nonradial mode (Zhou et al. 1999). However, the excitation of nonradial modes has not yet been physically understood in the case of SX Phoenicis stars with relatively high amplitudes. Recently, nonradial pulsation components were also detected from a frequency analysis of first-overtone RR Lyrae stars (Alcock et al. 2000). To identify the pulsation mode of SXP 1, we tried to obtain the phase differences between the $B-V$ color index and the V magnitude (Garrido 2000) but failed because our data are not of sufficient quality to determine the variation the of color index. Better data are needed to identify the pulsation mode of SXP 1.

TABLE 3

PHYSICAL PROPERTIES OF SXP 1

Property	Value
R.A. (J2000.0)	$21^h29^m39^s.4$
Decl. (J2000.0)......	$+12°11'43''.4$
$\langle V \rangle$	18.445
$\langle B \rangle - \langle V \rangle$	0.226
Period (days)	0.0406
f_2/f_1	0.988
Oscillations	Nonradial

5. SUMMARY

We have discovered the first SX Phoenicis star (SXP 1) in the globular cluster M15 from *BV* CCD photometry. Table 3 summarizes the physical parameters of SXP 1 derived in this study. Two very closely separated frequencies are detected in the light curves of SXP 1, which could be explained by excitation of a nonradial mode.

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