SX PHOENICIS STARS IN THE GLOBULAR CLUSTER NGC 5466

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ABSTRACT

Through time-series CCD photometry of the globular cluster NGC 5466, we have detected nine SX Phoenicis stars, including three new ones. All the SX Phoenicis stars are located in the blue straggler region in the color-magnitude diagram of NGC 5466. Five of them clearly show double-radial mode features, the periods of which are consistent with the theoretical ratio of the first-overtone mode to the fundamental mode ($P_1/P_f$). Normally, it has not been easy to secure a $P$-$L$ relation for the SX Phoenicis stars because their pulsational mode has been difficult to determine. The existence of five SX Phoenicis stars in NGC 5466 with double-radial modes allows us to reliably derive a $P$-$L$ relation for the fundamental mode of SX Phoenicis stars. Using seven SX Phoenicis stars, including five stars with double-radial modes, we derive a $P$-$L$ relation for the fundamental mode in NGC 5466, $\langle P \rangle = -3.25(\pm0.46)\log P + 14.70(\pm0.06), (\sigma = \pm0.04)$, corresponding to $\langle M_V \rangle = -3.25(\pm0.46)\log P - 1.30(\pm0.06)$ for an adopted distance modulus of $(m-M)_0 = 16.00$ and zero reddening.

Key words: blue stragglers — globular clusters: individual (NGC 5466) — stars: oscillations — stars: variables: other

1. INTRODUCTION

NGC 5466 (R.A. = 14°05′27″3, decl. = +28°32′04″; J2000.0) is a sparse globular cluster with an extremely low metallicity [Fe/H] = −2.22 (Harris 1996),2 having a large number of blue stragglers. Nemec & Harris (1987) found 48 blue straggler stars, which are mostly concentrated within $r = 3′$ from the center of the cluster. Several kinds of variable stars are known to exist in this cluster: six SX Phoenicis stars (Nemec & Mateo 1990; Chen & Corwin 1999), three eclipsing binaries (Mateo et al. 1990; Kallrath et al. 1992; McKinley & Corwin 1998), a Cepheid, and more than 20 RR Lyrae stars (Clement et al. 2001).

In this paper we present a photometric study of SX Phoenicis stars in NGC 5466. In a long-term search for short-period variable stars in Galactic globular clusters, we have found three new SX Phoenicis stars, Cl* NGC 5466 SXP 1, Cl* NGC 5466 SXP 2, and Cl* NGC 5466 SXP 3, in addition to the previously known six, Cl* NGC 5466 NH 27, Cl* NGC 5466 NH 29, Cl* NGC 5466 NH 35, Cl* NGC 5466 NH 38, Cl* NGC 5466 NH 39, and Cl* NGC 5466 NH 49 (Nemec & Mateo 1990), hereafter referred to as SXP 1, SXP 2, and SXP 3, respectively, for the new ones, and NH 27, NH 29, NH 35, NH 38, NH 39, and NH 49, respectively, for the known ones. Results on the eclipsing binaries, a Cepheid and RR Lyrae stars in NGC 5466 will be presented in a separate paper (Lee et al. 2004). We adopt zero interstellar reddening and the distance modulus $(m-M)_0 = 16.00$ in this study (Harris 1996).

This paper is organized as follows. Observations and data reduction are described in § 2. Section 3 describes the selection of variable stars in NGC 5466, and § 4 presents the light curves and frequency analysis of the SX Phoenicis stars. Section 5 discusses the characteristics of these SX Phoenicis stars, including mode identification and the $P$-$L$ relation. Finally, our primary results are summarized in § 6.

2. OBSERVATIONS AND DATA REDUCTION

2.1. Observations

We obtained time series CCD images of NGC 5466 for 22 nights from 1999 February 8 to 2002 March 23. Total observing time is 27.1 and 133.7 hr for the $B$ and $V$ bands, respectively. A total of 48 and 944 frames were obtained for the $B$ and $V$ bands, respectively. Because the observations were performed under various seeing ($0′′9 \sim 4′′5$) and weather conditions, we adjusted exposure times depending on the seeing and transmission of the night sky. The observation log is listed in Table 1.

The CCD images were obtained with a thinned SITe 2K CCD camera attached to the 1.8 m telescope at the Bohyunsan Optical Astronomy Observatory in Korea. 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 central region (7/6 x 5.7) of the cluster, out of the total observing field of 11/6 x 11.6. Nine SX Phoenicis stars are represented by circles labeled with their names.

### 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 flatten images. Instrumental magnitudes were obtained using the point-spread function (PSF) fitting photometry routine in the IRAF/DAOPHOT package (Stetson 1987; Massey & Davis 1992). Nemec & Harris (1987) presented photoelectric photometry of 36 stars in the outer region of NGC 5466, of which we select 10 stars located in our observing fields for the standardization of the instrumental magnitudes. For standardization, we selected nine and five frames for $V$ and $B$ bands, respectively, taken under good seeing conditions on 2002 March 12. The derived transformation equations are

$$
V = v + \text{const} - 0.071(\pm 0.01)(B - V),
$$

$$
B = b + \text{const} + 0.169(\pm 0.01)(B - V),
$$

where $v$ and $b$ are instrumental magnitudes of the $V$ and $B$ bands, respectively. The color coefficients are average values for nine frames for $V$ band and five frames for $B$ band, respectively. Constants are the zero points of the individual frames. Finally, we have obtained the standard magnitudes of the stars by averaging the magnitudes of all the frames. The residuals between photoelectric magnitudes and derived magnitudes for standard stars are $\Delta V = 0.001 \pm 0.027$ and $\Delta(B - V) = 0.005 \pm 0.056$, respectively. There are no systematic deviations depending on magnitudes or colors.

### 3. SELECTION OF VARIABLE STARS

In Figure 2 we display the $(V, B - V)$ diagram of a total of about 10,600 stars in the observing field of NGC 5466. The left panel shows the color-magnitude diagram for a central region at $r < 1\,^\circ$, and the right panel shows the color-magnitude diagram for an outer region at $r \geq 1\,^\circ$.

In Figure 2 the main sequence (MS), the red giant branch (RGB), and the horizontal branch (HB) are clearly seen on both panels. In addition, there are about 60 stars in the brighter and bluer region above the MS turnoff (squares in both panels) that are blue stragglers.

We applied the ensemble normalization technique (Gilliland & Brown 1988; Jeon et al. 2001) to normalize instrumental magnitudes between time-series CCD frames. We used about 100 normalizing stars ranging from 13.7 to 19.0 mag for the $V$ band and from 13.7 to 18.5 mag for the $B$ band. We excluded variable stars and stars located within $r = 0.5$ to avoid crowding effects. We used $B$-band data only for obtaining mean magnitudes, because the data quality was not good enough to apply frequency analysis. The normalization equation we used is

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

where $B$, $V$, and $m$ are the standard and instrumental magnitudes of the normalizing stars, respectively. The zero point is $c_1$, the color coefficient is $c_2$ and $c_3$ and $c_4$ are used to correct position-dependent terms such as atmospheric differential extinction, flat-field error, and variable PSFs. The typical values of the coefficients are $c_1 = -3.265$, $c_2 = -0.037$, $c_3 = 0.003$, and $c_4 = 0.002$. 

### Table 1: Observation Log

| Date (UT) | Start HJD (2,450,000+) | Duration (hr) | $N_{\text{obs}}$ | Seeing (arcsec) | Exposure Time (s) | Remarks |
|-----------|------------------------|---------------|-----------------|----------------|------------------|---------|
| 1999 Feb 8 | 1218.191 ($V$) | 4.4 | 32 ($V$) | 1.5–1.9 | 300 ($V$) | Thin cloud, moon light |
| 1999 Mar 27 | 1265.087 ($V$) | 6.2 | 56 ($V$) | 2.8–3.4 | 300 ($V$) | Moon light |
| 1999 Apr 4 | 1273.031 ($V$) | 3.0 | 28 ($V$) | 2.5–3.0 | 300 ($V$) | |
| 1999 Apr 21 | 1289.980 ($V$) | 8.1 | 57 ($V$) | 1.8–2.2 | 300 ($V$) | |
| 2000 Apr 7 | 1642.038 ($V$) | 6.8 | 40 ($V$) | 2.4–3.0 | 180 ~ 210 ($V$) | |
| 2000 Apr 8 | 1643.001 ($V$) | 6.7 | 42 ($V$) | 1.3–1.8 | 180 ($V$) | |
| 2000 Apr 10 | 1644.994 ($V$) | 7.6 | 51 ($V$) | 2.5–4.4 | 300 ($V$) | Thin cloud |
| 2000 May 4 | 1668.994 ($V$) | 7.0 | 18 ($V$) | 1.0–1.4 | 240 ($V$) | Many observing targets |
| 2001 Apr 7 | 2007.058 ($V$) | 6.6 | 72 ($V$) | 1.0–1.4 | 200 ($V$) | Full moon |
| 2001 Apr 12 | 2012.015 ($V$) | 7.3 | 49 ($V$) | 2.0–2.5 | 400 ($V$) | Moon light |
| 2001 Apr 21 | 2020.990 ($V$) | 7.0 | 39 ($V$) | 2.0–2.5 | 400 ($V$) | Thin cloud |
| 2001 Jun 8 | 2069.016 ($V$) | 4.9 | 40 ($V$) | 1.5–2.3 | 300 ($V$) | Thin cloud |
| 2002 Mar 9 | 2343.092 ($V$) | 1.6 | 14 ($V$) | 1.8–2.2 | 300 ($V$) | |
| 2002 Mar 10 | 2344.067 ($V$) | 7.4 | 57 ($V$) | 2.5–4.5 | 300 ($V$) | Bad seeing |
| 2002 Mar 11 | 2345.071 ($V$) | 7.0 | 51 ($V$) | 2.0–2.4 | 300–500 ($V$) | |
| 2002 Mar 12 | 2346.103 ($V$) | 6.6 | 44 ($V$) | 0.9–3.0 | 120–300 ($V$) | Many observing targets |
| 2002 Mar 16 | 2350.045 ($V$) | 7.8 | 38 ($V$) | 2.5–3.0 | 300–600 ($V$) | Many observing targets |
| 2002 Mar 17 | 2351.071 ($V$) | 2.1 | 16 ($V$) | 2.0–2.3 | 300 ($V$) | |
| 2002 Mar 18 | 2352.100 ($V$) | 6.2 | 48 ($V$) | 1.8–3.2 | 250–400 ($V$) | |
| 2002 Mar 19 | 2353.057 ($V$) | 7.5 | 86 ($V$) | 1.0–1.3 | 150–300 ($V$) | The best images |
| 2002 Mar 22 | 2356.048 ($V$) | 7.3 | 30 ($V$) | 3.0–3.2 | 600 ($V$) | Thin cloud |
| 2002 Mar 23 | 2357.176 ($V$) | 4.6 | 36 ($V$) | 2.3–3.0 | 300–400 ($V$) | |
Fig. 1.—Gray-scale map of a $V$-band CCD image of the globular cluster NGC 5466. The image is presented only for the central region ($7'6 \times 5'7$) of the cluster, out of the total observing field of $11'6 \times 11'6$. Nine SX Phoenicis stars are labeled by name.

Fig. 2.—Color-magnitude diagrams of NGC 5466: left Central region at $r < 1'0$; right outer region at $r \geq 1'0$. A blue straggler region is outlined by a box.
$c_3 = 0.000021$, and $c_4 = -0.000029$. The positions in the CCD, $P_x$ and $P_y$, range from 1 to 2048.

After photometric reduction of the time-series frames, we inspected luminosity variations by eye for about 10,600 stars in the entire field to search for variable stars. From this we have detected nine SX Phoenicis stars. Six of them are previously known, and three are newly discovered in this research. We also recovered 19 previously known RR Lyrae stars, three eclipsing binaries, and a Cepheid.

Among the nine SX Phoenicis stars, the three newly discovered ones are designated by SXP 1, SXP 2, and SXP 3. SXP 1 is located near a bright star, while SXP 2 and SXP 3 are located very close to the center of the cluster and have very low amplitudes (see Fig. 3). Although seven of the nine SX Phoenicis stars are located in the central region at $r < 1.5$, we could detect them easily because of the sparseness of the cluster. For the globular clusters M53 (Jeon et al. 2003) and M15 (Jeon et al. 2001), we found SX Phoenicis stars only in

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**Fig. 3.**—Observed data (circles) for nine SX Phoenicis stars. Synthetic light curves (solid lines) obtained from the multiple-frequency analysis (see Table 3) are superimposed on the data. We present the mean photometric errors of each observing day in the bottom left corner of each panel.
Fig. 3.—Continued
Fig. 3.—Continued
the outer region at \( r > 2.0 \); it is very difficult to detect SX Phoenicis stars in the central regions because of crowding. The coordinates, mean magnitudes, and color indexes of the nine 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).

### Table 2

| Name                  | R.A. (J2000.0) | Decl. (J2000.0) | \( \langle V \rangle \) | \( \langle B \rangle - \langle V \rangle \) |
|-----------------------|----------------|-----------------|-----------------|-------------------|
| Cl* NGC 5466 SXP 1 (new) | 14 5 39.25 | 28 31 18.5 | 18.939 | 0.188 |
| Cl* NGC 5466 SXP 2 (new) | 14 5 29.05 | 28 31 56.7 | 19.133 | 0.153 |
| Cl* NGC 5466 SXP 3 (new) | 14 5 28.12 | 28 34 49.1 | 19.277 | 0.174 |
| Cl* NGC 5466 NH 27 | 14 5 20.72 | 28 31 53.4 | 18.640 | 0.182 |
| Cl* NGC 5466 NH 29 | 14 5 23.61 | 28 31 37.9 | 18.798 | 0.229 |
| Cl* NGC 5466 NH 35 | 14 5 28.05 | 28 31 08.0 | 18.876 | 0.189 |
| Cl* NGC 5466 NH 38 | 14 5 28.10 | 28 32 37.7 | 18.790 | 0.178 |
| Cl* NGC 5466 NH 39 | 14 5 35.06 | 28 30 45.2 | 18.836 | 0.230 |
| Cl* NGC 5466 NH 40 | 14 5 25.86 | 28 31 02.7 | 19.112 | 0.183 |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

4. LIGHT CURVES AND FREQUENCY ANALYSIS

Figure 3 displays \( \nu \)-band light curves of the SX Phoenicis stars. In each panel we show the mean photometric error for each observing night by an errorbar in the lower left corner. Although NGC 5466 has a well-resolved structure, all the SX Phoenicis stars except for NH 39 still suffer from contamination effects due to neighboring stars. Some photometric data for the four SX Phoenicis stars located near the cluster center were lost because of poor seeing and/or bad sky conditions caused by moon light or thin clouds. 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 analysis to determine pulsating frequencies of the nine SX Phoenicis stars, using the discrete Fourier transform and linear least-square fitting methods (Kim & Lee 1995; Jeon et al. 2001). Figure 4 displays the power spectra of the light curves for the nine SX Phoenicis stars. Each panel shows the prewhitening process used to derive each peak in the power spectrum with window spectra represented in the inner panels. Low frequencies detected in all the SX Phoenicis stars in NGC 5466 except for NH 49 and SXP 2 resulted from variable seeing conditions and/or drift during long observing runs from 1999 to 2002. Synthetic light curves obtained from these analyses are superposed on the data in Figure 3, and they fit the data well. Some unrealistic light curves of NH 38 around HDJ 2452069.0 resulted from high-order fitting to a small amount of data.

The results of the multiple-frequency analysis of the nine SX Phoenicis stars are summarized in Table 3. The signal-to-noise ratios are defined to be the square root of the ratio of the power for each frequency to the average power after prewhitening all frequencies. We assume a real frequency to have an amplitude signal-to-noise ratio larger than 4.0, as found by Breger et al. (1993).

During the analysis we detected many harmonic frequencies and probable nonradial frequencies in addition to the primary frequencies of each star. Most of the frequencies have been affected by a 1 cycle day\(^{-1}\) alias effect. The primary period modes for these SX Phoenicis stars range from 0.0386 to 0.0552 days, and the semiamplitudes of the variability range from 0.023 to 0.221 mag.

We divided the sample of SX Phoenicis stars into three groups: (1) double-radial mode SX Phoenicis stars (SXP 2, SXP 3, NH 35, NH 38, and NH 39), (2) single-radial mode SX Phoenicis stars with long-term variations (SXP 1 and NH 29), and (3) single-radial mode SX Phoenicis stars without long-term variations (NH 27 and NH 49). Individual SX Phoenicis stars in each group are described in the appendix.

4.1. Double-Radial Mode SX Phoenicis Stars

Double-radial mode stars are very useful to identify the pulsating modes of SX Phoenicis stars. SXP 3, NH 35, and NH 39 show the double-radial mode oscillations. Their period ratios are \( P_{1H}/P_F = 0.7979, 0.7825, \) and 0.7826, respectively. The first radial modes are \( f_0, f_1, \) and \( f_1 \) of SXP 3, NH 35, and NH 39, respectively. The double-radial mode features of these three stars are considered to be intrinsic ones. Interestingly, NH 39 shows combination frequencies of the two radial modes; \( f_4 \) and \( f_5 \) corresponding to \( f_1 - f_1 \) and \( f_1 + f_1 \), respectively. For NH 35 \( f_4 \) is a suspected harmonic frequency of \( f_3 \) affected by 1 cycle day\(^{-1}\) aliases. The period ratios help us to identify their pulsation modes with confidence. The period ratios of SXP 3, NH 35, and NH 39 are close to the theoretical ratios of the fundamental and first-overtone mode for SX Phoenicis stars with extremely low metal abundances (Santolamazza et al. 2001). In Figure 5 we compare the period ratios of SXP 3, NH 35, and NH 39 with the theoretical period ratios for various \( \log L/L_\odot \) with \( Z = 0.0001 \) and \( M/M_\odot = 1.0 \) by Santolamazza et al. (2001).

Figure 5 shows that the two double-radial mode SX Phoenicis stars, NH 35 and NH 39, are located on the \( \log L/L_\odot = 0.8 \) line, and that SXP 3 is consistent with the \( \log L/L_\odot = 0.6 \) line. Using Table 2 of Santolamazza et al. (2001) we estimate the temperatures of all three stars to be about 7700 K.

SXP 2 and NH 38 in Table 3 are also suspected double-radial mode pulsators. But we could not obtain precise frequencies for the secondary radial modes because of the poor data quality. Their period ratios \( P_{1H}/P_F \) are 0.764 and 0.810, respectively. These values depart from the theoretical ranges for the ratio of \( P_{1H}/P_F \). The frequencies of the suspected secondary radial modes are probably real ones, according to the amplitude signal-to-noise ratios (see Table 3) and features of power spectra in Figure 4.
Fig. 4.—Power spectra of nine SX Phoenicis stars. Window spectra are shown in a small box in each panel.
If we assume that they are affected by 1 cycle day\(^{-1}\) aliases, the period ratios of SXP 2 and NH 38 can be 0.781 and 0.798, respectively, which are consistent with the theoretical \(P_{11}/P_F\).

We consider SXP 2 and NH 38 to be candidate double-radial mode SX Phoenicis stars.

### 4.2. Single-Radial Mode SX Phoenicis Stars with Long-Term Variations

SXP 1 and NH 29 show distinct low frequencies, 1.5616 and 0.4266 cycle day\(^{-1}\), and their \(V\) amplitudes are 0.076 and 0.158 mag, respectively. The low frequencies are clearly identified in the power spectra of Figure 4 and in the light curves of Figure 3. Their amplitude signal-to-noise ratios are 8.7 and 18.2, respectively. We have checked for bad pixels on the CCD images, finding none near these stars. We propose cautiously that the low frequencies of SXP 1 and NH 29 are caused by a nonradial \(g\)-mode and a contact binary, respectively. SXP 1 is a very interesting pulsator, if its nonradial mode is real. This is the first discovery in globular clusters of a pulsator that possesses \(p\)-mode (characterized by an SX Phoenicis star) and \(g\)-mode (characterized by a \(\gamma\) Doradus star), simultaneously. As an example of this type of pulsator, Handler et al. (2002) found the characteristics of \(\delta\) Scuti and \(\gamma\) Doradus type pulsations for a field binary HD 209295.

But Henry et al. (2004) found that a long-term period component of HD 207651, 1.3598 cycle day\(^{-1}\) = 0.73540 days, did not result from a \(\gamma\) Doradus type term but from the ellipticity effect. From the spectroscopic observations an eclipsing period was twice the long-term period seen in the photometry.

Figure 6 is a phase diagram of the long period of 2.3430 days for NH 29. It shows a distinct light variation. If this is a contact eclipsing binary star, the total period will be about twice the long-term period. Otherwise, it could be a \(g\)-mode frequency similar to the long-term variation of SXP 1. Unfortunately, the data are not good enough for accurate frequency analysis.

### 5. DISCUSSION

#### 5.1. Characteristics of the SX Phoenicis Stars

In Figure 7, we show the position of the nine SX Phoenicis stars in the color-magnitude diagram of NGC 5466, listing their mean magnitudes and color indices in Table 2. Figure 7 shows that all the SX Phoenicis stars are located in the blue straggler region, brighter and bluer than the main-sequence.
turnoff point. All of the known SX Phoenicis stars in globular clusters are blue stragglers, but there are nonvariable stars among the blue stragglers.

In Figure 8 we have compared the $V$ amplitudes and periods of the SX Phoenicis stars in NGC 5466 (filled circles) with those of SX Phoenicis stars in other globular clusters, field SX Phoenicis stars, and δ Scuti stars. It includes the SX Phoenicis stars in M53 (star symbols) and M15 (cross) discovered by our previous searches for variable blue stragglers in globular clusters (Jeon et al. 2001, 2003). The sources of the data in Figure 8 are Rodríguez et al. (2000) for field SX Phoenicis stars and δ Scuti stars and Rodríguez & López-González (2000) for SX Phoenicis stars in Galactic globular clusters. Figure 8 shows that the $V$ amplitudes and periods of the SX Phoenicis stars in NGC 5466 are consistent with those for SX Phoenicis stars in other globular clusters; the $V$ amplitudes increase steeply with increasing period, and the $V$ amplitudes of SX Phoenicis stars are larger than those of δ Scuti stars with the same period.

5.2. Radial Mode Identification

A method for mode identification is to use a pulsation constant, $Q$, denoted as $Q = P\rho^{1/2}$, where $P$ and $\rho$ are the period and mean density of variable stars, respectively. The $Q$ values of overtone mode are smaller than those of the fundamental mode (Breger 2000). The $Q$ values can be derived using a photometric method such as Strömgren $u v b y$ Hβ observation (Rodríguez et al. 2003). Another photometric method is to use SX Phoenicis stars with double-radial mode, but these are rare. Fortunately, five (including two candidates) of the SX Phoenicis stars in NGC 5466 are found to have double-radial modes, so their modes are identified clearly. All the double-radial mode stars (SXP 2, SXP 3, NH 35, NH 38, and NH 39) show the fundamental and first-overtone modes, as described in § 4.1.

The mode of the rest of the SX Phoenicis stars can be identified using amplitude, period, and luminosity. NH 27 is...
identified as a first-overtone mode star because its $V$ amplitude, 0.246 mag, is slightly lower, and especially because of its position in the period-luminosity diagram as shown in Figure 9. SXP 1 has a high amplitude and is located in the fundamental region in the period-luminosity diagram, so it is a fundamental-mode star. In Table 3, NH 35, NH 38, NH 39, and NH 49 show harmonic frequencies supporting asymmetric sinusoidal features. Moreover, their total light amplitudes have a range of 0.282–0.730 mag, which is characteristic of high-amplitude δ Scuti (HADS) stars. Thus, their modes are clearly identified as fundamental radial oscillations. Their primary and secondary radial periods correspond to the fundamental and first-overtone radial modes, respectively. NH 29 is the first-overtone mode star according to its low amplitude (0.142 mag), well-defined sinusoidal feature in the light curve (see Fig. 3), and its location in the period-magnitude diagram. Seven of nine SX Phoenicis stars in NGC 5466 show the fundamental mode or double-radial mode with fundamental and first-overtone modes. They are indicated by open and filled circles, respectively, in the color-magnitude diagram in Figure 7. Two filled triangles denote the first-overtone mode stars. The identified radial modes are listed in the last column of Table 3.

McNamara (2000, 2001) suggested that the light amplitude and the degree of asymmetry of the light curves are useful parameters for identifying the pulsating modes. Generally, this method is very useful for systems with a small number of pulsators and/or no double-radial mode stars. However, in many cases these criteria do not give a unique solution to identify pulsating modes, especially for SX Phoenicis stars with very low amplitudes and short periods such as SXP 2 and SXP 3 in NGC 5466.

5.3. Period-Luminosity Relation

The $P$-$L$ relation of SX Phoenicis stars in globular clusters is very useful to obtain the distance moduli of the clusters and nearby galaxies (McNamara 1995). However, it is not easy to define well the $P$-$L$ relation from observations because there is often a mixture of different pulsation modes (Jeon et al. 2003; McNamara 2001). But we can easily identify the pulsating mode using the double-radial mode stars as described in the previous section.

Figure 9 presents the $P$-$L$ relation for the SX Phoenicis stars in NGC 5466. It shows that the sample can be separated into two discrete groups; one is identified as a fundamental-mode group (filled circles), and the other is a first-overtone mode group (filled and open triangles). The solid line represents the fundamental $P$-$L$ relation, and the dashed line corresponds to that of the first-overtone mode stars shifted by the ratio $P_{1}/P_{F} = 0.783$. The $P$-$L$ relation for fundamental mode in NGC 5466 is derived to be

$$\langle V \rangle = -3.25(\pm 0.46) \log P + 14.70(\pm 0.06) \quad (\sigma = \pm 0.04),$$

which corresponds to

$$\langle M_V \rangle = -3.25(\pm 0.46) \log P - 1.30(\pm 0.06)$$

for an adopted distance modulus of $(m-M)_V = 16.00$ and $E(B-V) = 0.00$ (Harris 1996).

The empirical $P$-$L$ relations have been obtained using field HADS stars and/or cluster SX Phoenicis stars identified by their pulsating modes. The slopes derived by field HADS stars and SX Phoenicis stars in ω Cen show on the whole steeper ones up to −4.66 (McNamara 2000), whereas δ Scuti stars,
SX Phoenicis stars in other globular clusters, and theoretical results show flatter slopes up to $-2.88$ (Pych et al. 2001).

The slope of $-3.25$ for NGC 5466 is in good agreement with the results for M53 (Jeon et al. 2003) and M55 (Pych et al. 2001). Jeon et al. (2003) obtained a slope of $-3.01$ for the fundamental mode stars in M53 and Pych et al. (2001) derived a slope of $-2.88$ for the fundamental mode and a slope of $-3.1$ for the first-overtone mode stars in M55. The slope for NGC 5466 derived in this study also agrees well with the theoretical values of $-3.04$ by Santolamazza et al. (2001) and $-3.05$ by Templeton et al. (2002).

6. SUMMARY

Through time-series CCD photometry of the globular cluster NGC 5466, we detect three newly discovered and six known SX Phoenicis stars. Owing to the extremely open, well-resolved structure of NGC 5466, we could easily detect many short period variable stars such as SX Phoenicis stars and eclipsing binaries even in the central region. All the SX Phoenicis stars are found to be located in the blue straggler star region of the color-magnitude diagram. Physical parameters of these stars are summarized in Tables 2 and 3. From the Fourier analysis, we find five double-radial mode stars including two candidates. These stars are very useful to determine the radial modes of SX Phoenicis stars in NGC 5466. These stars show period ratios of the two radial modes that are consistent with the theoretical ratio of the first-overtone mode to the fundamental mode ($P_{11}/P_2$). Using seven SX Phoenicis stars that are considered to be pulsating in the fundamental mode, we derive a $P$-$L$ relation for the fundamental mode in NGC 5466, $(V) = -3.25(\pm0.46) \log P + 14.70(\pm0.06)$, $(\sigma = 0.04)$. The slope of $-3.25$ for NGC 5466 is in good agreement with the empirical results for M53 ($-3.01$; Jeon et al. 2003) and M55 ($-2.88$; Pych et al. 2001), and the theoretical results of $-3.04$ by Santolamazza et al. (2001) and $-3.05$ by Templeton et al. (2002).

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APPENDIX A

SXP 1.—This star is located very close to another bright star. We could detect four frequencies including a low frequency $f_2 = 1.5616$ cycle day$^{-1}$. Frequency $f_3$ is clearly a harmonic frequency of $f_1$ corresponding to $2f_1$. A close frequency $f_4$ for $f_3$ seems to be a nonradial frequency affected by $1$ cycle day$^{-1}$ aliases.

SXP 2.—During the prewhitening processes, we detected five more frequencies whose amplitude signal-to-noise ratios are larger than $3.6$, but we could only confirm three frequencies with amplitude signal-to-noise ratios larger than $4.0$ (see Table 3). The two frequencies, $f_1$ and $f_2$, seem to be a pair of double-radial modes, and $f_3$ is a combination frequency corresponding to $f_1 + f_2$. Probably $f_3$ was affected by $1$ cycle day$^{-1}$ aliases. The superimposed synthetic light curves of SXP 2 in Figure 3 are calculated using $f_1$ and $f_2$ only. In Figure 4, some frequency peaks are shown in the lower panel of SXP 2. To confirm these frequencies, better data are needed.

SXP 3.—During the prewhitening processes we detected six frequencies whose amplitude signal-to-noise ratios are larger than $3.7$, but we can only confirm three frequencies: $f_1 = 25.8994$, $f_2 = 25.4323$, and $f_3 = 32.7041$ cycles day$^{-1}$. Two frequencies, $f_1$ and $f_2$, might be a pair of double-radial mode, and $f_2$ may be a nonradial mode affected by a $1$ cycle day$^{-1}$ alias effect. Among the rest of the six frequencies a peak of $28.1463$ cycles day$^{-1}$ in Figure 4 seems to be intrinsic. But the amplitude signal-to-noise ratio is only $3.7$. To confirm this frequency, better data are needed.

NH 27.—Among the nine SX Phoenicis stars in NGC 5466, NH 27 is the brightest. We have detected four frequencies with amplitude signal-to-noise ratios larger than $4.0$ (see Table 3). Frequencies $f_2$ and $f_3$ are close frequencies to $f_1$. The primary frequency $f_1$ has a higher priority of a radial mode frequency among three close frequencies considering the higher amplitude and the existence of a harmonic frequency. However, the primary frequency $f_1$ is also a latent nonradial mode with the other two close frequencies. Although $f_2$ is a lower frequency (i.e., a longer period) than that of the primary frequency $f_1$, it seems to be a nonradial mode. Frequency $f_3$ can also be explained by the excitation of a nonradial mode. These closely separated nonradial mode frequencies were found in several recent observations of the SX Phoenicis stars (Jeon et al. 2001, 2003). The amplitude signal-to-noise ratio of $f_4$ is only $4.0$, but its frequency, $39.4356$ cycles day$^{-1}$, is identical to $2f_1$. In Figure 4 the fourth frequency of NH 27 is shown to be distinct. It is probably a harmonic frequency of the primary frequency $f_1$. We can easily see the asymmetric shape of the harmonic frequency and amplitude modulating feature by closely separated frequencies in Figure 3. The frequency ratios are $f_2/f_1 = 0.985$ and $f_3/f_1 = 0.980$.

NH 29.—The oscillating feature of NH 29 is very abnormal. It shows a distinct long-period variable feature as shown in Figure 3. The period of long-term variation is $2.3430$ days (see Fig. 6). Frequency $f_2$ of NH 29 is a radial frequency with a total $V$ amplitude of $0.138$ mag.

NH 35.—Five frequencies with the amplitude signal-to-noise ratio $\geq 5.0$ are detected from multiple-frequency analysis for NH 35. Frequencies $f_1$ and $f_2$ are radial mode described in § 4.1. Frequencies $f_2$, $f_3$, and $f_4$ are harmonic or combination frequencies corresponding to $2f_1$, $3f_1$, and $f_2 - f_1$, respectively. The total $V$ amplitude is $0.730$ mag. This star shows a typical feature of HADS stars with only one or two stable frequencies and a high amplitude (typically $\Delta V \geq 0.4$ mag) compared with the complicated oscillation pattern and several frequencies with low amplitude (typically $\Delta V \leq 0.05$ mag) of low-amplitude $\delta$ Scuti (Petersen & Christensen-Dalsgaard 1996) stars.

NH 38.—Since NH 38 is located near a brighter star as seen in Figure 1, observing data obtained with bad seeing conditions were not useful. Four frequencies are detected for NH 38. The primary and third frequencies, $f_1$ and $f_3$, show the possibility of a double-radial mode pair explained in § 4.1. Frequencies $f_2$ and $f_4$ seem to be harmonic frequencies of $f_1$ corresponding to $2f_1$ and $3f_1$. In Figure 4 there are two more frequencies peaked on the left side of $f_3$, but their amplitude signal-to-noise ratios are too low to confirm them.

NH 39.—Observations of NH 39, because it is well isolated, are hardly affected by seeing conditions. We detect six frequencies with an amplitude signal-to-noise ratio $\geq 4.1$. Frequencies $f_1$ and $f_2$ are identified as radial-mode frequencies by the their period ratio. Frequencies $f_3$, $f_4$, and $f_6$ are harmonic.
or combination frequencies corresponding to $2f_1$, $f_3 - f_1$, and $f_3 + f_1$, respectively. A closely separated frequency of $f_1$ is detected as $f_5$ with the amplitude signal-to-noise ratio of 5.1. NH 39 also shows characteristics of HADS stars, such as NH 35, with a total $V$ amplitude of 0.460 mag.

**NH 49.**—This star is identified by comparing $(V)$ magnitudes, period, and $V$ amplitudes of the primary periods (Nemec & Mateo 1990). NH 49 has a radial mode frequency $f_1$ and a harmonic frequency $f_2$. This star is a monoperiodic pulsator.

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