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Double-radial-mode SX Phoenicis stars in the globular clusters NGC 5466 and M71

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Abstract. Through time-series CCD photometry of the globular cluster NGC 5466, we found three double-radial-mode SX Phe stars, all of which are consistent with the theoretical period ratio of the first overtone mode to the fundamental mode (P_{1H}/P_F); their period ratios are 0.7825, 0.7826 and 0.7919, respectively. We also detected a double-radial-mode SX Phe star in M71. Its period ratio is 0.781, which is also consistent with the theoretical value.

1. Introduction

NGC 5466 is a sparse globular cluster with an extremely low metallicity [Fe/H] = −2.22 (Harris 1996), having a large number of blue stragglers (Jeon et al. 2003a; Nemec & Harris 1987). M71 is one of the most metal-rich Galactic globular cluster with [Fe/H] = −0.73, and has an interstellar reddening $E(B-V) = 0.25$ and a distance modulus $(m-M)_V = 13.75$ (Harris 1996). It shows a well-resolved structure and has a very red horizontal branch.

We performed photometric observations for 22 nights from 1999 February 8 to 2002 March 23 for NGC 5466 and for 15 nights from 2000 July 8 to 2002 October 23 for M71. The CCD images were obtained with a thinned SITe 2k CCD (2048 × 2048 pixels) camera attached to the 1.8-m telescope at the Bohyunsan Optical Astronomy Observatory (BOAO), Korea. The size of the field of view of a CCD image is $11.6' \times 11.6'$ at the f/8 Cassegrain focus of the telescope.

2. Results

We applied the ensemble normalization technique (Gilliland & Brown 1988) to normalize instrumental magnitudes between time-series CCD frames. We have detected nine SX Phe stars with three new ones in NGC 5466 (Jeon et al. 2003b). Five of the nine SX Phe stars in NGC 5466 are found to be double-radial-mode pulsators. In M71 an SX Phe star also turned out to be a double-radial-mode pulsator. Double-radial-mode stars are very useful to identify the pulsating modes of SX Phe stars.

In Table 1, D2, D3 and D5 of NGC 5466 show the double-radial-mode oscillations. Their period ratios are $P_{1H}/P_F = 0.7825$, 0.7826 and 0.7919 respectively. The double-radial-mode features of these three stars seem to be to be intrinsic, considering their power spectra and period ratios (Jeon et al. 2003b). The period ratios of D2, D3 and D5 are close to the theoretical period ratio of the fundamental and first overtone mode for SX Phe stars with extremely low metal abundance (Santolamazza et al. 2001). The period ratios help us to identify their pulsation modes with confidence.

D1 and D4 in Table 1 are also suspected double-radial-mode pulsators, but we could not obtain precise frequencies for the second-radial modes because of the poor data quality. Their period ratios P_{1H}/P_F are 0.764 and 0.810, respectively. They might be affected by $1\,\mathrm{d}^{-1}$ aliases. If we consider the $1\,\mathrm{d}^{-1}$ aliases, the period ratios of D1 and D4 could be 0.798 and 0.781, respectively, which are consistent with the theoretical ratio of P_{1H}/P_F. We consider D1 and D4 to be candidate double-radial-mode SX Phe stars.

We have detected four frequencies in D6 of M71. In Table 1 D6 is clearly a double-radial-mode star, in that the ratio of $f_1/f_2 = 0.781$ is consistent with the theoretical result for fundamental and first overtone modes (Gilliland et al. 1998; Templeton, Basu & Demarque 2002). Generally, the period ratio (or identically, the frequency ratio) increases with decreasing metal abundance.

2.1. Period-Luminosity relation

The period-luminosity (P-L) relation of SX Phe stars in globular clusters is very useful to obtain the distance moduli of the clusters and nearby galaxies. However, it is not easy to define well the P-L relation from the observations, because there is often a mixture of different pulsation modes. However, we can identify the pulsation mode using the double-radial-mode stars as described in the previous section. Fig. 1 presents the P-L relation for the five double-radial-mode SX Phe stars in NGC 5466.

The solid line represents the fundamental P-L relation, and the line is shifted to the dashed line corresponding to the P-L relation for the first overtone mode stars by the ratio $P_{1H}/P_F = 0.783$. The P-L relation for fundamental mode in NGC 5466 is derived to be

$$\langle V \rangle = -3.25(\pm 0.46) \log P + 14.70(\pm 0.06), \ (\sigma = \pm 0.04), \tag{1}$$

which corresponds to

$$\langle M_V \rangle = -3.25(\pm 0.46) \log P - 1.30(\pm 0.06) \tag{2}$$

for an adopted distance modulus of $(m - M)_V = 16.00$ (Harris 1996). To derive eq. (1), we used seven fundamental mode SX Phe stars of NGC 5466 (Jeon et al. 2003b). The slope of -3.25 for NGC 5466 is in a good agreement with the results for M53 (-3.01; Jeon et al. 2003a) and M55 (-2.88; Pych et al. 2001). 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, Basu & Demarque (2002).

Table 1. Pulsating properties of the double-radial-mode SX Phe stars in NGC 5466 and M71.

Name	$\langle V \rangle$	$\langle B \rangle - \langle V \rangle$		Freq.[a,b]	Amp.[b]	Modes	Remarks
NGC 5466							
D1	18.790	0.178	f_1	18.1207	0.189	F	$f_1/f_3 = 0.764$
(NH38)			f_2	36.6623	0.055	$2f_1$	
			f_3	23.7158	0.037	1H[c] ?	
			f_4	54.7930	0.038	$3f_1$	
D2	18.876	0.189	f_1	20.0583	0.221	F	$f_1/f_5 = 0.7826$
(NH35)			f_2	40.1167	0.056	$2f_1$	
			f_3	60.1750	0.032	$3f_1$	
			f_4	4.3640	0.029	$f_5 - f_1$	
			f_5	25.6302	0.027	1H	
D3	18.986	0.230	f_1	19.8124	0.128	F	$f_1/f_3 = 0.7825$
(NH39)			f_2	39.6248	0.032	$2f_1$	
			f_3	25.3187	0.024	1H	
			f_4	5.5092	0.019	$f_3 - f_1$	
			f_5	19.0786	0.015	NR[d]	$f_5/f_1 = 0.963$
			f_6	45.1339	0.012	$f_1 + f_3$	
D4	19.133	0.153	f_1	22.1600	0.023	F	$f_1/f_2 = 0.810$
			f_2	27.3563	0.012	1H[c] ?	
			f_3	47.9119	0.012	$f_1 + f_2$?	$f_1 + f_2 = 49.5$
D5	19.277	0.178	f_1	25.8994	0.031	F	$f_1/f_3 = 0.7919$
			f_2	25.4323	0.013	NR	
			f_3	32.7041	0.012	1H	
M71							
D6	16.333	0.467	f_1	16.3705	0.026	F	$f_1/f_3 = 0.781$
			f_2	20.9563	0.021	1H	
			f_3	4.9561	0.016	$f_2 - f_1$	
			f_4	8.5266	0.009	NR?	

[a] In d^{-1}.

[b] $V = Const + \Sigma_j A_j \cos\{2\pi f_j (t - t_0) + \phi_j\}$, t_0 = HJD 2 450 000.00.

[c] Probably affected by $1\,d^{-1}$ aliases.

[d] NR = nonradial

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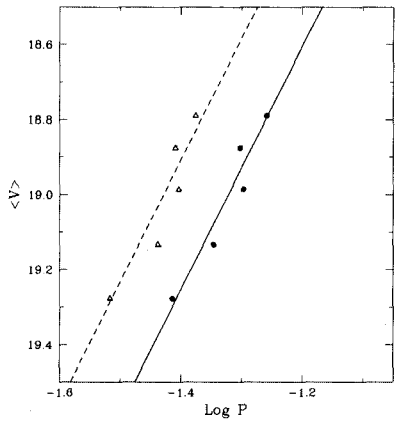

Figure 1. $\log P$ versus mean magnitude $\langle V \rangle$ diagram. Filled circles and open triangles denote the fundamental and first overtone elements for five double-radial-mode SX Phe stars in NGC 5466, respectively. The solid line represents the P-L relation for the SX Phe stars with fundamental modes ($\langle V \rangle = -3.25(\pm 0.46) \log P + 14.70(\pm 0.06)$, ($\sigma = \pm 0.04$) Jeon et al. 2003a,b), and the line is shifted to a dashed line corresponding to a P-L relation for the first overtone mode stars by the ratio $P_{1H}/P_F = 0.783$.

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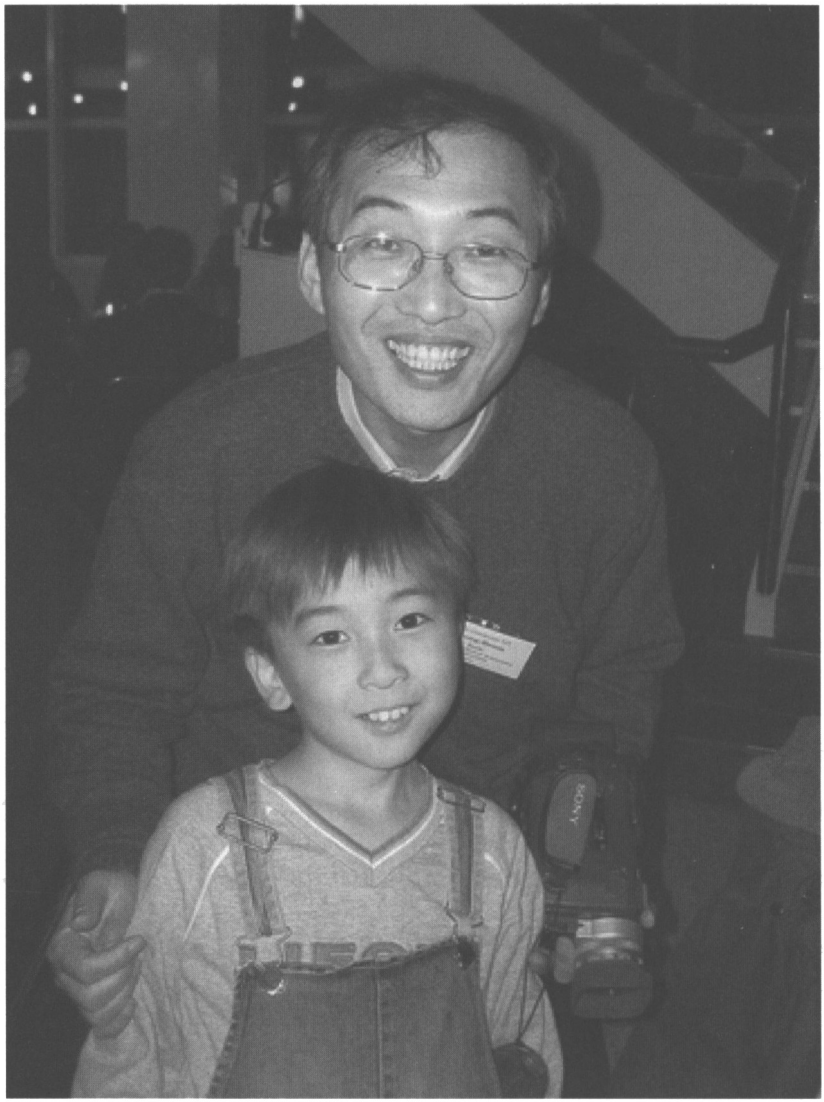

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