Astron. Astrophys. 362, 1041–1045 (2000)

ASTRONOMY
AND
ASTROPHYSICS

The mode identification and physical parameter determination of the δ Scuti star SAO 16394

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Received 3 January 2000 / Accepted 20 July 2000

Abstract. The star SAO 16394 was observed with the 85 cm telescope at the Xinglong Station of Beijing Astronomical Observatory of China from 8 to 17 April 1997 and identified as a new δ Scuti star in 1998. In order to determine its frequencies and pulsation modes accurately it was observed at the Xinglong Station in 1998 and 1999, and at the Sierra Nevada Observatory (Spain) in 1999. Period analyses were made for our data set (1997) and the data set (1997–1999). From the combined data set (1997–1999), the values of two frequencies are: 16.8493 and 23.0613 cd^{-1}. From our photoelectric observations, we obtained two physical parameters of SAO 16394: $\log L/L_{\odot}$ = 1.16, $\log T_{eff}$ = 3.92. We calculated the evolution sequences of stellar models with 1.00–2.00 solar mass in steps of 0.05$M_{\odot}$ and 8 physical parameters of each evolutionary phase. We suggest that the evolutionary sequence of the 1.85 $M_{\odot}$ model might represent the evolutionary sequence of SAO 16394. The 30th evolutionary phase of the evolutionary sequence of the model with 1.85 $M_{\odot}$ might represent the current location of SAO 16394. Depending on the Q values (Q_1 = 0.0336 day, Q_2 = 0.0246 day) and frequency ratio f_1/f_2 = 0.7306 we identify f_1 (16.8493 cd^{-1}) as the radial fundamental mode, f_2 (23.0613 cd^{-1}) as its first overtone.

Key words: stars: variables: δ Sct – stars: oscillations – stars: individual: SAO 16394

1. Introduction

SAO 16394 is a 7.2V magnitude star situated at $\alpha = 14^{\rm h}27^{\rm m}.6$, $\delta = +60°36'.5$ (1950 coordinates). Its spectral type is A2. It was used as a comparison star in observations of HR 5437 by Li & Jiang (1992). In their words: "no variability above 0^m.01 was observed". In order to obtain the correct pulsation frequencies of HR 5437, we observed HR 5437 from 8 to 17 April 1997 using the 85 cm telescope at the Xinglong Station of the Beijing Astronomical Observatory. The star SAO 16394 was used as a reference, and SAO 16408 was used as a comparison. After a preliminary period analysis, two pulsation frequencies (23.06 and 16.84 cd^{-1}) were found in SAO 16394, identifying SAO 16394 as a new δ Scuti variable star (Liu et al. 1998). In this paper, we submit more data from SAO 16394, make a comprehensive period analysis to obtain more accurate frequency information, determine some physical parameters, calculate appropriate stellar evolution models and attempt to identify the evolutionary status and pulsation modes for SAO 16394.

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Table 1. Observing log of SAO 16394 (1998–1999)

Date	Time duration (day)	Point number
1998.03.21	0.1861	267
1998.03.22	0.1639	236
1999.03.10	0.2090	294
1999.03.27	0.2048	292

2. Observations

In order to obtain more accurate values of pulsation frequencies and identify the pulsation modes of SAO 16394, we observed this star on 21, 22 March 1998 and on 10, 27 March 1999 using the 85 cm telescope at the Xinglong Station of the Beijing Astronomical Observatory. The 3-channel photometer (Michel & Chevreton 1991) with a Strömgren v filter was used. SAO 16408 was used as a comparison. The two stars and sky background were observed simultaneously. The integration time was one minute. No evidence for any variability of SAO 16408 was found. The measuring error is about 4 mmag. Four tracks of data were obtained from 1998 to 1999 covering a period of 371 days. The observing log is given in Table 1, where time duration is the length of observational run (in days) during each night, point number is the amount of data points obtained during each night.

In order to obtain physical parameters and to identify the evolutionary sequence, evolutionary phase and pulsation modes of SAO 16394, we obtained the Strömgren $uvbyH_\beta$ photometric data of this star using the 90 cm telescope at the Sierra Nevada Observatory (Spain) on 4 nights: 25, 27 January and 5, 7 February 1999. HD 127821, HD 126750 and SAO 16408 were used as comparison stars. For SAO 16394, 202 $uvby$ and 8 H_β data points were obtained. For HD 127821, 130 $uvby$ and 9 H_β data points were obtained. For HD 126750, 96 $uvby$ and 4 H_β data points were obtained, and for SAO 16408, 16 $uvby$ and 4 H_β

Table 2. Colour indices of SAO 16394 and 3 comparison stars

Object	V	$b-y$	m_1	c_1	β
SAO 16394	7.541	0.071	0.167	0.979	2.878
HD 127821	6.104	0.282	0.151	0.420	2.662
HD 126750	7.334	0.290	0.145	0.490	2.664
SAO 16408	8.245	0.269	0.149	0.448	2.683

Table 3. The pulsation frequency solutions of two data sets of SAO 16394

Time (year)	Frequency (cd^{-1})	Amplitude (mmag)	Phase (0–1)	Standard error (mmag)
1997	23.06	4.3	0.32	3.4
	16.84	4.0	0.48	
1997–1999	16.8493	4.1	0.44	4.0
	23.0613	3.9	0.34	

data points were obtained. From these observations, we calculated the colour indices of these stars (Table 2).

3. Period analysis

The period analyses were performed using the programme of Hao (1991) and the programmes PERIOD (Breger 1990) and PERIOD96 (Sperl 1996). In these programmes all parameters of pulsation are obtained using a combination of single-frequency Fourier transforms and multifrequency least squares fitting of brightness residuals (LSR). The details of the period analyses are referenced in Liu (1995, 1996). We repeated the period analysis for the data set which was obtained in 1997 (Liu et al. 1998), and combined all the data sets into one and made period analysis for this combined data set so as to obtain a coherent solution. All data points of the combined data set is shown in Fig. 1, where the ordinate is the magnitude difference of SAO 16394 and SAO 16408. The abscissa is the time (+HJD 2450500). All computed results for the two data sets are given in Table 3. The frequency is given in cycles per day, the amplitude and standard error are in milli-magnitude, and the phases are normalized to 1.

From the combined data set we obtained two frequencies: 16.8493 and 23.0613 cd^{-1}. They are the same as the values 23.06 and 16.84 cd^{-1} which were obtained from the 1997 data set, but are more accurate. They fit the data points very closely (see Fig. 1). The power spectra of the combined data set are shown in Fig. 2, together with the spectral window. The power spectrum with an annotation 'Data' is obtained from the original data. The frequency with the strongest power is the first frequency of 16.8493 cd^{-1}. The power spectrum with an annotation 'Data−1f' is obtained from the residuals (original data minus the first frequency). The frequency with the strongest power is the secondary frequency of 23.0613 cd^{-1}. In addition to the above two frequencies, we examined all power frequencies from 0 to 60 cd^{-1}. Although the sum of f_1 and f_2 is 39.9106 cd^{-1}, we didn't find any power spectra higher than the noise level from 30 cd^{-1} to 60 cd^{-1}. There are two groups of power spectra from 0 to 16 cd^{-1}, but their power spectra are not high enough to be resolved as the formal pulsation frequencies. They are also far from 6.112 cd^{-1} which is the difference between f_2 and f_1. Thus, we favour the two frequencies: 16.8493 cd^{-1} and 23.0613 cd^{-1}. Their power spectra are obviously higher than the others noted. It is interesting that the amplitude of each pulsation frequency is different from those of 1997 data set. The amplitude of 23.06 cd^{-1} (the first frequency in 1997) decreased from 4.3 mmag to 3.9 mmag. It became the secondary frequency in the pulsation. This situation might accurately describe the actual frequency of the star, but more observations are needed to determine whether the amplitude of 23.06 cd^{-1} decreases continuously.

4. Mode identification and physical parameter determination

(1) Depending on b−y, m_1, c_1 and β indices obtained from our photometric observations (see Table 2) and applying the calibration of Crawford (1979), we obtained an absolute magnitude M_v = 1.86 mag and zero interstellar reddening. If essentially zero interstellar reddening was considered, then the absolute bolometric magnitude of SAO 16394 M_{bol} = 1.86 mag. According to the calibration of Crawford (1979) and Moon & Dworetsky (1985), we obtained an effective temperature of SAO 16394 T_{eff} = 8400K. We also calculated M_{bol} of SAO 16394 using Hipparcos data. We also used other calibrations to obtain M_{bol} and T_{eff}. All results obtained by these different methods are consistent. Then, putting M_{bol} = 1.86 and $M_{bol\odot}$ = 4.75 mag into the basic formula $M_{bol} - M_{bol\odot} = -2.5 \log L/L_\odot$ we obtained the logarithm of luminosity of SAO 16394 in solar units: $\log L/L_\odot$ = 1.16. The logarithm of effective temperature, $\log T_{eff}$ = 3.92.

(2) Using the standard stellar structure and evolution code of Luo (1991, 1997), we calculated evolutionary sequences of some stellar models. The latest version of the OPAL opacity tables (Iglesias & Rogers, 1996) were used. H and He burning for evolution was considered. The initial composition is X = 0.68 and Z = 0.02. The standard mixing-length theory of convection with α = 1.0 was used. The evolutionary sequences of stellar models with mass from 1.00 to 2.00 $M_\odot$ in steps of 0.05 $M_\odot$ were calculated. In total, we calculated 21 evolutionary sequences. Each evolutionary sequence is composed of 220 evolutionary phases. In total, 4620 evolutionary phases were obtained. Including $\log L/L_\odot$ and $\log T_{eff}$, we could obtain 8 physical parameters at each evolutionary phase.

(3) Comparing the physical parameters ($\log L/L_\odot$ and $\log T_{eff}$) obtained from the observation of SAO 16394 to those obtained from theoretical calculation of stellar models, we found that the two parameters ($\log L/L_\odot$ = 1.16 and $\log T_{eff}$ = 3.92) obtained from observations and two parameters ($\log L/L_\odot$ = 1.1638 and $\log T_{eff}$ = 3.9291) obtained at the 30th evolutionary phase of a 1.85$M_\odot$ model are equal within the acceptable error range. We suggest that the evolutionary sequence of a 1.85 $M_\odot$ model might represent the evolutionary sequence of SAO 16394. The 30th evolutionary phase of the evolutionary sequence of the model with 1.85 $M_\odot$ might be the phase where

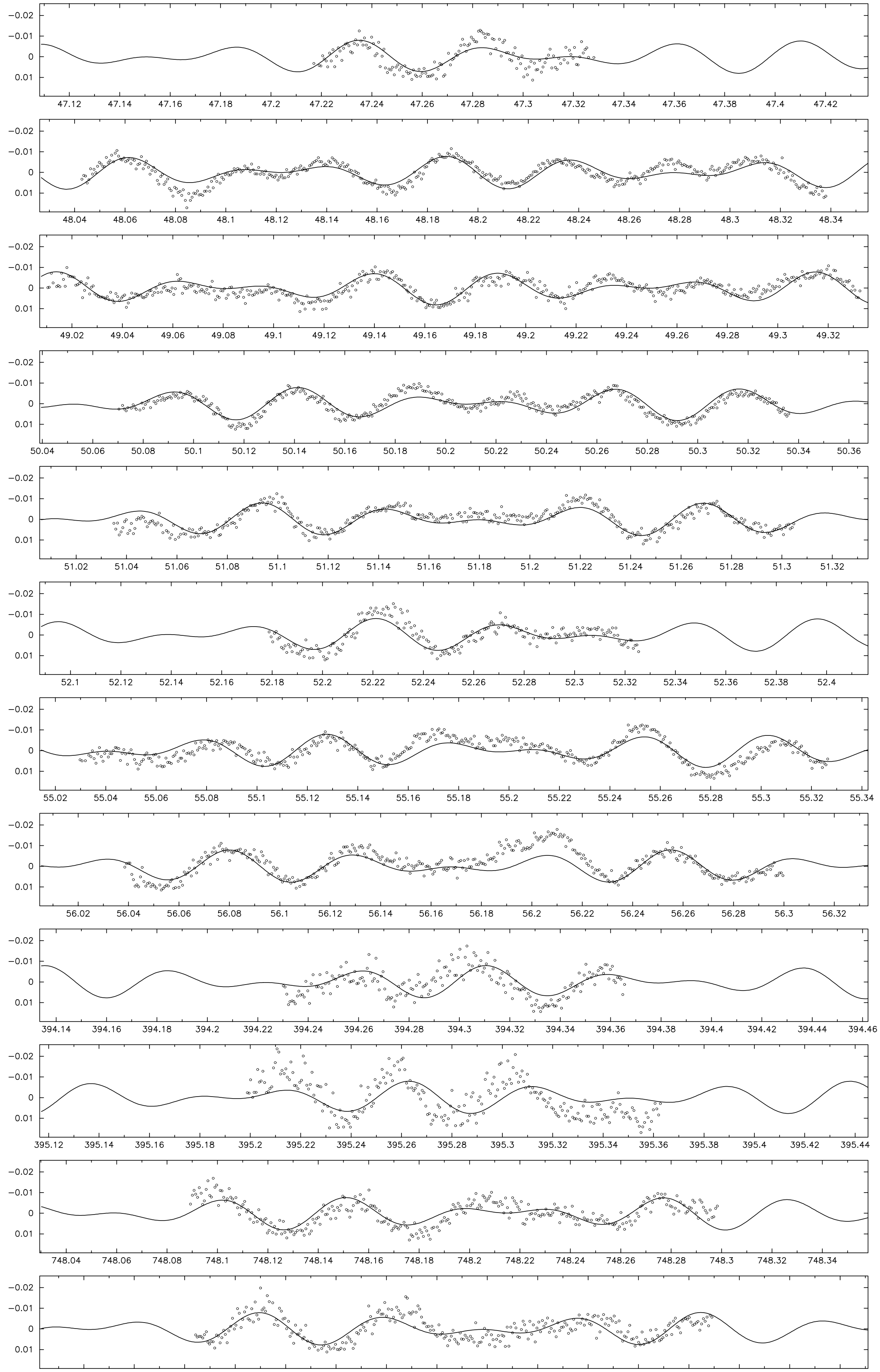

Fig. 1. The data points and curve fits of SAO 16394 during 1997–1999. The ordinate is the magnitude difference of SAO 16394 and SAO 16408. The abscissa is the time (+HJD 2450500). The fit of the two-frequency solution given in Table 3 is shown as a solid curve.

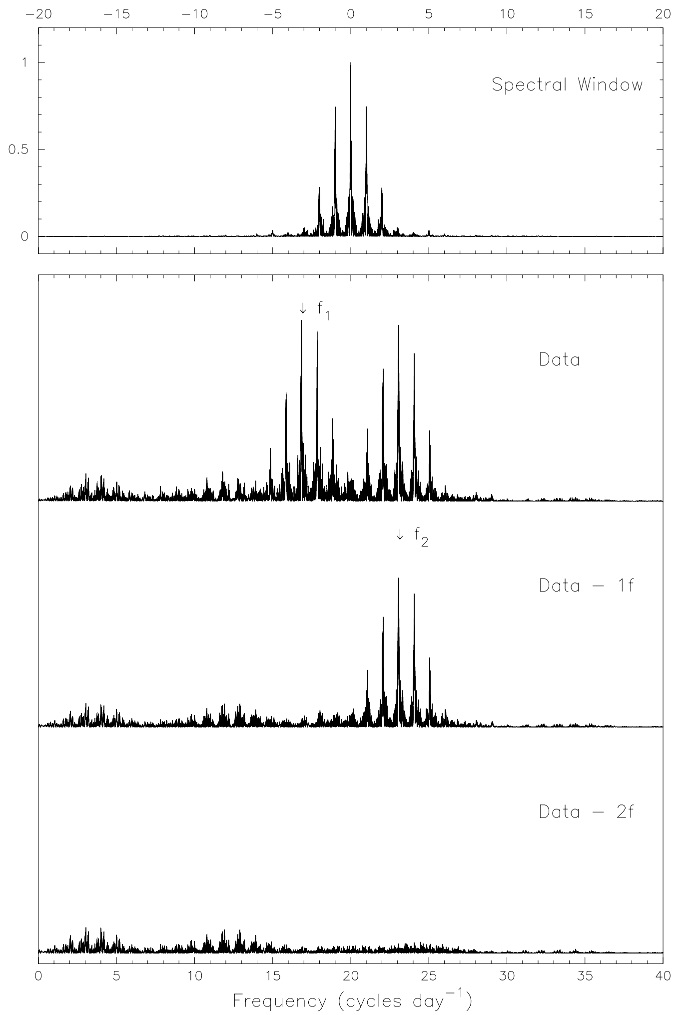

Fig. 2. Power spectra of the 1997–1999 data set of SAO 16394. The power spectrum with an annotation 'Data' is obtained from the original data. The frequency with the strongest power is the first frequency (16.8493 cd^{-1}). The power spectrum with an annotation 'Data−1f' is obtained from the residuals (original data minus first frequency). The frequency with the strongest power is the secondary frequency (23.0613 cd^{-1}). The power spectrum with an annotation 'Data−2f' is obtained from the residuals (original data minus first and secondary frequencies). The ordinate is the power (mag^2). The abscissa is the frequency (cd^{-1}).

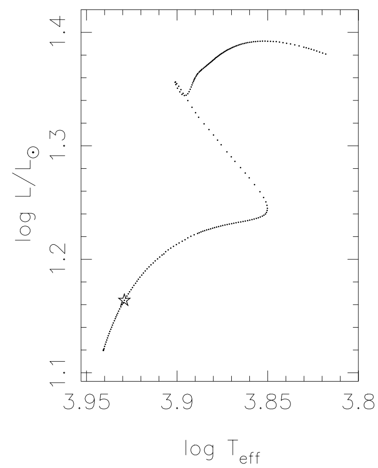

Fig. 3. The proposed evolutionary track of SAO 16394 with an initial chemical composition X=0.68, Z=0.02. The observed position of SAO 16394 is marked by an asterisk. The ordinate is luminosity and the abscissa is effective temperature.

Table 4. Physical parameters of SAO 16394 identified

Age(Gyr)	$M/M_{\odot}$	$\log L/L_{\odot}$	$\log T_{eff}$	$\log R/R_{\odot}$
0.3070	1.85	1.1638	3.9291	0.2536
$\log T_c$	$\log P_c$	$\log D_c$		
7.3190	17.1977	1.8088		

SAO 16394 is located at present. The identified evolutionary track of SAO 16394 is shown in Fig. 3. The 30th evolutionary phase where SAO 16394 is located is shown in Fig. 3 with an asterisk. The eight important physical parameters obtained from the evolution computation at the 30th evolutionary phase may thus represent the physical parameters of SAO 16394. These parameters are given in Table 4. In Table 4 Age (Gyr) is evolutionary age starting from zero-age main sequence in giga years, $M/M_{\odot}$ is stellar mass in solar units, $\log L/L_{\odot}$ is the logarithm of luminosity in solar units, $\log T_{eff}$ is the logarithm of effective temperature, $\log R/R_{\odot}$ is the logarithm of radius in solar units, $\log T_c$ is the logarithm of central temperature, $\log P_c$ is the logarithm of central pressure, $\log D_c$ is the logarithm of central density.

(4) Using the definition of the pulsation constant Q and using M and R from Table 4 we obtained Q = 0.5665/f. Thus, for f_1 = 16.8493 cd^{-1} we obtained Q_1 = 0.0336 day. For f_2 = 23.0613 cd^{-1} we obtained Q_2 = 0.0246 day. We obtained a frequency ratio f_1/f_2 = 0.7306. Using Table 2 of Breger (1979), which lists the radial Q values and period ratios for a typical δ Scuti star, we identify f_1 as the radial fundamental mode and f_2 as its first overtone.

5. Conclusion

We have made period analyses from two data sets: the 1997 data set and the combined data set. A consistent solution of two frequencies: 16.8493 and 23.0613 cd^{-1} was obtained. We obtained two physical parameters: $\log L/L_{\odot}$ = 1.16, $\log T_{eff}$ = 3.92 from our photometric data. We used the stellar structure and evolution code developed by Luo (1991, 1997) to calculate the evolutionary sequences of stellar models with 1.00–2.00 solar mass in steps of 0.05 $M_{\odot}$ and 8 physical parameters of each evolutionary phase were determined, and the pulsation modes identified. The main results obtained are given in four tables and three figures. Because two physical parameters ($\log L/L_{\odot}$ = 1.16 and $\log T_{eff}$ = 3.92) obtained from observations and two parameters ($\log L/L_{\odot}$ = 1.1638 and $\log T_{eff}$ = 3.9291) obtained at the 30th evolutionary phase of a 1.85$M_{\odot}$ model are completely the same within an acceptable error range, we conclude that the evolutionary sequence of a 1.85 $M_\odot$ model might represent the evolutionary sequence of SAO 16394. The 30th evolutionary phase of the evolutionary sequence of the model with 1.85 $M_\odot$ appears to be the phase where SAO 16394 is located at present. Using the Q values (Q_1 = 0.0336 day, Q_2 = 0.0246 day) and frequency ratio f_1/f_2 = 0.7306, the two frequencies might be associated with the radial fundamental mode and the first overtone, respectively.

Acknowledgements. The authors would like to express their thanks to the National Natural Science Foundation of China for the research grants. Eloy Rodríguez acknowledges partial research support from the Junta de Andalucia and the Direccion General de Ensenanza Superior (DGES) under project PB96-0840.

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