Astron. Astrophys. 341, 574–578 (1999)

ASTRONOMY AND ASTROPHYSICS

New observations of 53 Persei

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Received 22 September 1998 / Accepted 21 October 1998

Abstract. We gathered 37 new spectra of the B star 53 Persei spread over approximately 2 years. On these data, we performed a frequency and a mode analysis. We determined the physical parameters of 53 Persei and placed the star in the theoretical SPB instability strip. We also analysed the 110 photometric observations of the Hipparcos satellite. Our results show the presence of the two frequencies often quoted in the literature $\nu_1 = 0.461$ c/d, $\nu_2 = 0.594$ c/d and a third frequency $\nu_3 = 0.471$ c/d which was first proposed by Mills & Dukes (1994). It is the first time that two studies result in the same third frequency based on two different data sets. The mode analysis provides evidence for $l_1 = 1$ or $l_1 = 2$ for the dominant mode, supporting the conclusions of Smith & Huang (1994).

Key words: stars: early-type – stars: fundamental parameters – stars: individual: 53 Persei – stars: oscillations

1. Introduction

53 Persei (HD 27396) is one of the earliest studied variable mid-B stars of the northern hemisphere. Photometric (e.g. Percy & Lane 1977, Africano 1977, Buta & Smith 1979, Smith et al. 1984, Huang et al. 1994, Smith & Huang 1994, Chapellier et al. 1998) as well as spectroscopic data (e.g. Smith & McCall 1978, Smith et al. 1984, Le Contel et al. 1989, Chapellier et al. 1998) have been gathered from the mid seventies onwards. Our knowledge on the pulsational behaviour of 53 Per is still far from complete despite the fact that it has been observed so often.

53 Persei is the prototype of a group of B type line profile variables. However the star can also be considered as a Slowly Pulsating B star (SPB). It lies in the middle of the theoretical instability strip of the SPBs and recently Chapellier et al. (1998) showed that 53 Per satisfies all the observational characteristics of an SPB.

By now, several authors agree on a first frequency ν_1 around 0.46 c/d and on a second frequency ν_2 close to 0.60 c/d. (e.g. Smith et al. 1984: ν_1 = 0.464 c/d, ν_2 = 0.595 c/d; Huang et al. 1994: ν_1 = 0.462 c/d, ν_2 = 0.603 c/d; Chapellier et al. 1998: ν_1 = 0.462 c/d, ν_2 = 0.597 c/d), although some authors only mention periods shorter than 15 hours. Le Contel et al. (1989) reported that the radial velocity curve could be better fitted with one frequency 0.424 c/d than with the two frequencies mentioned by Smith et al. (1984). These latter authors, as well as Huang et al. (1994), propose that the observed deviation of the data from a fit based on ν_1 and ν_2 implies the existence of additional frequencies but none of them were able to show this definitely. Chapellier et al. (1998) claim to have found a third frequency around 0.27 c/d in their photometric data.

An unambiguous mode identification of the pulsations has not yet been achieved. From line profile fitting Smith & Buta (1979) found that the modes (l_1, m_1) = (3,-2) for ν_1 and (l_2, m_2) = (3,-3) for ν_2 gave the best agreement between theory and observations. This claim was restated by Smith and co-authors in 1984 after profile fitting of new spectroscopic data. Subsequently, Smith & Huang (1994) reported that this mode identification is erroneous. Using Voyager far-ultraviolet data in combination with U and V data of Huang et al. (1994), they re-identified the pulsational degree of the (dominant) mode with frequency ν_1 = 0.46 c/d to be l_1 = 2 or 1. This paper will present evidence that supports this latter mode identification.

Our study of 53 Per is part of a large long-term systematic study of SPBs that we have started a few years ago. The goals of this study are outlined by Aerts et al. (1998a) and will not be repeated here. The number of targets in this study was considerably increased after the discovery of some 100 new SPB candidates by Waelkens et al. (1998) based on Hipparcos data. Aerts et al. (1998a) have selected some 20 bright SPBs for further photometric and spectroscopic monitoring. Preliminary results of the first observing campaigns were recently presented by Aerts et al. (1998b).

The plan of the paper is as follows. In Sect. 2 we present new spectra of 53 Per and the results of a frequency analysis on the radial velocity data. In the third section we derive some general astronomical parameters of 53 Persei and we place the star in the theoretical instability strip of the SPBs. In the following section we use the moment method to obtain restrictions on the pulsational degree l of the dominant mode. In the fifth section we analyse the Hipparcos photometric data and we search for frequencies. Some concluding remarks are given in Sect. 6.

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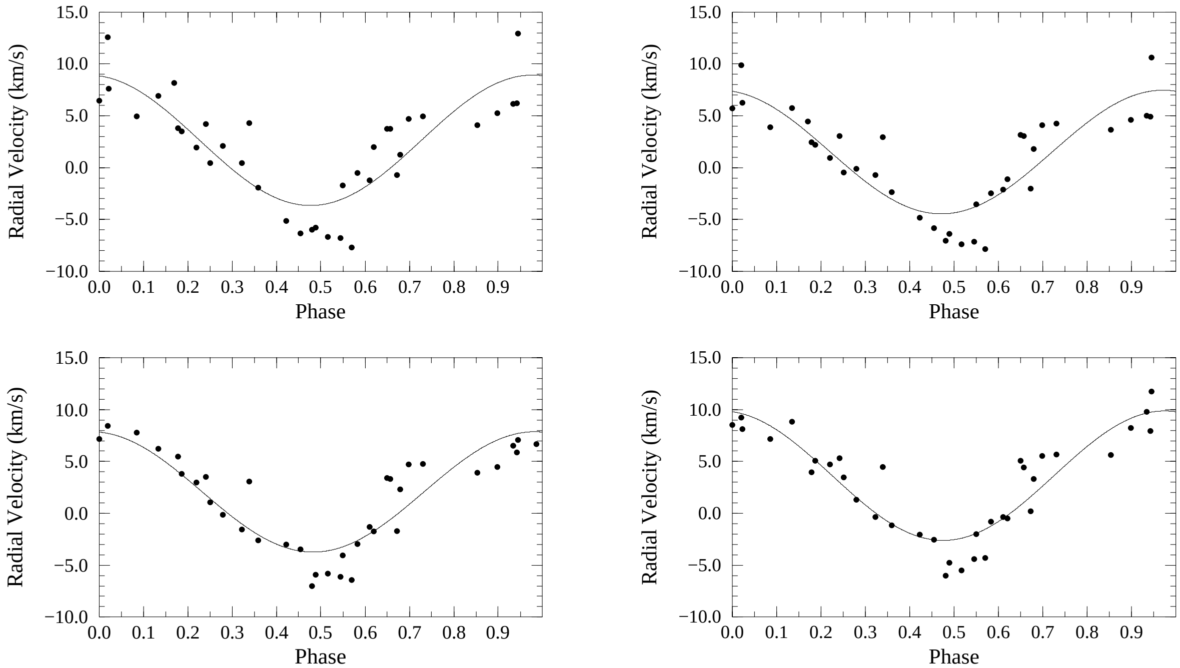

Fig. 1. Phase diagrams for the frequency ν_1 = 0.4612 c/d. The *upper left panel* shows the data for the H_α line, the *upper right* for the HeI line, the *lower left panel* for the SiII 6347.091 Å line and the *lower right panel* for the SiII 6371.359 Å line. The smooth curves are least squares fits for ν_1.

2. The spectroscopic data

We obtained 37 echelle spectra during a period from October 1994 until November 1996 with the 1-m Ritchey-Chretien reflector of the Ritter Observatory at the University of Toledo. We extracted 37 useful H_α lines, 37 HeI (5875.752 Å) lines and 36 measurements of the doublet SiII (6347.091 Å)-SiII (6371.359 Å). The HeI line is in fact a blend of the triplet HeI 5875.618 Å, HeI 5875.650 Å, and HeI 5875.989 Å but we used the average laboratory wavelength. After bias correction, flat-field correction and wavelength-calibration we normalised all spectra. Details on the observational setup and reduction package used, can be found in Gordon & Mulliss (1997). The spectra have a S/N ratio between 50 and 150.

To compute the radial velocity $v_{\rm rad}$ we fitted each line with a gaussian profile and calculated $v_{\rm rad}$ by means of the wavelength of the center of the profile using the Doppler formula. In the case of the H_α lines we avoided the Lorentz wings and we fitted only the gaussian center of the line. We mainly used the CLEAN method (Roberts et al., 1987) and goodness of fit in the least-squares sense to search for pulsational frequencies. We checked our results with the PDM method (Stellingwerf, 1978).

For each of the lines we found a prominent first frequency near ν_1 = 0.4612 c/d. This frequency explains from 73% of the variance in case of the H_α line up to 83% of the variance for the SiII 6371 Å line. The phase diagrams with this frequency for each of the lines are shown in Fig. 1. We prewhitened the data with ν_1 in order to search for another frequency. Unfortunately our data suffers from such a severe aliasing that we cannot extract a well-defined second frequency. For each line we find one or more of the following candidate frequencies that explains a large fraction of the variance in the residuals: 0.3773 c/d, 0.4461 c/d, 0.6227 c/d. From the window function (see e.g. Roberts et al., 1987), we derive that they are linked with each other. In case of the SiII 6371 Å line, the frequency 0.4461 c/d explains the largest fraction of the variance in the residuals: about 59%. For all the lines, the frequency 0.5935 c/d, which is very close to the second frequency found in the Hipparcos photometric data (this paper), is also present but only reduces, e.g. for the SiII 6371 Å line, 35% of the variance in the residuals. Prewhitening with the 0.5935 c/d leaves no significant trace of any of the above mentioned frequencies. Because this frequency is also close to the one reported by Smith et al. (1984) we adopt 0.5935 c/d as second frequency. The third frequency ν_3 = 0.4712 c/d of the Hipparcos data seems not to be present in the radial velocity data.

3. Astronomical parameters of 53 Persei

The parallax of 53 Persei was measured by Hipparcos to be (7.03 $\pm$ 0.79) mas which results in a distance $d = (142 \pm 16)$ pc.

Fracassini et al. (1988) list the different apparent diameters of 53 Persei from different authors. We ignore the somewhat outlying value by Hertzsprung (1922) and adopt a mean value of 2.7 10^{-4} arcsec. For a distance of 142 pc this apparent diameter results in a true diameter of R = 4.1 $R_\odot$.

53 Per has been measured 3 times in the Geneva photometric system. Despite this small number we applied the new photometric calibration by Künzli et al. (1997) to the mean magnitudes in the different filters to obtain values for the effective temperature and the gravity. This results in $T_{\rm eff}$ = 15300 K and $\log g$ = 4.03. Because the photometric amplitude is small (about

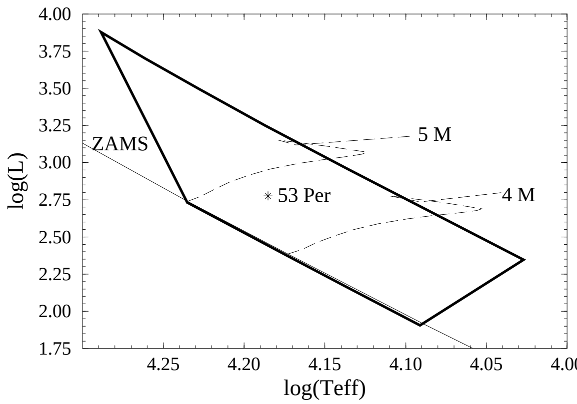

Fig. 2. Position of 53 Per in the theoretical SPB instability strip computed by Pamyatnykh (1998). The evolutionary tracks were computed by Schaller et al. (1992). The luminosity is expressed in solar units.

0.02, see e.g. Smith et al. 1984), the obtained mean magnitudes probably do not differ very much from the real mean magnitudes.

With an average visual magnitude m_V of 4.84 and the previously derived distance one computes the absolute visual magnitude M_V to be about -0.92.

To compute the bolometric magnitude, we first determined the bolometric correction (BC). Flower (1996) investigated the relation between $T_{\rm eff}$ and BC. From the literature he collected 335 stars for which $T_{\rm eff}$ and BC were known. He then showed that for the hotter stars the BC does not visibly depend on the luminosity class. For O stars this was already noticed by Chlebowski & Garmany (1991). From the database of Flower we extracted the 39 stars with $T_{\rm eff} \geq 10^4$ K; these comprise 17 main sequence stars, 5 subgiants, 7 normal giants, 2 bright giants and 8 supergiants. We verified that these stars indeed seem to obey one $T_{\rm eff}$ -BC relation and fitted this relation with a third-degree polynomial. From this polynomial we calculated the BC of 53 Per to be about -1.27. This results in a bolometric magnitude of $M_{\rm bol} = M_V + BC =$ -2.19.

Once the bolometric magnitude is known, one easily calculates that the luminosity is $\log(L/L_\odot)$ = 2.76. Here we used a value of 4.75 for the bolometric absolute magnitude of the Sun (Lang 1992). Knowing $T_{\rm eff}$ and $\log(L/L_\odot)$ we placed 53 Persei in the theoretical SPB instability strip (Fig. 2) computed by Pamyatnykh (1998).

With the above-mentioned values for the effective temperature and the luminosity we use the grids of stellar models by Schaller et al. (1992) to estimate the mass of the star. This results in a value of M = 4.7 $M_\odot$.

To perform the mode identification described in the following section, we finally computed K, the ratio of the amplitude of the horizontal to the amplitude of the vertical motion in the zero-order rotation approximation (see e.g. Smeyers & Tassoul 1987):

$$K = \frac{GM}{R^3\omega^2} \approx 74.437 \cdot \left(\frac{M}{M_\odot}\right) \left(\frac{R}{R_\odot}\right)^{-3} \frac{1}{\nu^2} \qquad (1)$$

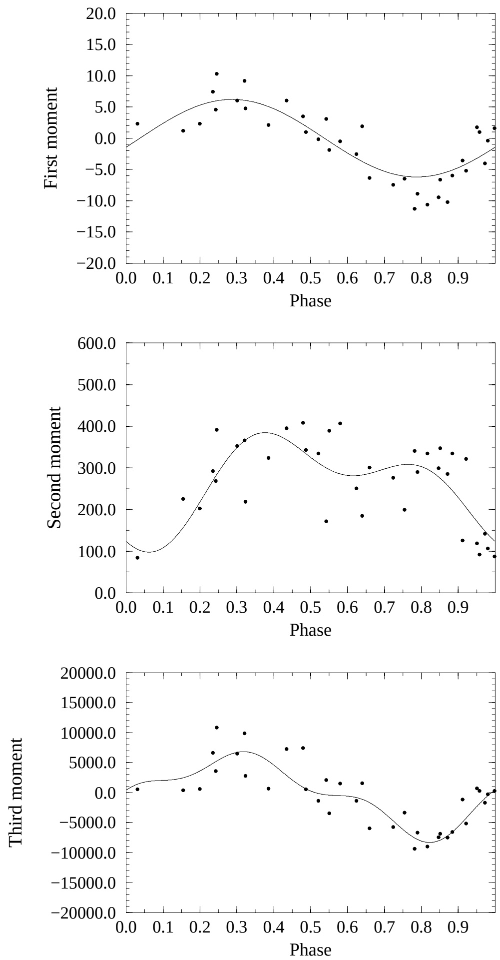

Fig. 3. For the line SiII 6371 Å: the *upper panel* shows the first moment $\langle v^1 \rangle$, the *middle panel* shows the second moment $\langle v^2 \rangle$ and the *lower panel* shows the third moment $\langle v^3 \rangle$. The smooth curves are least squares fits.

In these equations, M stands for the mass, R for the radius, ω for the angular frequency and ν for the frequency (expressed in c/d) of the star. For the values of M and R computed above and for ν_1 = 0.4612 c/d one finds $K_1 \approx 24$.

4. Mode identification

Our aim is to identify the dominant mode (l_1, m_1) with frequency ν_1 = 0.4612 c/d. To do so we used the moment method as outlined by Aerts (1996) and references therein. The mode identification is obtained by a discriminant which is a function of the observed and the theoretically calculated amplitudes of the first three moments $\langle v^1 \rangle$, $\langle v^2 \rangle$, and $\langle v^3 \rangle$ of the line profiles. Theoretically $\langle v^1 \rangle$ can be represented with one term varying with ν_1, $\langle v^2 \rangle$ with a constant term plus two terms varying respectively with ν_1 and $2\nu_1$, and $\langle v^3 \rangle$ with three terms varying respectively with ν_1, $2\nu_1$, and $3\nu_1$. We computed the moments of the observed line profiles and fitted them with a sum of varying terms as described above, for the SiII 6371 Å line and the SiII 6347 Å line. The fits for the SiII 6371 Å line are shown in Fig. 3. The SiII 6347 Å line gives very similar results. The fit to

Table 1. The different minima γ_l^m of the discriminant for the SiII lines. The "best solution" for l and m is defined as the one for which γ_l^m attains its lowest value. s_f expresses the minimal uncertainty on the values of γ_l^m. The meaning of the other symbols is as follows: v_p is the amplitude of the radial part of the pulsational velocity expressed in km/s, i is the inclination angle, v_Ω is the projected rotational velocity, expressed in km/s and σ denotes the standard deviation, also expressed in km/s, of the gaussian assumed intrinsic profile.

SiII 6371 Å – s_f = 0.14

γ_l^m	l	$\|m\|$	v_p	i	v_Ω	σ
0.85	1	1	1.8	16°	5.9	1.6
1.19	2	2	1.0	36°	5.0	2.0
1.56	0	0	12.6	5°	21.8	10.5
1.57	2	1	1.0	83°	5.4	2.1
1.66	1	0	1.9	83°	5.0	2.1

SiII 6347 Å – s_f = 0.16

γ_l^m	l	$\|m\|$	v_p	i	v_Ω	σ
0.92	1	1	2.1	12°	5.1	2.0
1.01	2	1	1.1	85°	5.0	2.0
1.10	2	2	1.2	30°	5.0	2.0
1.47	2	0	1.0	47°	5.0	2.0
1.59	3	0	0.5	28°	5.2	2.1

the first, the second, and the third moment explain respectively 78%, 54%, and 76% of the variance. These values are rather good and justify our use of a monoperiodic model. Even though the fit to the second moment is not very accurate, it is clear that the double-wave component is smaller than the sinusoidal component. This implies that the pulsation is non-axisymmetric. The best identifications with the discriminant (using a K-value as derived in the previous section) for both the SiII lines are summarized in Table 1. For the degree l we searched in the grid (0,1,2,3) but $l = 3$ modes never show up as one of the more probable possibilities. The results suggest that the mode is one of the following: $(l_1, |m_1|)$ = (1,1), (2,2) or (2,1). Note that our results do not imply that the inclination angle i must be larger than 45° as is stated by Smith & McCall (1978).

5. The Hipparcos photometric data

The satellite Hipparcos made 110 useful measurements of 53 Persei spread over a little more than 3 years. We performed a frequency analysis on this data set with the same tools as for the spectroscopic data. The frequency ν_1 = 0.4613 c/d is the frequency that explains the largest fraction of the variance (about 59%) and appears as the first frequency in the Θ-statistics of PDM. A phase diagram with this frequency is shown in Fig. 4. The frequency 0.4274 c/d reduces the same fraction of variance but one can show that this is an alias of ν_1. The disappearance of this frequency after prewhitening with ν_1 confirms this.

We prewhitened our data with ν_1 and searched for a second frequency. The frequency 0.5939 c/d shows up, and is able to explain about 36% of the variance in the residuals. There are frequencies that explain a larger fraction of the variance e.g. 0.7578 c/d. Several of them can be linked with 0.5939 c/d (through the window function). Moreover the frequency 0.5939 c/d shows up in a recent extensive photometric data set (Dukes, private communication) as second frequency. We therefore adopt 0.5939 c/d as the second frequency ν_2. Together with ν_1, ν_2 reduces about 77% of the variance in the original data.

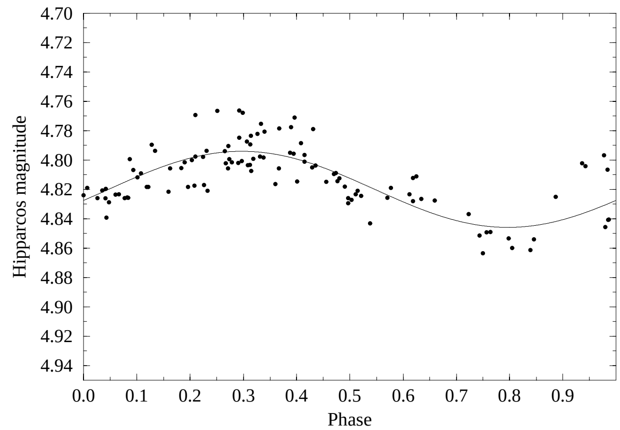

Fig. 4. A phase diagram of the Hipparcos photometric data with ν_1 = 0.4613 c/d.

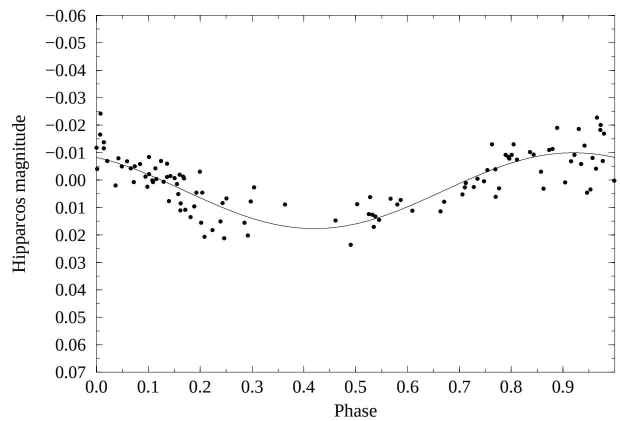

Fig. 5. A phase diagram of the Hipparcos photometric data with ν_3 = 0.4712 c/d after prewhitening with ν_1 and ν_2.

We prewhitened with ν_2 and searched again for other frequencies. This time the frequency 0.4712 c/d explains about 64% of the variance in the residuals leaving other candidate frequencies far behind. We adopt this frequency as a third frequency ν_3. A phase diagram with this frequency after prewhitening with ν_1 and ν_2 is shown in Fig. 5. Together with ν_1 and ν_2, ν_3 explains 93% of the variance in the original data.

The frequency ν_3 explains about 35% of the variance in the residuals after prewhitening with ν_1, about the same fraction as ν_2. Prewhitening the original data with ν_1 and ν_3 and searching for another frequency, gives clearly ν_2 as result, indicating that 0.5939 c/d is indeed a real second frequency. A phase diagram with this frequency after prewhitening with ν_1 and ν_3 is shown

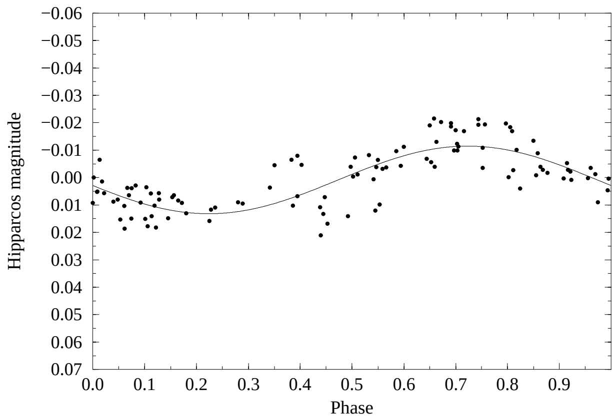

Fig. 6. A phase diagram of the Hipparcos photometric data with ν_2 = 0.5939 c/d after prewhitening with ν_1 and ν_3.

in Fig. 6. The Hipparcos photometric data set gives a clear confirmation of the third frequency found by Mills & Dukes (1994). For the first time for 53 Persei, the same third frequency is found by two different groups in two different data sets.

Further prewhitening with ν_3 left the variance of the residuals comparable with the mean error on the magnitude so that we could not convincingly find additional frequencies.

6. Conclusions

From our spectroscopic observations of 53 Per we could show the presence of the frequency 0.461 c/d. This frequency is found by several authors as the main one since the seventies, indicating that it is a stable frequency that dominates the pulsation over a long time-scale. From the Hipparcos photometry we could find a second frequency 0.594 c/d and a third frequency 0.471 c/d. This third frequency was first found by Mills & Dukes (1994). Our results confirm the presence of this third frequency for 53 Per.

From the mode analysis we conclude that the dominant mode is not a zonal mode, and that the degree l_1 is 1 or 2. Computing the physical parameters of 53 Persei puts the star in the middle of the theoretical SPB instability strip.

With its peak-to-peak amplitude of about 15 km/s, 53 Per is one of the SPBs of which the modes can be found from an extensive data set of line profiles. However, the complete frequency spectrum of the star first needs to be determined before an unambiguous mode identification of the different modes can be achieved. From all the data sets available for 53 Per so far, it is not yet possible to derive a definite set of frequencies. This shows that a systematic long-term follow-up program dedicated to 53 Per and to SPBs in general, is the only way to apply asteroseismology to multiperiodic g-mode pulsators. For some southern SPBs such a study is ongoing (Aerts 1998a).

Acknowledgements. We would like to thank Dr. Robert J. Dukes for putting some of his results on 53 Per at our disposal prior to publication. This research has made use of the SIMBAD astronomical database operated at the CDS in Strasbourg, France.

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