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Asteroseismology of the β Cephei star ν Eridani – II. Spectroscopic observations and pulsational frequency analysis

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ABSTRACT

We undertook a multisite spectroscopic campaign for the β Cephei star ν Eridani. A total of 2294 high-resolution spectra were obtained from telescopes at 11 different observatories around the world. The time base of dedicated multisite observations is 88 d. To this data set we have added 148 older, previously unpublished spectra, such that the overall time-span of the 2442 spectra is 430 d. The analysis of the radial velocity variations derived from the Si III triplet centred on 4560 Å leads to 19 significant frequencies, of which seven correspond to independent pulsation frequencies. Five of these are members of multiplets with an average spacing of 0.018 ± 0.002 cd^{-1}. Our spectroscopic results agree well with those derived from a simultaneous multisite photometric campaign of the star, albeit that we do not recover their low frequency at 0.43218 cd^{-1}. We find three different candidate frequencies below 1 cd^{-1} instead. We also find that the radial velocity amplitude of the main mode has increased by some 30 per cent over the last 15 years, which is consistent with the photometry data. We derive a relative equivalent width variation of 6.5 per cent, which is completely dominated by the main radial mode. The phase difference between the radial velocity and light variations for the main frequency is $97\overset{\circ}{.}9 \pm 1\overset{\circ}{.}8$, which is clearly deviant from the adiabatic value and confirms the radial nature of the dominant mode. The spectral line broadening leads to an upper limit of 20 km s^{-1} for $v \sin i$, which is consistent with the long rotation period derived from the frequency splittings.

Key words: techniques: spectroscopic – stars: early-type – stars: individual: ν Eridani – stars: oscillations – stars: variables: other.

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1 INTRODUCTION

The research domain of asteroseismology has received a strong impetus since its successful application to the Sun (helioseismology), to several white dwarfs (for recent applications, see Vauclair et al. 2002; Handler, Metcalfe & Wood 2002) and also to solar-like stars (for a review, see Bedding & Kjeldsen 2003). So far, seismic studies have concentrated mainly on such stars because they have very rich frequency spectra consisting of short-period oscillations. However, stellar evolution codes are most uncertain for stars with large convective cores. A successful application of asteroseismology to these objects would lead to a large step towards our understanding of their evolution.

Most efforts to achieve high-precision seismology for stars more massive than the Sun with convective cores were concentrated on δ Scuti stars and relied on frequencies derived from photometric multisite campaigns (see Breger et al. 2002, for a recent example). The lack of unique mode identifications, however, hampered the detailed derivation of the internal structure of such stars.

Stars of spectral type B have even larger convective cores and longer oscillation periods than δ Scuti stars. However, their internal structure is relatively simple, as they do not possess an outer convective zone. Their oscillations are driven by the κ mechanism acting in the metal opacity bump situated around 200 000 K (Dziembowski & Pamyatnykh 1993; Gautschy & Saio 1993). Efforts to perform seismic studies of the B0–2 main-sequence β Cephei stars started in 1996 (Dziembowski & Jerzykiewicz 1996) for the star 16 (EN) Lac and, a few years later, for 12 (DD) Lac (Dziembowski & Jerzykiewicz 1999). Again, unknown mode identification of some of the non-radial modes limited the detailed modelling. New seismic analyses have been performed very recently by Handler et al. (2003) for the three stars IL Vel, V433 Car and KZ Mus and by Thoul et al. (2003) for 16 (EN) Lac. The most in-depth study so far was presented by Aerts et al. (2003b) for the star HD 129929, in which evidence for moderate overshooting with a parameter $\alpha_{\rm ov} = 0.1$ and non-rigid rotation could be derived from six detected and well-identified oscillation modes, among which are components of frequency multiplets. The latter is the first study for which the standard structure models cannot explain the well-identified frequency values unless overshooting occurs.

A major drawback for additional seismic applications on β Cephei stars is the lack of agreement between photometric and spectroscopic mode identifications. The latter have been performed for many bright β Cephei stars (Aerts & De Cat 2003) but 16 (EN) Lac is one of the few multiperiodic objects for which both photometry and spectroscopy point towards the same mode identification for the detected non-radial modes (Aerts et al. 2003c). In an effort to improve this situation, and with the goal to perform the most in-depth seismic application on a β Cephei star, Handler & Aerts (2002) set up a large spectroscopic and photometric multisite campaign for the star ν Eridani (HD 29248, V mag 3.92, spectral type B2 III). This campaign took place between 2002 October and 2003 January. The first results, based only on the photometric data, together with the history of the target and our selection criteria are presented in Handler et al. (2004, hereafter Paper I). In the following, we report on results based on the radial velocities obtained from our spectroscopic data. The pulsational mode identification and seismic modelling of the identified oscillations will be the subject of future papers.

This paper is organized as follows. In Section 2 we begin with a description of our data and the reduction process. We then discuss our calculation of the time series of radial velocities of ν Eridani in Section 3. Section 4 is devoted to the detailed frequency analysis, and we end with discussions and future work in Section 5.

2 OBSERVATIONS AND DATA REDUCTION

The spectroscopic observations were carried out with 11 different telescopes at observatories on five continents; they are summarized in Table 1. In all but two of the cases, the instrument was an echelle spectrograph.

Table 1. Log of the spectroscopic measurements of ν Eridani. The Julian Dates are given in days, with respect to 245 2000. N denotes the number of spectra, ΔT is the time-span expressed in days, $\Delta\lambda$ is the wavelength step expressed in m Å resulting from the resolving power of the instrument at the position of the Si III triplet and S/N denotes the average signal-to-noise ratio measured at the continuum between 4550 and 4551 Å (see Fig. 1). A '$\star$' denotes a linear array instead of an echelle spectrograph. The Mount John observations do not contain the Si III triplet, thus they were not included in the radial velocity analysis of the current paper; they will be used in future analyses.

Observatory	Longitude	Latitude	Telescope	Julian Date		Data amount and quality				Observer(s)
				Begin	End	ΔT	N	$\Delta\lambda$	S/N	
Mt. Stromlo Observatory, Australia	+149° 04′	−35° 19′	1.9-m	608	611	3.1	68			DJ
				623	628	5.0	79	51	210	DJ
South African Astronomical Observatory	+20° 49′	−32° 22′	1.9-m	598	604	6.3	132			ERC, GH
				626	632	6.2	168	69	120	LAB
Pico dos Dias Observatory, Brazil*	−45° 35′	−22° 32′	1.6-m	551	562	11.1	71	61	800	AB
Haute Provence Observatory, France*	+5° 43′	+43° 46′	1.52-m	590	616	26.1[a]	112	23	450	PM
Tautenburg Observatory, Germany	+11° 42′	+50° 59′	2.0-m	600	628	28.1[b]	73	28	370	HL
La Palma Observatory, Spain	−17° 53′	+28° 45′	2.6-m NOT	588	601	13.2	70	19	640	II, JHT, KU
Apache Point Observatory, USA	−105° 49′	+32° 47′	3.5-m	595	598	2.3	201	76	430	JK
Calar Alto Observatory, Spain	+2° 33′	+37° 13′	2.2-m	654	663	9.0	82	20	440	SD, IT, AH
McDonald Observatory, USA	−104° 01′	+30° 40′	2.1-m	599	606	7.3	318			UH
				654	663	9.2	488	43	480	PDC
La Silla Observatory, Chile	−70° 44′	−29° 15′	1.2-m Euler	227	240	13.1	148			TM, KU
				569	582	13.2	181			TM
				624	638	14.3	251	18	360	MATG
Mt. John Univ. Obs., New Zealand	+170° 28′	−43° 59′	1.0-m	627	629	2.1	19	–	–	PLC, JB, DJW
Total						429.9	2442			

[a]36 spectra taken on JD 245 2590 and the additional 76 spectra between JD 245 2612 and 245 2616.
[b]Six spectra taken on JD 245 2600, 30 on JD 245 2621 and 37 on JD 245 2628.

Table 2. Multifrequency solution for the radial velocities derived from our time-resolved spectroscopy of ν Eridani. Formal error estimates for the independent frequencies range from 8×10^{-6} cd^{-1} for f_1 to ± 0.00014 cd^{-1} for f_{10}.

Number	Identification	Freq. (cd^{-1})	Ampl. (km s^{-1})	S/N
1	f_1	5.763298	20.20 ± 0.07	152.9
2	f_2	5.654014	7.69 ± 0.10	57.8
3	f_3	5.620097	6.87 ± 0.10	51.7
4	f_4	5.637432	6.92 ± 0.09	52.0
5	$f_1 + f_2$	11.417312	2.36 ± 0.08	29.2
6	$f_1 + f_3$	11.383395	2.02 ± 0.09	25.0
7	$f_1 + f_4$	11.400730	1.87 ± 0.07	23.1
8	$f_1 + f_2 + f_3$	17.037409	1.26 ± 0.08	18.7
9	f_9	6.242458	0.78 ± 0.08	6.0
10	f_{10}	7.898225	0.78 ± 0.08	6.8
11	$2f_1 + f_2 + f_3$	22.800707	0.70 ± 0.07	11.7
12	$2f_1 + f_3$	17.146693	0.65 ± 0.09	9.7
13	f_{13}	6.221429	0.62 ± 0.09	4.8
14	$2f_1 + f_2$	17.180610	0.73 ± 0.10	10.9
15	$2f_1 + f_4$	17.163392	0.52 ± 0.07	7.8
16	$f_1 + f_{10}$	13.661523	0.39 ± 0.08	5.3
17	$3f_1$	17.289894	0.37 ± 0.08	5.5
18	$3f_4$	16.912296	0.32 ± 0.07	4.7
19	$1 + f_2 + f_3$	12.274111	0.30 ± 0.08	3.8

The integration times were typically ∼10 min, depending on the instrument and on the atmospheric conditions. This leads to a temporal resolution of <5 per cent for the main four intrinsic modes of ν Eridani (for their frequency values we refer to Table 2).

All raw data were subjected to the usual reduction process, which consists of de-biasing, flat-fielding, background subtraction and wavelength calibration by means of a Th/Ar and/or a quartz lamp. The spectra were shifted to the heliocentre, and the Heliocentric Julian Dates of mid-exposure were calculated.

Subsequently, the Si III triplet centred on 4552.622, 4567.840 and 4574.757 Å was considered. It is well known that these triplet lines in the spectrum of B0–2 main-sequence stars are the best for a study of the pulsational behaviour of such stars because they are not affected very much by blending, they are strong lines and they are so close to the top of the star's energy distribution that they are almost insensitive to temperature variations (De Ridder et al. 2002). (Re)Normalization of the continuum flux near this Si triplet was carried out in a homogeneous way by calculating the best-fitting cubic spline function through the continuum near these wavelengths and then dividing the local spectrum by this spline.

We superimpose in Fig. 1 the average profile of the Si III λ4553 Å line of ν Eridani from each observatory (note that the Mount John data are not included in this paper, as they do not contain the Si triplet). It is important to note that these averages are in good agreement with each other as far as the central position of the line is concerned, the small differences in depth being mainly due to the partial coverage of the beating of the numerous modes (for a list, see Paper I or Table 2 in this paper). The averages from two observatories appear to deviate from the others: the Pico dos Dias (upper curve) and Tautenburg (lower curve) averages. However, the data sets from both instruments contain profiles which are fully consistent with corresponding ones from the other instruments. This proves that different beating patterns and/or the limited time spread (as also indicated in the footnote of Table 1) are responsible for the deviant average profiles, and not the instrumental and/or signal-to-noise ratio (S/N) effects.

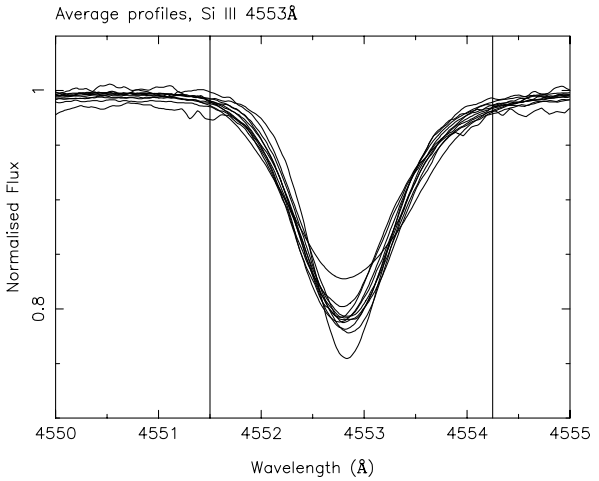

Figure 1. The average profile of the Si III λ4553 Å line of ν Eridani plotted for each of the observatories separately.

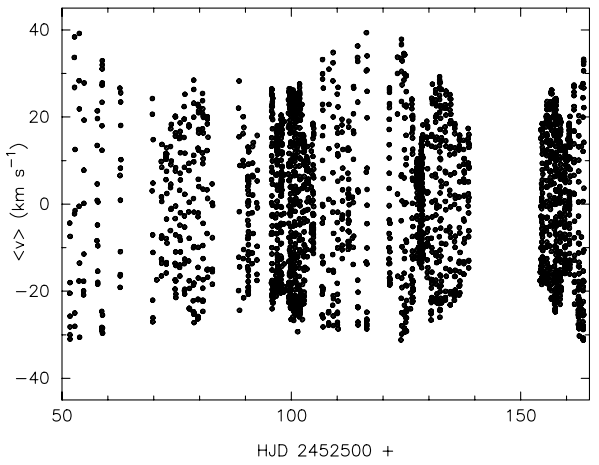

Figure 2. The time series of the average Si III radial velocities of ν Eridani derived from each spectrum taken during the dedicated multisite campaign.

The absence of large wavelength shifts in the central position of the average profiles allows us to exclude the possibility of ν Eridani being a spectroscopic binary with a period that would be relevant for the study of its intrinsic line-profile behaviour.

3 RADIAL VELOCITY AND EQUIVALENT WIDTH DETERMINATION

The radial velocities of ν Eridani we present in this paper correspond to the centroids of the Si III triplet lines. These centroids are calculated using the following equation

$$\mathrm{Vrad} = \frac{\sum_{i=1}^{N}(1 - I_i)(x_i - x_0)\triangle x_i}{\sum_{i=1}^{N}(1 - I_i)\triangle x_i}, \quad (1)$$

where I_i is the normalized flux value measured at wavelength pixel λ_i and $\triangle x_i \equiv x_i - x_{i-1}$ where x_i is the velocity corresponding to λ_i with respect to the laboratory wavelength λ_0. We made two different choices for the determination of the wavelength range $[x_1, x_N]$ in equation (1), which led to three different ways of determining Vrad:

(i) summation over a carefully chosen, constant region in wavelength (see, for example, the vertical lines indicated in Fig. 1);

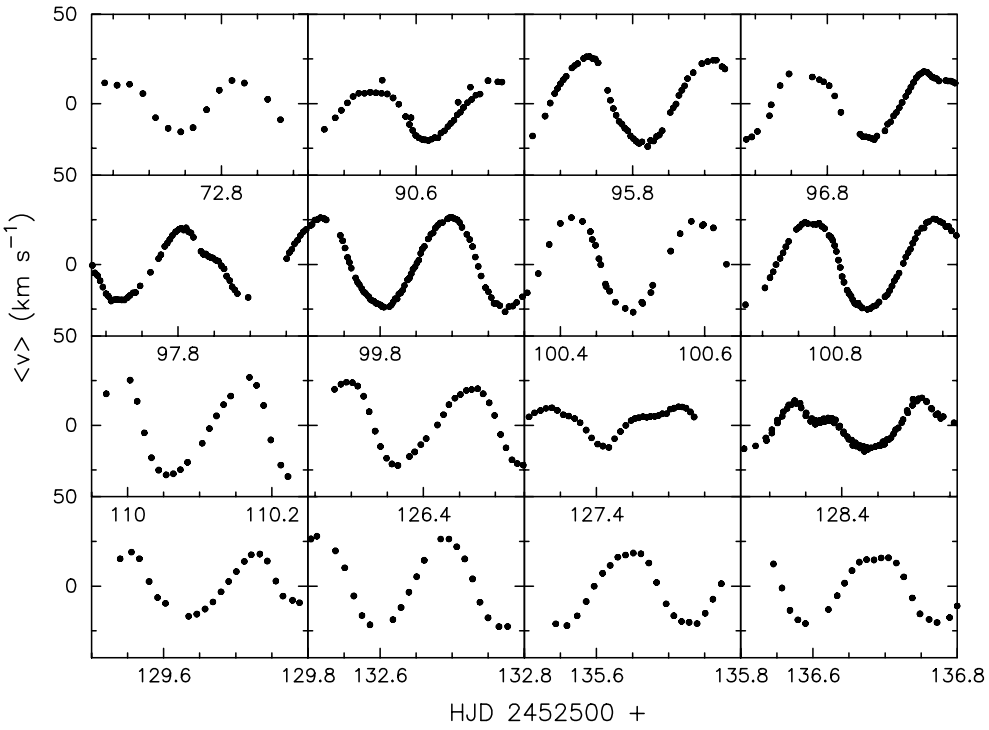

Figure 3. Radial velocities of ν Eridani during some selected nights of the dedicated multisite campaign.

(ii) summation over a dynamical region in wavelength, which typically extends over a few angstrom and which is adopted for each profile separately;

(iii) same as in (ii), but after a local renormalization of the continuum.

For each of these methods we then determined the average radial velocity per observatory for each of the three Si III lines. These averages range from 16.1 to 19.5 km s^{-1} for the bluest Si III line, with similar averages being found for the two redder lines. As was the case with the average line profiles, the difference in average radial velocities from the different observatories is again introduced by the different coverages of the overall beat pattern. We then duplicated our data sets and proceeded with our analysis by applying to one of the duplicates a correction for the small differences in radial velocity. This correction involved shifting the radial velocities to average zero per observatory, i.e. by determining the normalized first moment, $\langle v \rangle$ (for a definition, see Aerts, De Pauw & Waelkens 1992) for each of the Si III lines per spectrum per method.

For each spectrum we then calculated an average radial velocity from the three separate Si III lines, for each of the indicated methods. We show in Fig. 2 the time series of the first normalized moment variations computed with method (i) for the average of the three Si III lines, for the dedicated multisite campaign. The nightly variations for some selected nights are displayed in Fig. 3. A beating phenomenon resulting from multiperiodicity is clearly visible and the radial velocity amplitude is large, of the order of 20 km s^{-1}, in agreement with previous studies (e.g. Aerts, Waelkens & De Pauw 1994a). The error bars denoting the standard deviation resulting from this procedure are not indicated in Figs 2 and 3 for clarity, but they are plotted in Fig. 4, which we discuss further on. In what follows we present the results for this particular data set of normalized first moments, of which we have used only those radial velocity measurements with a standard error below 3 km s^{-1}. To this data set we have added the older, previously unpublished CORALIE data (see Table 1) using the same quality criterion. This new data set now contains 2367 data points[1] with an average standard deviation of 0.9 km s^{-1}. Our adopted quality criterion therefore implies a reduction of only 3 per cent of the data set size. We stress, however, that all the accepted frequencies (see Table 2) were also obtained with the complete data set of 2442 data points, regardless of the method used for the radial velocity calculation or whether we apply the correction to obtain $\langle v \rangle$.

We have also determined the equivalent width (EW), calculated as the denominator in equation (1), of each of the three lines of the Si III triplet, using the same three methods as outlined above as far as integration over the profile is concerned. It is well known that the EW variations of β Cephei stars are small, typically of the order of a few per cent (De Cat 2002). However, ν Eridani is one of the exceptions, because of its dominant radial large-amplitude mode (Aerts et al. 1994a; De Ridder et al. 2002). We display in Fig. 4 the phase diagrams for the main frequency of 5.763298 cd^{-1} of the EW for the bluest Si III line, as well as for the radial velocity and for the magnitude of the Strömgren y filter data presented in Paper I. The relative amplitude of the EW variation is 6.5 per cent. The EW variations are completely dominated by the radial mode (see the following section). It is therefore only useful to compare the phase behaviour of the EW, $\langle v \rangle$ and Strömgren y for this frequency. We find the following phase differences: $\phi_{\langle v \rangle} - \phi_y = 0.272 \pm 0.005$ and $\phi_{\rm EW} - \phi_y = 0.044 \pm 0.008$, expressed in radians. The $\phi_{\langle v \rangle} - \phi_y$ value implies a clear deviation from the adiabatic value of 0.25, while the antiphase behaviour between the EW and the photometric light curve agrees with the effective temperature of ν Eridani (De Ridder et al. 2002).

[1] This data set is available upon request from the first author.

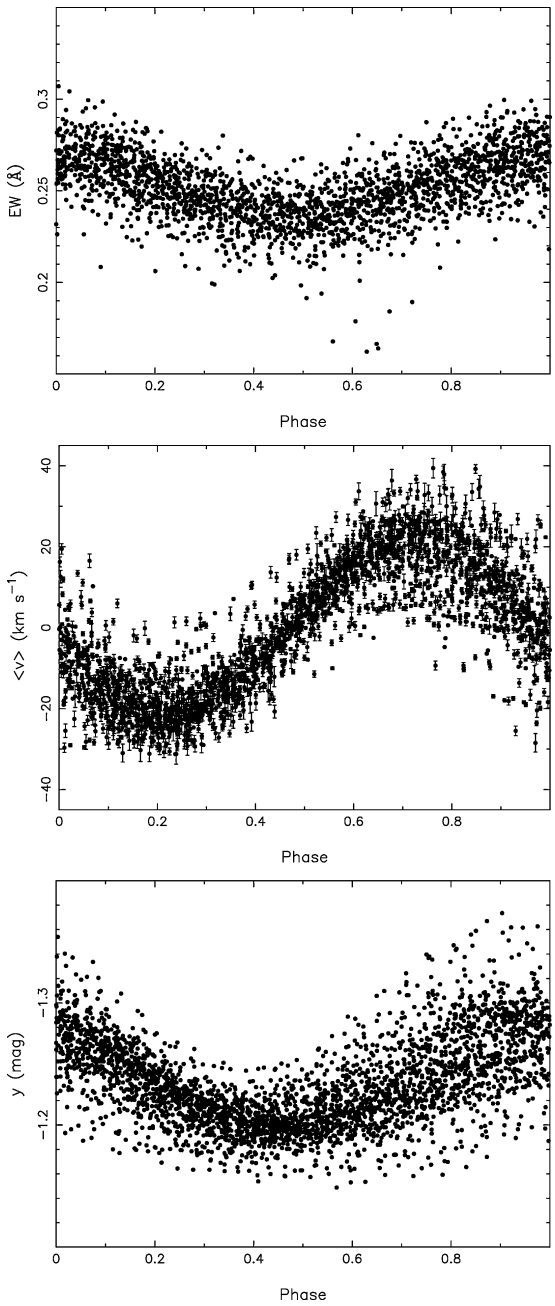

Figure 4. Phase diagram according to f_1 of the equivalent width of the Si III λ4553 Å line (top), of the radial velocity (including standard errors derived from averaging over the three Si lines of the triplet, middle) and of the Strömgren *y* data taken from Paper I (bottom). The reference epoch was each time taken to be HJD 245 2500.

4 FREQUENCY ANALYSIS

We have followed the same procedure outlined in Paper I in order to derive the intrinsic frequencies of ν Eridani from its radial velocity variations. We used PERIOD 98 (Sperl 1998) as well as unpublished software to do so. The results are graphically depicted in Fig. 5, while the frequency values and their amplitudes are listed in Table 2. The uppermost panel of Fig. 5 represents the spectral window, calculated in the same way as that presented in Paper I. A comparison with fig. 2 of Paper I shows that the spectroscopic data suffer slightly more from aliasing than the photometric data. However, the time base of the spectroscopy is longer, thus the accuracy for the frequency determination should, in principle, be higher.

The main frequency $f_1 = 5.6733$ cd^{-1} found in the photometry is even more dominant in the radial velocity variations. It has an amplitude of ∼20 km s^{-1}, corresponding to a S/N ratio of 153. The noise level was determined in the same way as in Paper I, i.e. it is the average amplitude (as determined by an integration over the periodogram) in a 5-cd^{-1} interval centred on the considered frequency, after pre-whitening by all significant peaks.

We pre-whitened the data with a synthetic sinusoidal curve with the frequency, amplitude and phase that led to the smallest residual variations. We then proceeded with a search for additional frequencies, in the same way as in Paper I, i.e. by optimizing each time the frequency values through a non-linear regression analysis with the frequencies as free parameters, using as a starting value the frequency found from the periodograms. We then found the same results as in photometry, i.e. three further independent frequencies f_2, f_3, f_4 and the combination frequencies $f_1+f_2, f_1+f_3, f_1+f_4$, $f_1+f_2+f_3$. We did not optimize the combination frequencies, but fixed them to the values resulting from the optimized intrinsic frequencies $f_1, \ldots, f_4$ (just as in Paper I). After pre-whitening with these eight mentioned frequencies, the amplitude at low frequencies becomes noticeable (see Fig. 5). We neglect this for the time being and concentrate on the higher frequencies. We clearly recover the two frequencies f_9 and f_{10} of the newly discovered modes we reported in Paper I. After further pre-whitening with these two modes and two more combination frequencies, we detect f_{13}, which is the lowest frequency component in the residuals of an apparent triplet around f_9. The photometric data (Paper I) clearly favour the right peak of this triplet because of less aliasing, but leave our f_{13} as an additional suspected frequency. As f_{13} has higher amplitude in our data, we then pre-whitened with that frequency. Besides f_{13}, we find six additional combination frequencies. All the 19 frequencies listed in Table 2 are significant with respect to the usual four S/N ratio criteria (3.5 for combination frequencies – see Breger et al. 1999).

After pre-whitening with the 19 frequencies given in Table 2, we turn to the study of the power at low frequency. This results in three candidate frequencies, f_{20}, f_{21}, f_{22}, with S/N above 3 (where the noise level is calculated from the same periodogram as for the accepted frequencies, i.e. after pre-whitening with the 19 frequencies listed in Table 2). They are listed in Table 3. None of these corresponds to the frequency $f_A = 0.432$ cd^{-1} found in Paper I.

The frequencies f_{20} and f_{21} do not reach the necessary amplitude to be accepted, given our adopted noise criterion. A natural question is whether any of the frequencies in the [0, 1] cd^{-1} range are due to the addition of the data sets from the different instruments. The frequencies f_{20} and f_{21} are also found independently in the CORALIE spectra (by far the most stable spectrograph among those used) after pre-whitening with $f_1, \ldots, f_{19}$, even if we consider only the ∼70-d time string. This suggests that f_{20} and f_{21} are probably real. However, the McDonald data, which have a time base of 64 d, do not reveal either f_{20} or f_{21} after pre-whitening with $f_1, \ldots, f_{19}$. Furthermore, these low frequencies are not found in the photometry (Paper I), thus we therefore caution against over-interpreting f_{20} and f_{21}. We do point out that the number 22 frequency of 0.01909 cd^{-1}, which is formally significant (see Fig. 6), corresponds to a period of 50.4 d, which might be the surface rotation period of the star. This frequency, however, is not present in any of the separate data sets after pre-whitening with $f_1, \ldots, f_{19}$. Future detailed seismic modelling should be able to shed light on this.

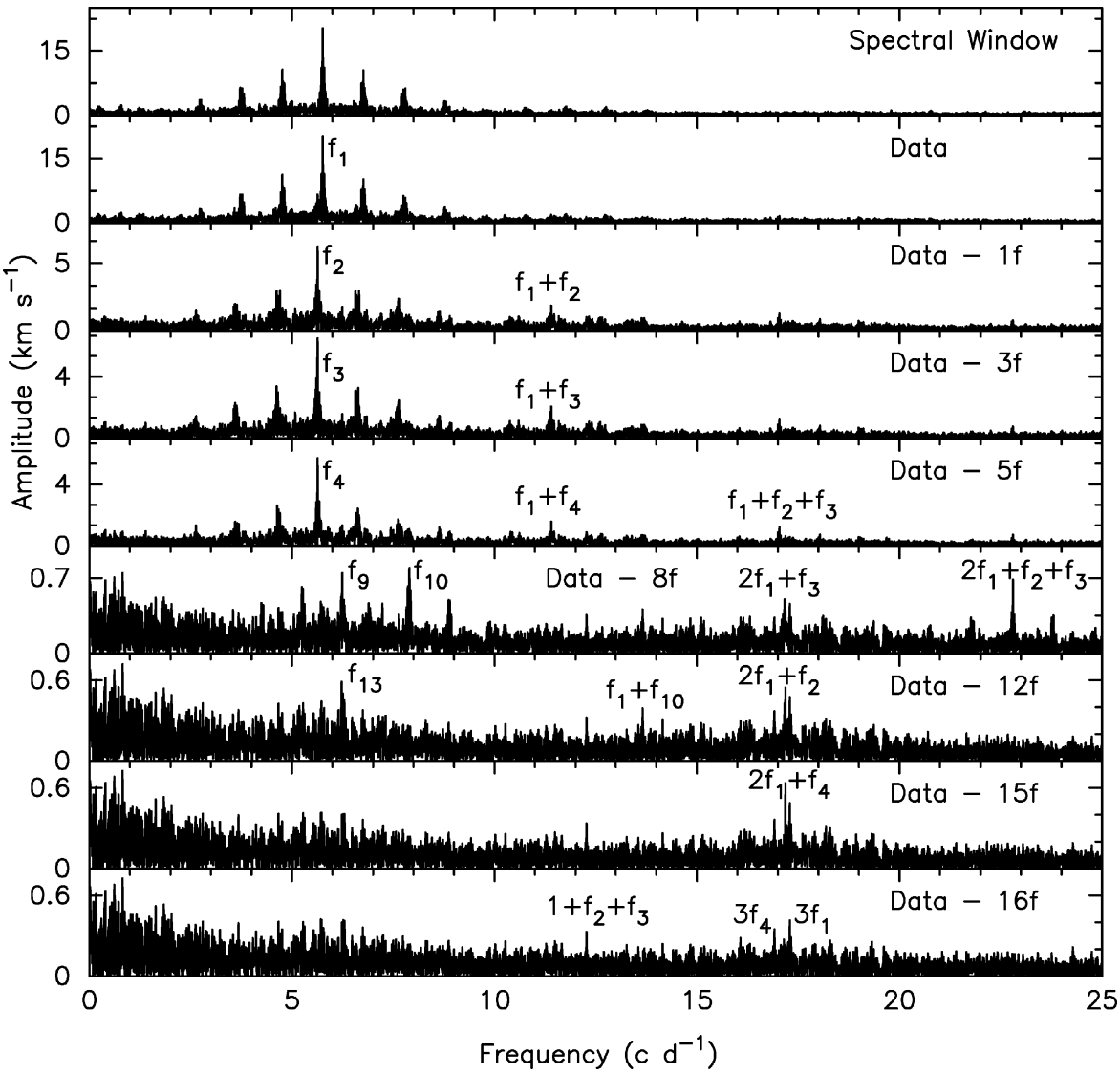

Figure 5. Amplitude spectra of ν Eridani computed from the radial velocities. The uppermost panel shows the spectral window of the data. All subsequent panels show the periodograms after different stages of pre-whitening (note the different scale). We refer to the text for details.

Table 3. Results from a multifrequency fit after subtraction of all frequencies listed in Table 2 for candidate additional frequencies. These are to be regarded as uncertain for the moment.

Number	Identification	Freq. (cd^{-1})	Ampl. ($km\ s^{-1}$)	S/N
20	f_{20}	0.82443	0.74 ± 0.07	3.5
21	f_{21}	0.61384	0.73 ± 0.07	3.4
22	f_{22}	0.01909	0.90 ± 0.08	4.1

After pre-whitening with f_{20}, f_{21}, f_{22} we find a peak at 1.069 cd^{-1} with an amplitude corresponding to 2.7 S/N. From here on, all of the additional candidate frequencies have amplitudes below 3 S/N. We show in Fig. 6 the periodogram between 0 and 2 cd^{-1} after pre-whitening with all the frequencies listed in Table 2. The three frequencies listed in Table 3 are indicated in this figure, as is the noise level.

The final amplitude spectrum is shown in Fig. 7. This should be compared with that shown in fig. 4 of Paper I.

We next discuss the amplitude increase of 25 per cent of the modes in the photometric data over the past 40 years reported in Paper I. We

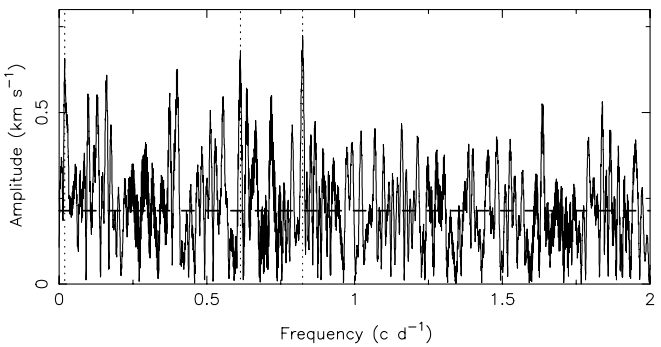

Figure 6. Amplitude spectrum of ν Eridani computed from residual radial velocities after pre-whitening with the 19 frequencies listed in Table 2. The dotted lines indicate the frequencies f_{19}, f_{20} and f_{21} given in Table 3. The dashed horizontal line indicates the noise level as defined in the text. We refer to the text for further details.

have reconsidered the 74 spectra published in Aerts et al. (1994a), obtained between 1987 November 6–14 with the European Southern Observatory (ESO) Coudé Auxiliary Telescope (CAT). As already emphasized by Aerts et al. (1994a) this time base is insufficient to

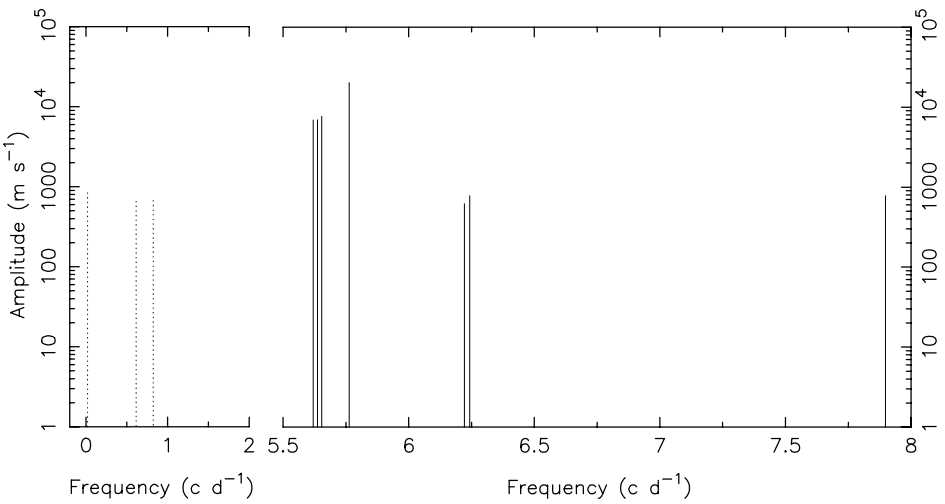

Figure 7. Final amplitude spectrum of the intrinsic frequencies derived from the radial velocities. The unambiguous intrinsic frequencies listed in Table 2 are indicated by a full line while the uncertain frequencies given in Table 3 are represented by the dotted lines. We stress that the *x*-axis is interrupted and has a different scale for both panels. Moreover, the *y*-axis is logarithmic and we have expressed the amplitudes in m s^{-1} in order to suppress the dominance of the main mode in the graph.

resolve the triplet f_2, f_3, f_4 and only f_1 and f_2 were found from a frequency analysis. We have fitted the first normalized moment of these older data by fixing f_1, f_2 as in Table 2 and we find the amplitudes $A_1 = (15.7 \pm 0.7)$ km s^{-1} and $A_2 = (9.1 \pm 0.8)$ km s^{-1}. Imposing f_1 an f_2 to the radial velocities from the CORALIE data taken in 2001 (see Table 1) leads to $A_1 = (19.6 \pm 0.5)$ km s^{-1} and $A_2 = (7.3 \pm 0.6)$ km s^{-1}, which agree with the current amplitudes listed in Table 2 within the errors. We therefore conclude that the main mode of ν Eridani has increased its radial velocity amplitude by 29 per cent between 1987 and 2001. This is consistent with the 25 per cent increase in the photometric amplitude of that mode found in Paper I. However, we find that the mode with f_2 has *decreased* its amplitude by 18 per cent, while an increase is reported in Paper I. Hence, the radial velocity data derived from modern high-resolution spectra suggest that the mode with frequency f_2 must have exchanged some of its energy with the main radial mode between 1987 and 2001, unless beating of the unresolved triplet components modified its measured amplitude.

Going further back in time, Kubiak (1980) performed frequency analyses on all radial velocity data available at that time, i.e. those gathered by Henroteau (1921, 1927), Struve et al. (1952) and Struve & Abhyankar (1955). He reported the amplitudes 19.3, 7.2, 8.0 and 6.3 km s^{-1} for f_1, f_2, f_3 and f_4 respectively, for the 455 data points with a time base of 457 d in 1923–1924 of Henroteau (1927). For the 345 data points gathered by Struve et al. (1952) and by Struve & Abhyankar (1955) in the years 1951–1954, Kubiak obtains 16.2, 11.3, 3.6 and 6.3 km s^{-1} for f_1, f_2, f_3 and f_4, respectively. Although Kubiak estimates the uncertainty of the amplitudes to be $\sim$2 km s^{-1}, it seems that the amplitudes of the four strongest modes change on a time-scale of decades. Furthermore, it appears that the triplet mode with frequency f_2 has higher amplitude whenever the main radial mode's amplitude has decreased, and vice versa.

5 DISCUSSION AND FUTURE PLANS

We have provided the most extensive data set of high-resolution spectroscopic data of a β Cephei star so far. The previous record holders were 12 (DD) Lac (Mathias et al. 1994), β Cephei (Aerts et al. 1994b), β Crucis (Aerts et al. 1998), 16 (EN) Lac (Lehmann et al. 2001) and 19 Mon (Balona et al. 2002). Between 500 and 1400 spectra were obtained for each of these five stars, but all from single-site campaigns, thus only a limited number of mode frequencies were detected from these older data. Moreover, some of the detected modes in these stars have uncertain mode identifications, and this remains a problem for a seismic application to 19 Mon (Balona et al. 2002), β Crucis (Briquet & Aerts 2003), 12 (DD) Lac (Dziembowski & Jerzykiewicz 1999) and β Cephei (Telting, Aerts & Mathias 1997; Shibahashi & Aerts 2000). Seismic analyses of 16 (EN) Lac were carried out by means of photometric mode identification by Dziembowski & Jerzykiewicz (1996) and recently by means of the addition of spectroscopic mode identification by Thoul et al. (2003).

Our current spectra of ν Eridani were gathered during a three-month multisite campaign involving 11 spectrographs, which is the first of its kind for this type of pulsating star. A total of 2442 spectra were obtained. We disentangled 19 frequencies from the radial velocity data, while three frequencies are reported as additional candidates.

From the observed splittings, we infer a long rotation period of 56 d in the case of rigid rotation and a zero Ledoux splitting constant. An estimate of the rotation velocity of ν Eridani can be derived from the narrowest profiles we have at our disposal. Indeed, when the profiles are narrowest, the effect of the pulsational broadening to the overall line broadening is minimal. Overall, the profiles are broadened by pulsation, rotation and thermal motions. For ν Eridani's temperature, the thermal broadening amounts to $\sim$8–10 km s^{-1}. The pulsational broadening is difficult to estimate without having solved the complete mode identification, including the derivation of the amplitude, of all the oscillation modes. However, it must be several km s^{-1} given that four high-amplitude modes are beating. The FWHM of the narrowest Si III profiles leads to a minimal overall broadening of $\sim 23 \pm 2$ km s^{-1}. This implies that 20 km s^{-1} is a strict upper limit for $v \sin i$. Abt, Levato & Grosso (2002) also list a $v \sin i$ of 20 km s^{-1}. If we interpret the splittings as due to rigid rotation and pure acoustic modes, and if we assume a stellar radius of $\sim$6 R$_\odot$, then we end up with an equatorial rotation velocity of $\sim$5 km s^{-1}, which is compatible with our spectroscopically determined upper limit for $v \sin i$. Note that this upper limit

for $v \sin i$ is a serious overestimate of the true equatorial rotation velocity resulting from the frequency splittings. This situation is completely analogous to the star HD 129929 (Aerts et al. 2003c) which is also a very slow rotator among the β Cephei stars. For ν Eridani we find a ratio between the intrinsic frequencies and the rotation frequency below 0.3 per cent assuming a zero Ledoux constant. This allows us to neglect rotational effects, such as the Coriolis force and the centrifugal forces, in future seismic modelling of the star.

The photometric frequency content of ν Eridani derived in Paper I consists of 23 accepted frequencies. Of those 23 frequencies, 17 are common to the 19 reported here from the radial velocities, given that our spectroscopic f_{13} may be either the left peak of the triplet, for which the right peak is found in Paper I, or the monthly alias of that right peak, and given that we find a 1-d alias of $f_2 + f_3$. The two other frequencies are harmonics of f_1 and f_4. A common set of 17 frequencies between multicolour photometry and high-resolution spectroscopy, among which are seven intrinsic frequencies, has never been obtained before for a β Cephei star. This constitutes a very promising starting point for mode identification and seismic modelling, the results of which will be presented in future papers. We point out that we will be searching for additional frequencies in several different line profile diagnostics, on which we will also report in the near future. This might reveal additional frequencies connected with higher-degree modes.

The biggest discrepant result from the photometric and radial velocity data sets is the absence of $f_{\rm A} = 0.43218$ cd^{-1} (Paper I) in the latter. It is noteworthy that a similar situation occurs for the β Cephei star EN (16) Lac, for which Jerzykiewicz (1993) reported the frequency 0.165 cd^{-1} (which is twice the orbital frequency) from photometry, while this frequency was not found in the much more extensive spectroscopic data (Lehmann et al. 2001). The star 19 Mon is the only β Cephei star so far for which a low frequency is consistently found in both photometric and spectroscopic data (0.17019 cd^{-1}; Balona et al. 2002). It is not clear for any of these three β Cephei stars what the physical interpretation of the low frequency is.

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