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CONFIRMATION OF SOLAR-LIKE OSCILLATIONS IN η BOOTIS

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ABSTRACT

We obtained time-series spectroscopy of the G0 subgiant η Boo in an attempt to confirm the solar-like oscillations reported by Kjeldsen and coworkers in 1995. We recorded 1843 spectra over six consecutive nights with the Nordic Optical Telescope, which we used to measure equivalent widths of strong temperature-sensitive lines. We also measured velocities from 1989 spectra obtained through an iodine reference cell at Lick Observatory over 56 nights that were badly affected by weather. Our analysis also included velocity measurements published by Brown and coworkers and the original Kjeldsen equivalent width measurements. All four data sets show power excesses consistent with oscillations, although with a range of amplitudes that presumably reflects the stochastic nature of the excitation. The highest peaks show regularity with a large separation of $\Delta\nu = 40.4\ \mu$Hz, and we identify 21 oscillation frequencies from the combined data.

Key words: stars: individual (η Bootis) — stars: oscillations — techniques: radial velocities

1. INTRODUCTION

The search for solar-like oscillations is finally yielding success. Observations of the subgiants Procyon (Martic et al. 1999; Barban et al. 1999) and β Hydri (Bedding et al. 2001; Carrier et al. 2001) have shown very good evidence of oscillations. More recently, there has been an unambiguous detection of *p*-mode oscillations in the main-sequence star α Cen A by Bouchy & Carrier (2001, 2002). All these results were based on velocity measurements obtained using high-dispersion spectrographs with stable reference sources.

Another method for detecting oscillations was suggested by Kjeldsen et al. (1995, hereafter Paper I). This involved monitoring changes in the equivalent widths (EWs) of temperature-sensitive spectral lines. In Paper I we reported evidence of oscillations in the G0 subgiant η Boo, based on measurements of Balmer line EWs. We presented this as the first clear evidence of solar-like oscillations in a star other than the Sun. The observations were obtained over six nights with the 2.5 m Nordic Optical Telescope on La Palma and consisted of 12,684 low-dispersion spectra. In the power spectrum of the equivalent width measurements, we found an excess of power at frequencies around 850 μHz. The average amplitude inferred for the oscillations was about 7 times greater than solar, in rough agreement with the empirical scaling relation suggested by Kjeldsen & Bedding (1995). Comb analysis of the power spectrum, described in Paper I, suggested a regular spacing of $\Delta\nu = 40.3\ \mu$Hz. Based on this, we identified 13 oscillation modes. Similar observations of the daytime sky showed the 5 minute solar oscillations at the expected frequencies.

The frequencies for η Boo reported in Paper I, taken with available estimates of the stellar parameters, were in good agreement with theoretical models (Christensen-Dalsgaard, Bedding, & Kjeldsen 1995; Guenther & Demarque 1996). Particularly exciting was the occurrence in theoretical models—and apparently in the observations—of "avoided crossings," in which mode frequencies are shifted from their usual regular spacing by the effects of gravity modes in the stellar core. Since then, the improved luminosity estimate for η Boo from *Hipparcos* measurements has given even better agreement with the measured value of $\Delta\nu$ (Bedding, Kjeldsen, & Christensen-Dalsgaard 1998).

Meanwhile, a search for velocity oscillations in η Boo by Brown et al. (1997) has failed to detect a signal, setting limits at a level below the value expected on the basis of the EW results. Although the data were sparse (22 hr spread over seven successive nights) and the precision was degraded by the relatively fast rotation of the star ($v \sin i = 13$ km s^{-1}), the analysis by Brown et al. (1997) was careful and thorough, and the results seem to be inconsistent with those of Paper I. More recently, Carrier, Bouchy, & Eggenberger (2003; and also Bouchy, Carrier, & Eggenberger 2003) reported velocity measurements using the CORALIE and ELODIE spectrographs that showed a clear excess of power and a frequency spacing of 39.6 μHz.

In this paper we present additional observations of η Boo, obtained in 1998 in both EW and velocity. We also reanalyze our 1994 EW measurements and the velocity measurements of Brown et al. (1997). We confirm our earlier claim for oscillations in η Boo and identify more than 20 oscillation frequencies from the combined data.

2. DATA

2.1. *Equivalent Width Observations* (*NOT98*)

We observed η Boo over six nights during 1998 May using ALFOSC (Andalucia Faint Object Spectrograph and Camera) on the 2.5 m Nordic Optical Telescope on La Palma. This is the same telescope used in Paper I but with a different

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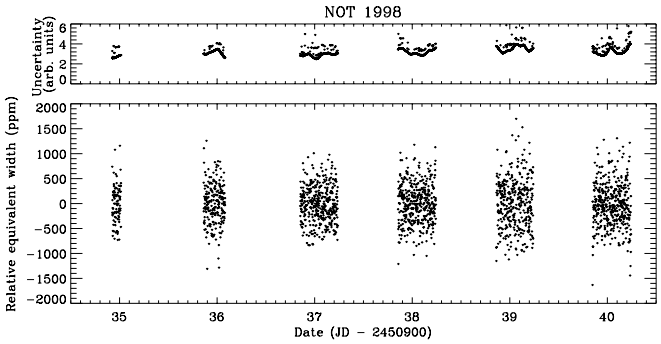

FIG. 1.—EW measurements of η Boo obtained at the NOT98 (*bottom*) and the corresponding uncertainties (*top*).

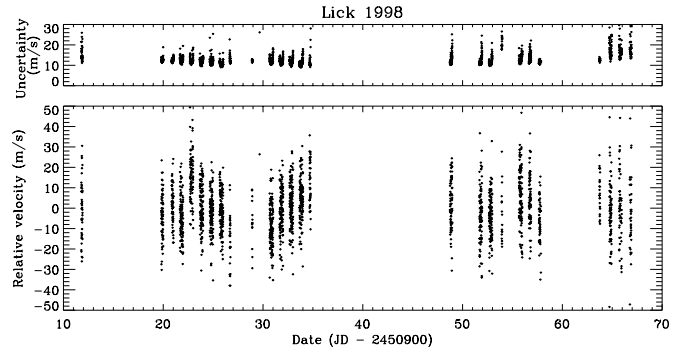

FIG. 2.—Velocity measurements of η Boo obtained at Lick (*bottom*) and the corresponding uncertainties (*top*).

spectrograph. We obtained seven echelle orders covering the range 370–700 nm at a dispersion of 0.04 nm pixel^{-1}. The CCD was a Loral 2k × 2k device, of which we used 700 × 1200 pixels.

Spectra were taken with a typical exposure time of 11 s and a dead time between exposures of 17 s. They were averaged in groups of three before writing to disk, resulting in a total of 1843 spectra (sampling rate 1/84 s) in 44.2 hr over six consecutive nights (1998 May 1–6). The distribution of spectra over the six nights was 88, 222, 377, 391, 358, and 407.

We used the method described by Kjeldsen et al. (1999) to measure equivalent widths of six strong temperature-sensitive lines: Hα, Hβ, Hγ, Mg I, Na I, and Fe I. A weighted mean of these six values was calculated, taking into account the differing temperature sensitivities of the lines. The resulting time series is shown in Figure 1.

2.2. *Velocity Observations* (*Lick98*)

We also observed η Boo in 1998 with the Hamilton Echelle Spectrometer and the 0.6 m Coudé Auxiliary Telescope at Lick Observatory (Vogt 1987). To produce high-precision velocity measurements, the star was observed through an iodine absorption cell mounted directly in the telescope beam.

We were allocated 56 of the 59 nights from 1998 April 6 to June 3, but the weather was unseasonably poor, permitting observations on only 26 nights (and many of these were partly lost). The exposure time was 120 s, with a dead time between exposures of the same amount. On the 11 best nights we obtained 95–120 spectra per night (sampling rate 1/245 s), and the total number of spectra obtained was 1989 (about one-third of that possible with no weather losses).

Extraction of radial velocities from the echelle spectra followed the method described by Butler et al. (1996). As mentioned in § 1, the precision is degraded by the relatively fast stellar rotation. The star is a spectroscopic binary with a period of 494 days (Bertiau 1957), and the orbital motion was removed from the velocity time series by fitting and subtracting a fifth-order polynomial. The resulting velocity measurements are shown in Figure 2. We are confident that the long-term velocity variations are not instrumental, given that velocities for τ Ceti, which we observed on most of the nights, were stable at the 5 m s^{-1} level. These night-to-night variations in η Boo are presumably due to stellar activity, which is commonly observed in rotating G-type stars (see, e.g., Saar, Butler, & Marcy 1998; Santos et al. 2000).

2.3. *Published Equivalent Width Observations* (*NOT94*)

We have included in this analysis the time series of 12,684 EW measurements (NOT94) obtained with the Nordic Optical Telescope in 1994. These are identical to the data presented in Paper I, with the exception that a high-pass filter was not applied. The result is an increase in noise at low frequencies, as expected from a $1/f$ noise source, which more accurately reflects the actual stellar and instrumental noise (for more details, see Bedding & Kjeldsen 1995).

2.4. *Published Velocity Observations* (*AFOE95*)

We have also analyzed 555 velocity measurements (AFOE95) of η Boo obtained with the AFOE spectrograph during 22 hr spread over seven successive nights in 1995 March. These measurements were described by Brown et al. (1997) and were kindly provided to us in electronic form by T. Brown.

3. ANALYSIS AND DISCUSSION

The power spectrum of each time series was calculated as a weighted least-squares fit of sinusoids (Frandsen et al. 1995; Arentoft et al. 1998), with a weight being assigned to each point according to its uncertainty estimate. The results for the four data sets are shown in Figures 3–6. In each case, we show both the conventional power spectrum (*top*) and a smoothed version in which the vertical scale has been converted to power density (*bottom*). As discussed by Kjeldsen

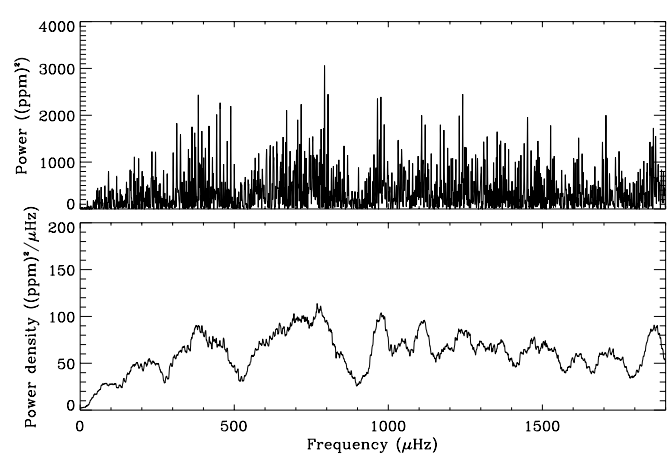

FIG. 3.—Power spectrum of the NOT98 EW measurements of η Boo

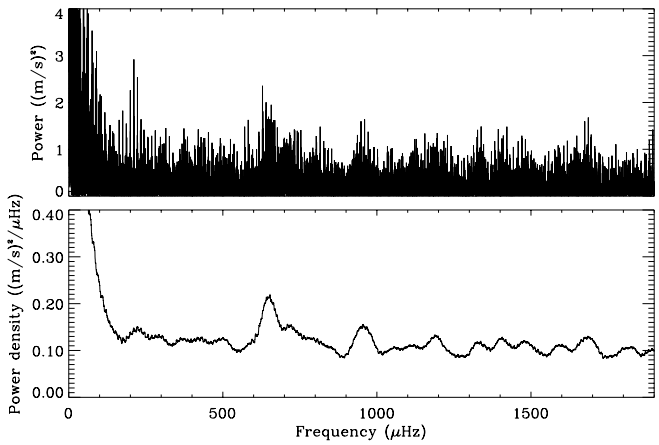

FIG. 4.—Power spectrum of the Lick98 velocity measurements of η Boo.

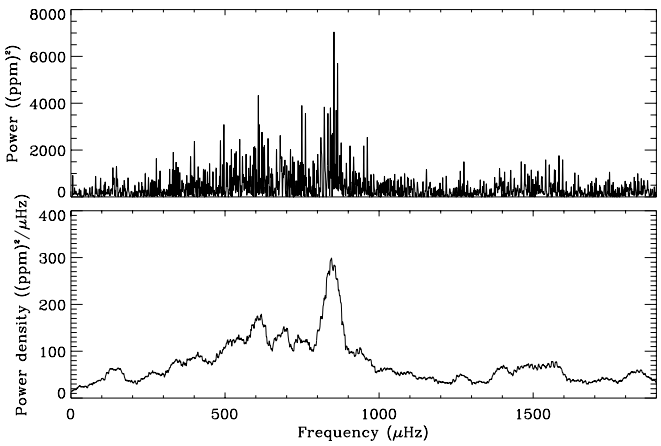

FIG. 5.—Power spectrum of the NOT94 EW measurements of η Boo that were published in Paper I.

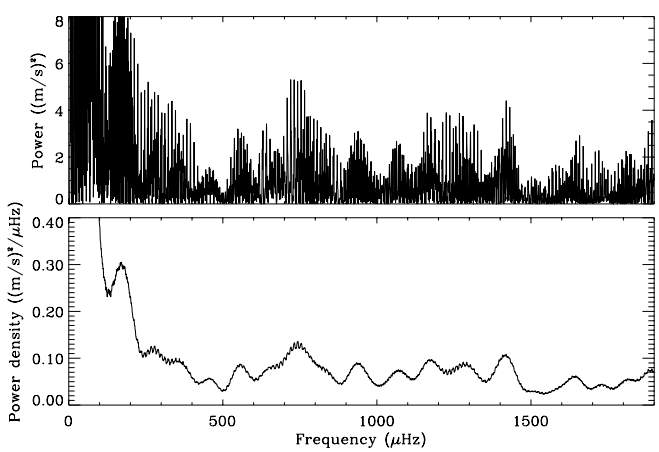

FIG. 6.—Power spectrum of the AFOE95 measurements of η Boo that were published by Brown et al. (1997).

& Bedding (1995), Appendix A.1, and Kjeldsen et al. (1999), § 5, the conversion to power density is achieved by multiplying by the effective observing time, which we calculated in each case by integrating under the spectral window.

Some level of excess power in the range 600–1100 μHz is apparent in all four data sets, although it is strongest in the NOT94 data. Further discussion of the measured power levels is given below in § 3.4. First, however, we will discuss the oscillation frequencies.

Mode frequencies for low-degree solar-like oscillations are approximated reasonably well by the asymptotic relation

$$\nu_{nl} = \Delta\nu(n + \tfrac{1}{2}l + \epsilon) - l(l+1)D_0 \ . \qquad (1)$$

Here n and l are integers that define the radial order and angular degree of the mode, respectively; $\Delta\nu$ (the so-called large separation) reflects the average stellar density, D_0 is sensitive to the sound speed near the core, and ϵ is sensitive to the surface layers. It is conventional to define $\delta\nu_{02}$, the so-called small separation, as the frequency spacing between adjacent modes with $l = 0$ and $l = 2$. We can further define $\delta\nu_{01}$ to be the amount by which $l = 1$ modes are offset from the midpoint between the $l = 0$ modes on either side. If the asymptotic relation holds exactly, then it is straightforward to show that $D_0 = (1/6)\delta\nu_{02} = (1/2)\delta\nu_{01}$.

3.1. *Extraction of Frequencies*

We extracted the frequencies of the strongest peaks in each power spectrum in the range 600–1100 μHz. We used a simple iterative algorithm, in which the highest peak was identified and the corresponding sinusoidal variation was subtracted from the time series. The power spectrum of the residuals was then calculated and the process was iterated until all peaks with amplitudes more than 2.5 times the noise floor had been extracted. The number of peaks extracted from the four data sets is summarized in Table 1.

Setting the threshold at 2.5 σ gives us a chance to detect the weaker oscillation modes, but it also means we will select some noise peaks. To investigate this, we have conducted simulations in which we analyzed noise spectra that contained no signal. The last column in Table 1 shows the number of peaks found above the 2.5 σ threshold. This indicates that about 6 of the 35 detected peaks are expected to be due to noise.

3.2. *Large Frequency Separation*

We next investigated whether the extracted frequencies have a regular spacing, as is expected for p-mode oscillations. In Paper I, we described a comb analysis of the NOT94 power spectrum that revealed a regular spacing of $\Delta\nu = 40.3$ μHz. Here we analyze the 22 frequencies from the other three data sets (AFOE95, NOT98, Lick98) using

TABLE 1
RESULTS OF THE FREQUENCY ANALYSIS

Data Set	Noise Level	Extracted Peaks	Noise Peaks
NOT94	15.1[a]	13	1.3 ± 0.4
AFOE95	0.67[b]	5	1.0 ± 0.3
NOT98	16.3[a]	3	0.5 ± 0.2
Lick98.....	0.41[b]	14	3.3 ± 1.0

[a] In units of parts per million.
[b] In units of meters per second.

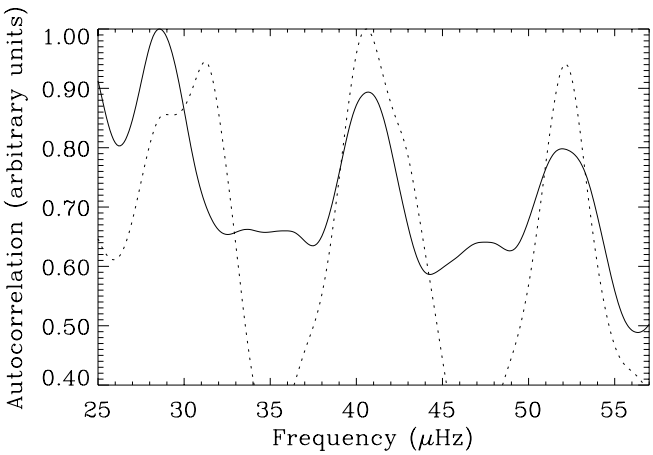

FIG. 7.—The autocorrelation of the 22 frequencies, together with their daily aliases, that were extracted from AFOE95, NOT98, and Lick98 data sets (*solid line*) and for the 13 frequencies from the NOT94 data (*dotted line*). The peaks at 40 μHz represent the large frequency separation of η Boo.

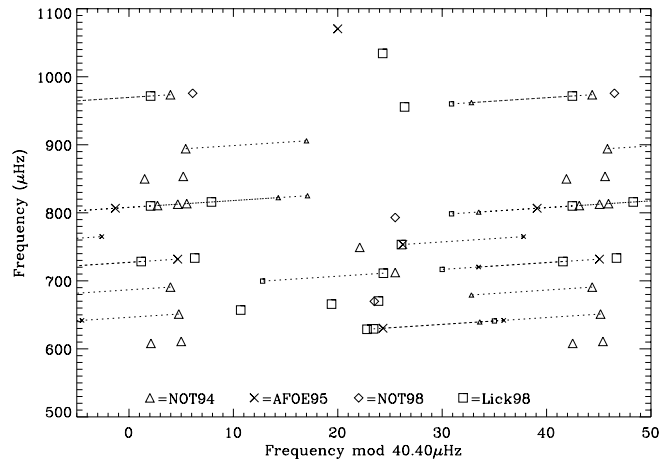

FIG. 8.—Echelle diagram showing the 35 frequencies from the four data sets. The 15 cases for which we believe the frequencies should be shifted by 1 day^{-1} (11.57 μHz) are represented by two symbols connected by a dotted line, with the smaller symbol showing the frequency without any shift.

autocorrelation, as follows: First, each extracted frequency was allocated a power corresponding to the square of its signal-to-noise ratio (S/N), in order to give higher weight to the more reliable peaks. Second, to allow for the likelihood that some of the extracted frequencies should be shifted by ± 1 day^{-1} (± 11.57 μHz), we extended the table of frequencies by a factor of 3 by including these sidelobes (but with half the power of the central peaks). We then calculated the autocorrelation of these 66 frequencies. This is shown, smoothed to a resolution of 3.5 μHz, as the solid line in Figure 7.

The three peaks in the autocorrelation correspond to the large separation and its daily aliases, leading us to estimate a value of $\Delta\nu = 40.4$ μHz. For comparison, the dotted line in Figure 7 shows the autocorrelation for the 13 frequencies extracted from the NOT94 data, which yields a large separation of $\Delta\nu = 40.5$ μHz. The excellent agreement between these independent data sets confirms the results of Paper I and also agrees well with the value of 39.6 μHz reported by Carrier et al. (2003). In summary, there can be no doubt that the large frequency separation of η Boo is about 40 μHz, which is in excellent agreement with theoretical models (Christensen-Dalsgaard et al. 1995; Guenther & Demarque 1996).

3.3. *Identification of Frequencies*

Given the large separation, we next attempted to identify the individual modes, remembering that some of them will need to be shifted by ± 11.57 μHz. Figure 8 shows the 35 frequencies from all four data sets, displayed in an echelle diagram. We expect modes with a given l-value to form vertical ridges, for $l = 0$, 1, and 2. We were able to achieve this by shifting 15 frequencies by ± 11.57 μHz, as shown in the figure. The final frequencies are given in Table 2. Note that the number of peaks that are classified as noise is consistent with the estimates made above (see Table 1).

A possible problem is that, modulo the large separation, peaks corresponding to $\nu_{nl} - 11.57$ μHz for $l = 1$ are only separated by 1.1 μHz from peaks corresponding to $\nu_{nl} + 11.57$ μHz for $l = 2$. It is possible that some of those peaks have been shifted the wrong way and are therefore

TABLE 2
IDENTIFICATION OF EXTRACTED FREQUENCIES

Frequency (μHz)	Mode ID	Data Set	S/N
608.1	$l = 2$	NOT94	4.4
611.0	$l = 0$	NOT94	3.6
628.8*	$l = 1$	Lick98	3.7
629.4* = 641.0 − 11.57		Lick98	3.0
630.3* = 641.9 − 11.57		AFOE95	3.0
651.2 = 639.6 + 11.57	$l = 0$	NOT94	3.1
657.1	Noise	Lick98	3.2
665.8	Noise	Lick98	2.9
669.9*	$l = 1$	NOT98	2.7
670.3*		Lick98	2.7
690.8 = 679.2 + 11.57	$l = 0$	NOT94	3.1
711.2* = 699.6 + 11.57	$l = 1$	Lick98	2.9
712.3*		NOT94	3.3
728.4 = 716.8 + 11.57	$l = 2$	Lick98	3.0
731.9* = 720.3 + 11.57	$l = 0$	AFOE95	3.4
733.5*		Lick98	2.9
749.3	$l = 1$?	NOT94	4.4
753.3*	$l = 1$	Lick98	2.6
753.4* = 765.0 − 11.57		AFOE95	2.9
793.1	$l = 1$	NOT98	2.8
806.7	Noise	AFOE95	3.0
810.1* = 798.5 + 11.57	$l = 2$	Lick98	2.6
810.7* = 822.3 − 11.57		NOT94	4.3
812.7* = 801.1 + 11.57	$l = 0$	NOT94	3.1
813.5* = 825.1 − 11.57		NOT94	3.1
815.9	Noise	Lick98	3.0
849.9	$l = 2$	NOT94	2.8
853.6	$l = 0$	NOT94	5.6
894.2 = 905.8 − 11.57	$l = 0$	NOT94	3.2
955.6	$l = 1$	Lick98	2.5
971.7 = 960.1 + 11.57	$l = 2$	Lick98	3.0
973.6* = 962.0 + 11.57	$l = 0$	NOT94	3.2
975.7*		NOT98	2.9
1034.3	$l = 1$	Lick98	2.6
1070.4	Noise	AFOE95	2.5

NOTE.—The triplet and pairs of duplicate frequencies are marked with asterisks.

TABLE 3
OSCILLATION FREQUENCIES FOR η BOOTIS (μHz)

n	$l = 0$	$l = 1$	$l = 2$
13	...	...	608.1 (0.4)
14	611.0 (0.5)	629.4 (0.3)	...
15	651.2 (0.6)	670.1 (0.5)	...
16	690.8 (0.6)	711.8 (0.4)	728.4 (0.6)
17	732.6 (0.4)	749.3 (0.4)[a]	...
	...	753.4 (0.5)[a]	...
18	...	793.1 (0.7)	810.5 (0.4)
19	813.1 (0.4)	...	849.9 (0.7)
20	853.6 (0.3)	...	...
21	894.2 (0.6)	...	...
22	...	955.6 (0.8)	971.7 (0.6)
23	974.5 (0.7)	...	...
24	...	1034.3 (0.7)	...
$\Delta\nu_l$	40.45 (0.07)	40.89 (0.19)	40.41 (0.10)

[a] Value excluded from the calculation of $\Delta\nu_l$.

wrongly identified. The relevant peaks are 699.6 μHz (from Lick98), which we identified as an alias of an $l = 1$ mode, and 822.3 μHz (from NOT94), which we identified as an alias of an $l = 2$ mode. A similar reservation, although to a lesser extent, applies to peaks corresponding to $\nu_{nl} - 11.57$ μHz for $l = 0$ and to $\nu_{nl} + 11.57$ μHz for $l = 1$, which are only separated by 1.9 μHz.

Note that we have identified the peak at 749.3 μHz as possibly being an $l = 1$ mode that is displaced by an avoided crossing. This peak has the second-highest S/N of all the peaks and is therefore not likely to be due to noise or to be an alias. In any case, shifting this peak by $\pm 11.57 \mu$Hz would not bring it into agreement with $l = 0$ or 2.

Some of the frequencies are detected more than once as indicated by an asterisk in Table 2. In those cases, we have combined the measurements into a weighted average. The final list of 21 frequencies is given in Table 3, and these are shown as an echelle diagram in Figure 9. The uncertainties in the frequencies reflect the S/N of the relevant peak (or peaks).

We next estimated the large separation separately for each value of l, and the results are given in the last line of Table 3 (two modes, which may be affected by avoided crossings, were excluded from the fit). The weighted average

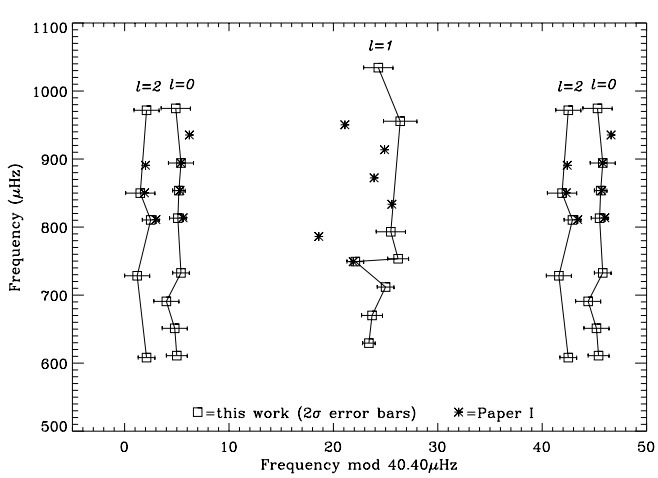

FIG. 9.—Echelle diagram showing the 21 frequencies from Table 3, with 2 σ error bars. For comparison, we also show the 13 frequencies reported in Paper I.

TABLE 4
FREQUENCY SEPARATIONS FOR η BOOTIS

Variable	Value (μHz)
$\Delta\nu$	40.47 ± 0.05
$\delta\nu_{02}$	3.00 ± 0.35
$\delta\nu_{01}$	0.78 ± 0.45
D_0	0.49 ± 0.06
ϵ	1.09 ± 0.02

of these three $\Delta\nu_l$ yields the value of $\Delta\nu$ shown in Table 4. The other parameters in that table were calculated by fitting the same 19 frequencies to the asymptotic relation. All are consistent with the values given in Paper I but have smaller uncertainties, thanks to the larger number of detected frequencies.

In Figure 9 we also show the 13 frequencies reported in Paper I. We can see that six were recovered in the new analysis, while five were not recovered but lie close to one of the ridges (within typical uncertainties), so perhaps can still be taken as reliable detections. Finally, two frequencies (786.2 and 950.3 μHz) fall well away from the $l = 1$ ridge and were not confirmed by the revised analysis. It is possible that they represent mixed modes that are shifted by avoided crossings, but further observations are needed to confirm this.

3.4. *Oscillation Amplitudes*

The above analysis gives strong evidence that the highest peaks in the four power spectra are due to solar-like oscillations. However, we have also noted that the amplitude of the power excess is somewhat stronger in the NOT94 observations than in the other three data sets. It seems plausible that these differences reflect the stochastic nature of the excitation mechanism, but a more definite statement is hampered by our limited knowledge of the amplitudes of oscillations in subgiant stars. It is also possible that some contribution to the variations is due to an unidentified systematic error in the calibration that was used to convert equivalent width amplitudes to velocities (see Paper I).

Taken at face value, the observations indicate that peak oscillation amplitudes in η Boo are typically 3–5 times solar. This conclusion is consistent with the upper limits reported by Brown et al. (1997) from the AFOE95 data.

4. CONCLUSIONS

We have presented new observations of η Boo in velocity (Lick98) and equivalent width (NOT98) that show some evidence of excess power in the range 600–1100 μHz. The velocity measurements (AFOE95) published by Brown et al. (1997) also show a slight power excess when smoothed. None of these signals is as strong as the original equivalent width observations NOT94, Paper I), which may reflect the stochastic nature of the excitation or may indicate a problem with the calibration of the NOT94 equivalent width estimates.

We extracted the highest peaks in each data set and used the autocorrelation to search for regularity. The three newer data sets (AFOE95, NOT98, and Lick98) combined to give a clear autocorrelation signal at a spacing of $\Delta\nu = 40.4$ μHz, giving independent confirmation of the results of Paper I. This, combined with the recent work by Carrier

et al. (2003), left little doubt that the large frequency separation of η Boo is about 40 μHz. This allowed us to identify 21 frequencies in η Boo, which have been compared with theoretical models by Di Mauro et al. (2003). The results confirm the claim made in Paper I for the first clear evidence of solar-like oscillations in a star other than the Sun. Future observations of η Boo, particularly with the *MOST* (*Microvariability and Oscillation of Stars*) spacecraft (Matthews et al. 2000),[8] should measure more oscillation modes with greater frequency precision.

[8] See also http://www.astro.ubc.ca/MOST.

We would be pleased to make the data available on request. Please contact T. R. B.

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