Seismology of δ Scuti stars with COROT: prospects for mode identification

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ABSTRACT

δ Scuti stars are high amplitude, nonradial multiperiodic oscillators. The major problem is the identification of the observed frequencies as specific oscillation modes, however this step is important to provide constraints upon the internal structure of the star.

We show here that despite the complicated frequency distributions which can be expected from COROT space mission for a typical δ Scuti star, it will be possible to identify at least some modes or at least the degree for low-ℓ modes from space data.

1. Introduction

The δ Scuti stars are pulsating variables located in the lower part of the classical instability strip with spectral type from A2 to F0. They are multiperiodic pulsators oscillating with large amplitude compared to solar-like oscillations (amplitudes from ground-based observations range between a few mmag to 1/10 mag) and periods less than 0.3 days. Only a few 5 to 10 frequencies in general and in some cases up to 30 frequencies in the case of FG Vir (Breger et al. 1998) have been detected from the ground. The observed frequencies span an interval in which models predict much more frequencies than observed. Either the corresponding modes are not excited or they are excited up to much smaller amplitudes that can be detected from ground-based observations. We do not yet understand how modal selection operates, this prevents to identify firmly modes associated with individual frequencies (e.g. to determine the degree, azimuthal order and radial order of each mode) and therefore to take full advantage of the available seismological tools. A better knowledge of the global structure of the frequency spectrum would provide precious indications about modal selection processes. This requires to detect oscillations with much smaller amplitudes and therefore to increase significantly the signal-to-noise ratio.

Observations from space will be characterized by a much higher signal-to-noise ratio than from the ground. This will result in the detection of a much larger set of modes for each δ Scuti star, by detecting new small amplitude modes and high degree modes. Indeed, high ℓ modes are expected to be excited but visibility effects i.e. averaging geometrical effects when observing in integrated light, decrease the observed amplitudes to much smaller values than can be observed from the ground. But the detection of a much larger number of frequencies will yield frequency spectra very much complicated and then it is legitimate to wonder whether mode identification will not be even more difficult to obtain (Dziembowski et al. 1998)? The purpose of this work is to show how, in space data, it is possible to identify at least some modes or at least the degree of the low-ℓ modes, and this despite the complications due to the presence of high ℓ modes.

Spectroscopic or photometric techniques have been deviced to identify modes (Garrido et al. 2000). This work is a progress report on our effort to develop an alternative method which does not involve any knowledge of a model and using very precise data, i.e. frequencies, rather than amplitude and phase. An ideal case was presented in Baglin et al. (2000). In this paper, modes up to ℓ= 10 were assumed to be detected with the low detection threshold of space data. The detected range of frequencies was assumed to be broad enough toward high frequencies and then it included lower frequency part of the asymptotic p-mode regime. It was shown there that although the frequency spectrum is more complex than the one from ground-based observations, it is still possible to obtain the mean value of the large separation and to proceed further in attempting to determine the degree of at least some modes which will constitute the cornerstone of a mode identification.

However from ground-based observations the detected frequencies do not include part of the asymptotic regime. We do not know whether space data will provide frequencies in the asymptotic regime. In the present paper, we therefore discuss the case where these frequencies are not detected. Section 2 describes how the frequency spectrum is built. In Section 3, patterns are searched using frequency spacing histograms. Then echelle diagrams are computed. Discussion and perspectives are given in Section 4.

2. Amplitude distribution: visibility effect

We consider a 1.85 $M_\odot$ model (see Baglin et al. 2000 for more details) and retain modes with degree from 0 to 10 with frequencies in the theoretical unstable range [80-410]μHz given by the oscillation code written by W. A. Dziembowski (1982). High frequencies which falls in the asymptotic regime are not included. The oscillation amplitudes are computed in the COROT photometric system (370-950 nm), according to Watson (1988) for the flux change for a nonradial pulsation. Stellar model atmospheres are built for that specific purpose with ATLAS9 (Heiter et al. 2001 in prep.) and consistent limb darkening coefficients computed (Barban et al. 2001, in prep.). For the non adiabatic phase lag between temperature and pressure variations, we use the values given by Dziembowski's oscillation code. The intrinsic amplitude is assumed to be the same for all the modes and is chosen so that ℓ= 0 modes have an amplitude of 1 mmag as typically observed from the ground. For the amplitudes of modes with higher degrees, we used the amplitude ratio with ℓ= 0. The amplitude ratio depends on the inclination to the line of sight. We averaged the amplitudes obtained for values of the inclination to the line of sight of 0, 20, 40, 60, and 80 degrees.

Figure 1 with a typical result illustrates the visibility effect. In the case of Fig. 1, from the ground with a maximum amplitude of 10^{-3} in relative flux, we are able to detect some ℓ= 0, 1 and 2 modes and from space with COROT, we will see some ℓ= 0,1,2,3,4,6,8 and 10 modes. So depending on the threshold, we must expect to detect more or less modes with different ℓ. Whether odd highest ℓ modes (5,7,9) will be detected depend on intrinsic amplitude and detection threshold. The different feature for even and odd modes from ℓ= 4 is attributed to geometric and limb-darkening terms of the expression of flux change. Similar results have

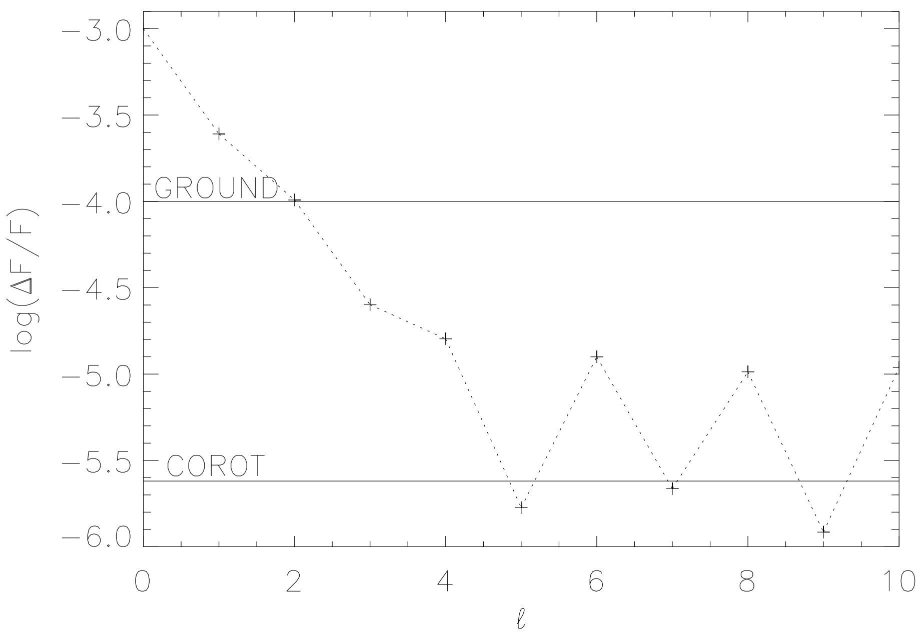

Fig. 1.— Oscillation amplitudes in intensity as a function of ℓ. This graph is obtained for a frequency 210 μHz. The line marked "GROUND" corresponds to a typical detection threshold obtained from the ground: 10^{-4}. The line marked "COROT" corresponds to the expected space detection threshold of $2\ 10^{-6}$.

been obtained by Balona & Dziembowski (1999) and by I. Roxburgh (private communication).

To be more realistic, we have adopted an amplitude distribution which looks like FG Vir data (Breger et al. 1998). We arbitrarily defined an amplitude distribution with gaps which yields a frequency spectrum looking like the one of FG Vir. (Barban et al. 2000).

3. Search for patterns in the frequency spectrum

Although the considered oscillation modes are not in the asymptotic regime, We nevertheless search in the frequency spectrum built in Section 2 for some frequency equidistances. Differencies between two frequencies are computed to build a histogram of these differencies which we call a *frequency spacing histogram* (e.g. Breger et al. 1999).

When all the unstable mode frequencies are included, no specific structure can be detected. The histogram is perturbed by high ℓ modes which do not respect the equidistance and by mixed and g modes (Barban et al. 2000).

If now we turn to the COROT case, no significant improvement is obtained when we keep the unstable modes with amplitude above $2\ 10^{-6}$. The histogram is still perturbed by nonequidistant modes as in the precedent case. The same is true when we remove high ℓ modes which perturb the histogram by increasing the amplitude threshold. That means that now we keep modes with amplitude higher to 10^{-5} (Fig. 2)

Because mixed modes of low degree contaminate low frequency regime, we keep the same amplitude threshold of 10^{-5} and remove the low frequency modes which are mostly mixed modes and perturb the histogram. Figure 3 shows:

- an excess of signal between approximately 40 and 50 μHz with a strong peak at 40 μHz. This peak is interpreted as a mean value of the large separation ($\overline{\Delta\nu}$, $\Delta\nu = \nu_{n,\ell} - \nu_{n-1,\ell}$), which differs from the asymptotic value, i.e. 47 μHz.

- a low frequency decrease. The decrease at low frequencies is attributed to the remaining mixed modes.

From the ground with a detection threshold of 10^{-4}, we would obtain Fig. 4.

We have shown here that from space data it is possible, at least, to recover a mean value of the large separation which is not the asymptotic one but which can help to identify modes as we will see in the next Section. Ground based observations can serve to confirm space observations and vice-versa.

3.1. Towards mode identification

Once $\overline{\Delta\nu}$ is known either as described above (or with another method), it is possible to built an echelle diagram (Unno et al. 1989). This diagram emphasizes the signature of the small separation predicted by the asymptotic theory in function of the degree l of the modes:

$$\nu_{n,\ell+2} - \nu_{n+1,\ell} \sim 2(2\ell+3)D_\ell(\nu) \tag{1}$$

where $D_\ell(\nu)$ is a quantity which depends on the derivative of the sound speed, and is particularly sensitive to the stellar core (Unno et al. 1989). This can be used as a first step towards identifying the detected modes as ℓ place themselves in different patterns. In the case where we are not in the asymptotic regime, we know here that remains such trend at lower frequencies. Then this method can also be used where we are not in the asymptotic regime using the mean value of the large separation corresponding to the considered region.

From simulated ground-based data, it is difficult to say something very precise because of the too small number of modes (Fig. 5). Without models it is difficult to know if the pattern in the echelle diagram is due to ℓ= 0 or ℓ= 1.

With the set of modes corresponding to modes with frequencies greater than 200 μHz and with modes with amplitude greater than 10^{-5}, we saw in the last Section that we can determine a mean value of the large separation. This set of modes is now used to build an echelle diagram (Fig. 6) corresponding to the mean

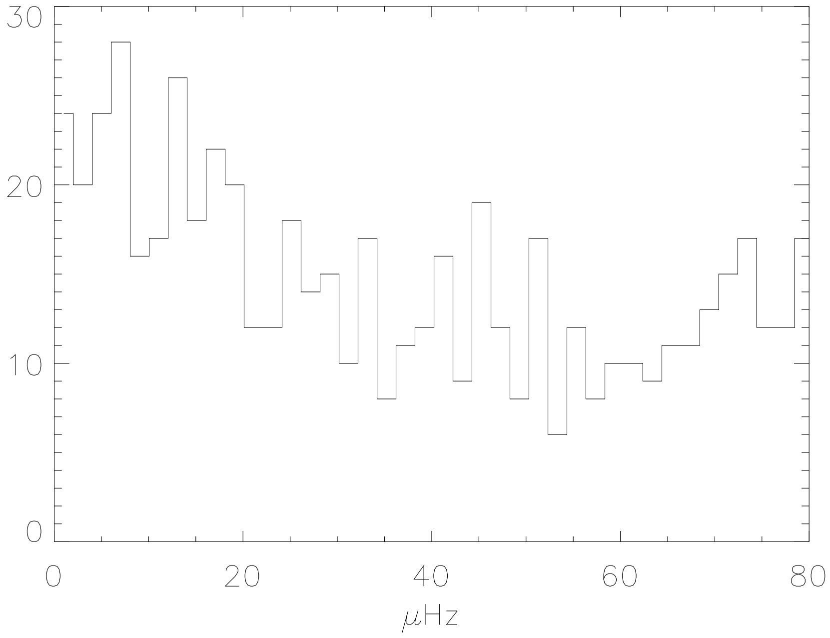

Fig. 2.— Frequency spacing histogram computed in the frequency unstable domain for modes with amplitude greater than or equal to 10^{-5}

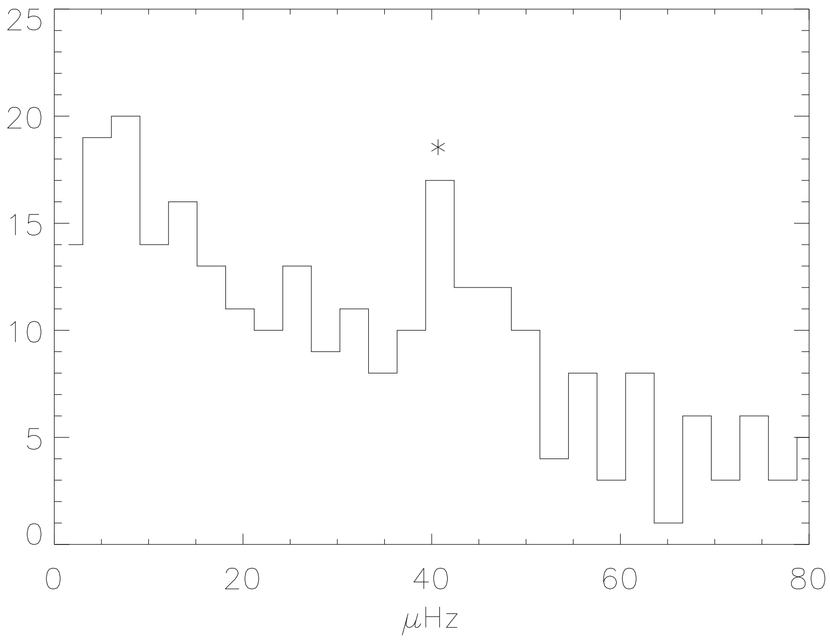

Fig. 3.— Frequency spacing histogram computed from the modes frequencies in [200-409]μHz and for modes with amplitude greater or equal than 10^{-5}.

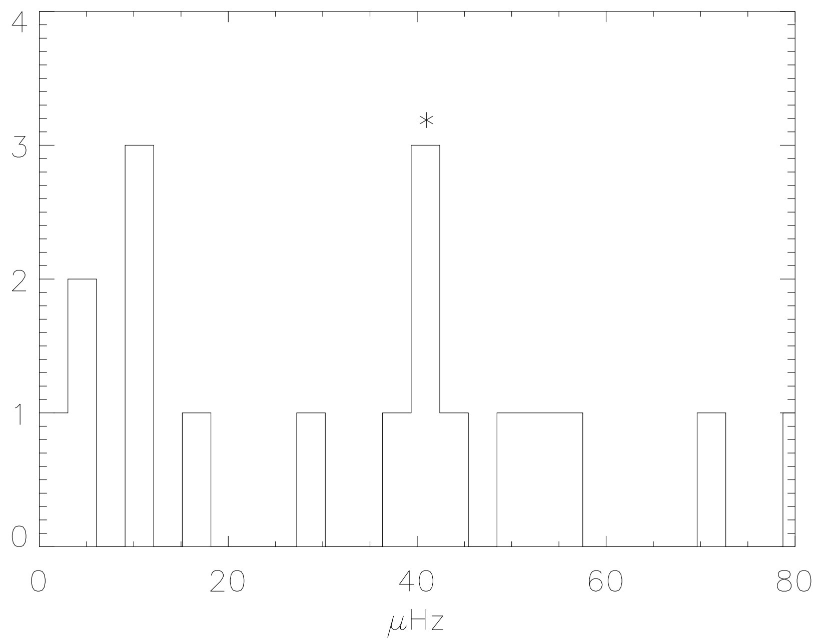

Fig. 4.— Frequency spacing histogram computed from the modes frequencies in [200-409] μHz and for modes with amplitude greater or equal than 10^{-4}.

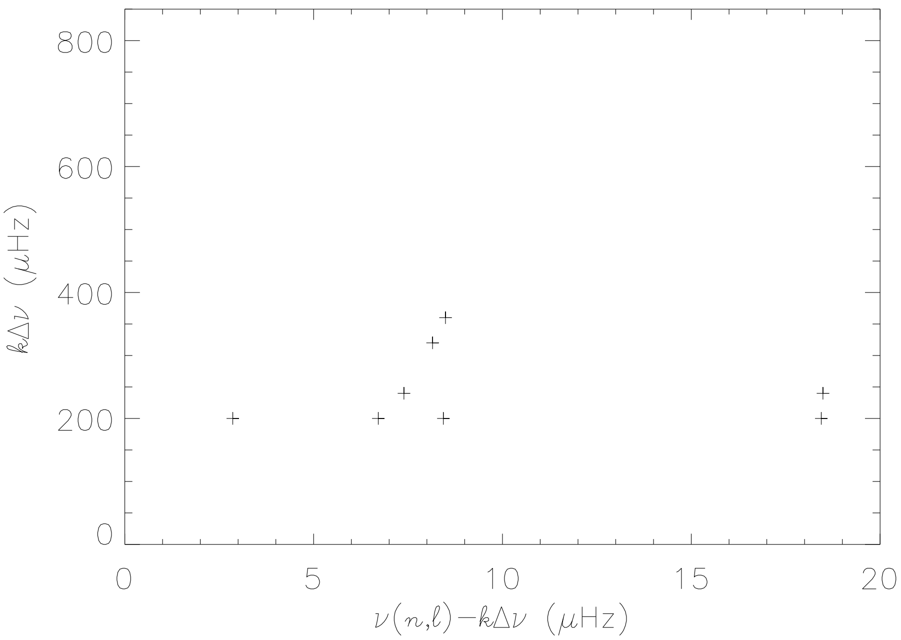

Fig. 5.— Echelle diagram with k as an integer with $\Delta\nu$ ==40 μHz for ℓ==0 to ℓ==10 modes between 200 and 409 μHz and amplitudes greater than 10^{-4}.

value of the large separation found (i.e. 40 μHz).

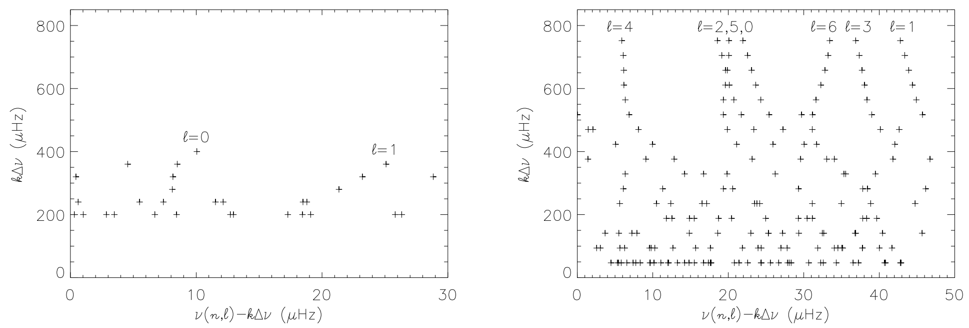

Fig. 6.— Echelle diagram with k as an integer. Left: with $\Delta\nu$ = 40 μHz for modes between 200 and 409 μHz and amplitudes greater than 10^{-5}. Right: with $\Delta\nu$ ==47 μHz for modes between 50 and 800 μHz.

The unstable modes we consider in this present case have frequencies in the range where everything is mixed up in the echelle diagram of the "ideal case" (Fig. 6, Right). However selecting higher frequencies in the unstable domain and using the value of the large separation given by the histogram (Fig. 6, Left), we can recover nice structures associated to ℓ==0,1 and 2. We are not far from mode identification.

4. Conclusion and perspectives

We have built a frequency data set as can be expected from space data and have shown that it is still possible to recover patterns in the complicated simulated space data frequency spectrum and then to be not far from modes identification. Although dependent on the amplitude pattern chosen here, it is still reasonable to conclude that there exists a regime in frequency and amplitude which is not reacheable from the ground and which remains simple enough to determine ℓ= 0, 1, 2 modes. Once these modes are determined, the other modes can be easily identified.

The frequency data does not include rotational splittings. The study of the effect of rotation is a work in progress. Another next issue will be extracting structure associated to high degree modes and mixed modes.

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