Part 2.4. Delta Scuti Stars

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Seismology of δ Scuti Stars: Problems and Prospects

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1. Introduction

The current state of seismology of δ Scuti stars is reviewed with particular emphasis on seismic signatures of the extension of their mixed central region and of rotation. We refer also to Goupil et al. (2000) and more generally to Breger & Montgomery (2000) for more details.

δ Scuti stars are population I pulsating stars with spectral type A-early F, located on or near the main sequence. They are found in the lower part of the classical instability strip in a HR diagram (Fig. 1). Masses range from $\sim 1.5 M_\odot$ to $\sim 2.5 M_\odot$ and δ Scuti stars are either in a stage of H-core or H-shell burning. On the main sequence, the high temperature sensitivity of the dominant CNO cycle causes a large convective core to develop, which later shrinks leaving behind a gradient $\nabla\mu$ in the mean molecular weight.

For the mass and effective temperature ranges of δ Scuti stars, semiconvection, radiation pressure, mass loss and dynamo play no significant role. The total angular momentum is conserved, hence most of these stars are moderate to fast rotators with $v \sin i$ up to 200, even 250 km s^{-1} (Rodríguez et al., 2000) although angular momentum can be redistributed within the star. In fact, many hydrodynamical processes acting together or competing against each other are likely to occur in the radiative region and in the vicinity of the convective core. The overshooting from the convective core causes the extension of the mixed region beyond the Schwarzschild convective radius and this affects evolution. Balance between meridional circulation and rotationally induced turbulence generates some mixing of chemicals and redistribution of angular momentum (Zahn, 1992; Talon et al., 1997; Maeder, 1999), affecting both the evolution and the rotation profile. Gravity waves from the convective core can also modify the properties of the inner layers (Schatzman & Morel, in preparation). Hence open questions concerning the internal properties of δ Scuti stars are for instance whether the rotation profile is shellular, what is the strength of the differential rotation and the extension of the central mixed region.

2. δ Scuti stars: multiperiodic nonradial pulsators

These variable stars are multiperiodic nonradial oscillators with periods in the range $P \sim 0.5$ h - a few hours. They oscillate with low radial overtones n up to ~ 7 and with degrees ℓ up to 20. Their oscillation modes are destabilized by the usual opacity mechanisms with the main driving arising in the HeII ionization region. Because the driving mechanism is very temperature sensitive, luminous δ Scuti stars are more evolved than fainter ones. The theoretical blue and red edges for the fundamental radial mode in Fig. 1 were calculated with a time dependent convection treatment (Houdek et al., 1999). Bluer stars are pulsating in higher overtones than the fundamental. Note that a meaningful comparison between observations and theoretical models in Fig. 1 must take into account a number of observational and theoretical uncertainties.

2.1. Extension of the mixed central region

Several theoretical works have investigated the overshoot process (Roxburgh, 1989; Zahn, 1991; Canuto, 2000). In practice, most stellar models still use a very simple prescription: $d_{ov} = \alpha_{ov}\, H_p$ where the overshoot distance d_{ov} is a fraction α_{ov} of the pressure scale height H_p. This fraction is a free parameter whose value is empirically determined from observations. For instance, fitting the width of the main sequence yields $\alpha_{ov} \sim 0.1 - 0.3$ (Maeder & Meynet, 1989). Constraints imposed by 2 $M_\odot$ eclipsing binaries also yield a value of $\alpha_{ov} = 0.17 \pm 0.05$ (Ribas et al., 2000). Such empirical determinations actually measure the extension of the mixed central region whatever the cause of the mixing, whether it is due to overshooting, rotation or other processes or likely a combination of them all. This likely explains the different values for d_{ov} obtained when considering classes of stars with different masses and ages.

One important seismic signature of the mixed central region is seen in Fig. 2 (left) which shows the evolution of dimensionless frequencies (σ) with stellar age from the pre-main-sequence (PMS) to the main-sequence (MS) stages. The dimensionless frequency σ of a radial mode with a given radial order remains roughly constant with evolution. This is also true for nonradial p modes most of the time except when they undergo an avoided crossing i.e. when a g mode entering the p domain and a p mode exchange their physical nature (Aizenman et al., 1977). Dziembowski & Pamyatnykh (1991) suggested to use these particular modes as a seismic diagnostic for the extension of the convective core (see also Roxburgh & Vorontsov, 2001) as they have significant amplitudes in the vicinity of the core.

2.2. Effect of rotation on oscillation frequencies

We introduce two parameters: $\epsilon = \Omega/\Omega_g$ where Ω is the rotation frequency, $\Omega_g = (GM/R^3)^{1/2}$ and $\mu = \Omega/\omega$ where ω is the mode frequency. Here ϵ roughly measures the strength of the centrifugal force compared to gravity and μ roughly measures the Coriolis effect. Unstable modes of δ Scuti stars have dimensionless frequencies in the range $\sigma \sim 1 - 8$, i.e., cyclic frequencies $\nu = 80 - 500\mu$Hz while the rotational velocity is $v \sim 50 - 150$ km s^{-1}, which corresponds to a rotational cyclic frequency of $\Omega/(2\pi) \sim 5 - 16\mu$Hz. In the $\epsilon - \mu$ diagram (Fig. 2 right), the corresponding region shows that for these stars, while rotation can still be treated as a perturbation in some specific cases, it is in general necessary to go beyond first order as centrifugal distortion cannot be neglected. The effect of rotation on the oscillation frequencies of spheroidal modes has been the subject of several studies (Saio, 1981; Smeyers & Martens, 1983; Dziembowski & Goode, 1992; Soufi et al., 1998). By comparison, for slower rotators, lower frequency oscillators like SPB and γ Dor stars, the centrifugal force may usually be neglected whereas a perturbation treatment to include Coriolis effects is no longer valid (Rieutord, these proceedings).

Rotational degeneracy: As a consequence of distortion and Coriolis second order effects $O(\epsilon^2)$, when rotation is large enough, modes with close frequencies can no longer be described using single spherical harmonics as it is the case in absence of rotation. Figure 3 (left) illustrates this effect for a 1.8 $M_\odot$ model built with uniform rotation. It is a zoom of Fig. 2 for two $\ell = 2 (n = 3, 4)$ modes which undergo an avoided crossing. Rotational degeneracy occurs for each $\ell = 2$ mode with its closest neighbor $\ell = 0$ mode (not shown). Although in dimensionless units the deviation from a regular behavior is small, it becomes significant when using real units . As a result of rotation, avoided crossings arise at cooler $T_{\rm eff}$.

Cubic order frequency corrections due to rotation: These are of order of μ^3, $\mu\epsilon^2 \sim 10^{-5}$, which corresponds to frequency corrections $\delta\omega/(2\pi) \sim 1 - 10\mu$Hz at these rotation velocities ($\sim$ 150 km/s); hence they are non-negligible. They are most important for non axisymmetric modes. Figure 3 (right) shows this effect for a $1.8 M_\odot$ model with uniform rotation: the frequency difference between m and $-m$ components of a multiplet (with given ℓ, n) $d_m = (\nu_m - \nu_{-m})/(m(C-1))$ is plotted versus $\nu_{m=0}$ for a $\ell = 2$ mode (C is the Ledoux constant). In the absence of cubic effects, the ℓ quantities d_m $(m = 1, \ell)$ are the same and yield the true rotation. When cubic effects become non-negligible, the true rotation value can be lost. It is however possible to combine the different d_m so as to eliminate these high order perturbations and to recover the rotation rate as shown here with the solid line with dots (Goupil et al., in preparation).

Local conservation of angular momentum: When the rotation profile in the equilibrium model is assumed to derive from local conservation of angular momentum, the period ratios of radial modes evolve differently than for a uniform rotation or no rotation. As an example, the period ratio P_1/P_0 of the first overtone to the fundamental radial modes for a 1.8 $M_\odot$ model takes the values 0.799, 0.778, 0.773 at ages corresponding to a central hydrogen left content 0.91,0.44,0.18 % respectively and a rotational velocity 180, 140, 100 km s^{-1} respectively. This is to be compared with values of the same period ratio of models built with (180, 140, 100 km s^{-1} respectively) uniform rotation velocities, i.e., 0.797, 0.767, 0.773, respectively. When the star has evolved enough, its rotation rate has decreased and $P_1/P_0 \sim 0.773$ which is also the period ratio without rotation (Suarez et al., in preparation).

Rotationally induced mixing: The reality is more complicated as it is likely that the rotation is neither uniform nor its profile determined by conservation of local angular momentum but some case in between. Figure 4 (left) shows several evolutionary tracks in an HR diagram which correspond to different assumptions

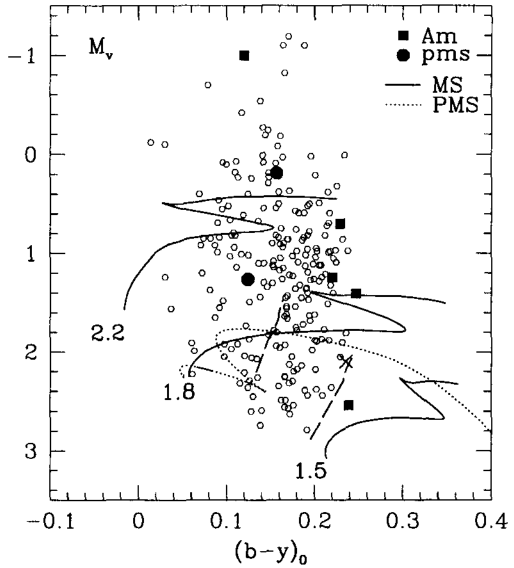

Figure 1. Absolute magnitude versus Strömgren color indice $(b-y)_0$. Open circles are observed δ Scuti stars from Rodriguez et al. (2000, see also Rodriguez & Breger, 2001 for details). Theoretical luminosities and effective temperatures were transformed into observed quantities using the BaSel Stellar Library (Lejeune et al., 1998). The solid lines represent theoretical evolutionary tracks – obtained with the CESAM code (Morel, 1997) – for 3 masses (in solar unit, labeled in front). The dotted line pictures the PMS 1.8 $M_\odot$ evolution. The dashed lines indicate the theoretical blue and red edges for the fundamental radial mode. Two PMS stars (filled circles) and a few Am variable stars (squares) are represented. The cross is discussed in Sect. 3.

for the core overshooting amount and the rotation. Rotation induces mixing which can be interpreted as overshooting in an HR diagram although the tracks are not quite equivalent. For instance, the track without overshoot but with rotational velocity $v = 100$ km s^{-1} at the triangle in Fig. 4 (left) mimicks evolution with an overshoot 0.2 H_p and no rotation. We now consider 3 models which are at the same location in the HR diagram (triangles), which can be representative of FG Vir as shown by the error bars (from Breger et al., 1998). The structures of these models – as represented here by the Brünt-Väissälä frequency N (Fig. 4 right) – are similar but extra mixing due rotation modifies the shape of the inner maximum of N. Signatures of these fine structures in frequencies of mixed and g modes should be detectable.

Rotation modifies the photometric parameters which yield the effective temperature and the luminosity. These effects have been recently recomputed (Pérez Hernández et al., 1999; Deupree, 2001): stars appear red-shifted, with

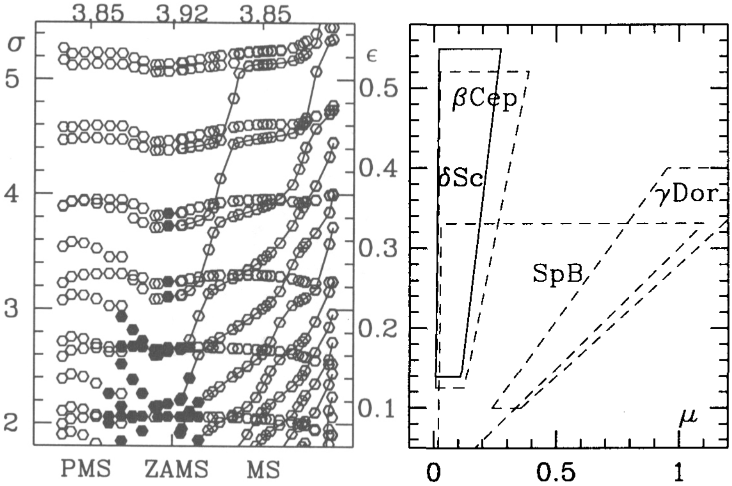

Figure 2. Left: evolution of dimensionless frequencies σ with age for a $1.8\,M_\odot$ model from PMS to end of MS stages. Full dots are stable modes. Solid lines help to follow the progression of the avoided crossings. Only $\ell = 0$ and $\ell = 2$ are shown. The fundamental radial mode has $\sigma \sim 2$, the first overtone has $\sigma \sim 2.6$. The top scale is $\log T_{\rm eff}$. Right: $\epsilon - \mu$ diagram: solid lines delimit the region relevant for δ Scuti stars. Regions for other types of stars are also shown.

increased or decreased luminosity depending on i. The effect can be as large as $\Delta T_{\rm eff} = 100\,{\rm K} - 450\,{\rm K}$; $\Delta M_{\rm v} = 20 - 25\%$. This can have drastic consequences for overshoot and stellar age determinations which are important for studies of galactic evolution. When the age of a cluster is determined by a fit with an isochrone, an uncertainty of $\Delta\alpha_{ov} = 0.15$ on the amount of overshoot leads to an uncertainty of $\sim 25\,\%$ on the age (Lebreton et al., 1995). The Hyades are a very well known cluster. In the hook region – at the end of core H burning – which yields the age and is sensitive to the overshoot amount, stars are rapid rotators. Effects of rotation on photometric parameters have been used to compute isochrones for models with a rotational velocity 100 km s^{-1} for the Hyades cluster and compare with the observed Hyades stars (Lebreton et al., 2001). The resulting change of the isochrone shapes can modify the age cluster by a few million years. In the hook region, there are 8 δ Scuti stars among the rapid rotators (Antonello & Pasinetti, 1998). Seismic constraints on the overshooting from these pulsating stars, once their rotation is taken into account, will be valuable.

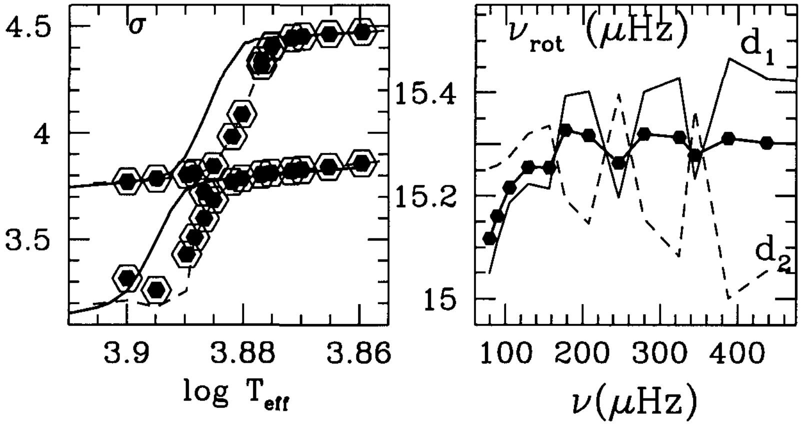

Figure 3. Left: Zoom of Fig. 2 for 1.8 $M_\odot$ models with zero rotation (solid line). The dashed line is for rotation (v = 150 km s^{-1}) up to second order effect but without rotational degeneracy. Dots do include rotational degeneracy. Right: d_m for $\ell = 2$ modes for a 1.8 $M_\odot$ model ($X_c = 0.35$) with v = 144 km s^{-1} with $m = 2$ (dashed line), $m = 1$ (thin solid line). The solid line with dots is $d_1 + d_2$ and the true rotation rate is $\nu_{\rm rot} = 15.3\mu$Hz.

3. Vibrational instability: driving/damping

Studies of energetic properties of stellar oscillations usually use the simplest assumption of *frozen in convection*, i.e. neglect of the convective flux perturbation. In that situation, recent works have confirmed that very high degree modes (up to 1000) can be excited by opacity driven mechanisms. Modes with $\ell < 12$ can probe the inner interior properties, while modes with $\ell > 12$ are trapped in the envelope (Balona & Dziembowski, 1999). However, investigation of the stability properties of the modes for δ Scuti stars requires a *nonlocal time dependent formulation of the convection and its coupling with pulsations*. Using such an adapted version of mixing length theory (Gough, 1977; Houdek et al., 1999), it is found that the turbulent pressure is essential in stabilizing the opacity driven modes. Additional effects such as acoustic emission are no longer negligible for these masses and can play a destabilizing role by decreasing the efficiency of the convective transport (Houdek, 2000).

Solar like oscillation for δ Scuti stars ? For a model near the red edge (cross in Fig. 1), 3 radial modes (fundamental and first two overtones) are found unstable. Furthermore, the computed acoustic power for the stable high frequencies is large enough that amplitude in velocity can reach 1 m s^{-1} (Samadi et al., 2001), an amplitude detection level already reached in other stars[1]. Hence, models predict that some δ Scuti stars can present simultaneously both types of oscillations. This would be very valuable as the high frequency modes are easier to identify.

Microscopic diffusion with mild turbulence in the outer layers, has had time to act (Turcotte et al., 2000; Turcotte, these proceedings) but for rapidly rotating δ Scuti stars, sedimentation effects are destroyed by rotation. On the other hand, effects of *fast rotation* (up to $O(\epsilon^2)$) upon modal stability was investigated in the case of pulsating hot (OB) stars (Lee & Baraffe, 1996; Saio et al., 2001); some conclusions are likely to apply to δ Scuti stars as well. For the few cases investigated, the rotational stabilizing effect is stronger for high frequency than low frequency p modes as rotation is larger in the outer layers. Furthermore the stabilizing effect of rotation is different for modes with different degrees or azimuthal orders. For instance, the mode with $\ell = |m| = 3$ is stabilized by rotation at $\epsilon > 0.2$ whereas $\ell = |m| = 1$ is less affected. These differential effects can play a role in modal selection and yield unexpected amplitude distributions and frequency spectra. For the most rapid rotators, we must turn to nonperturbative approaches such as those developed by Clement (1998) and Deupree (2001) for instance. Another effect of rotation in modal selection occurs via resonant nonlinear interactions responsible for amplitude limitations (Dziembowski et al., 1988; Buchler et al., 1997). Globally, we must expect excitation and modal selection effects different for young (i.e. rapidly rotating and hot) stars and more evolved (i.e. slowly rotating and cool) stars.

Pre-main sequence δ Scuti stars: The number of known stars (or potential candidates) in this class is now 9 but it increases rapidly (Kurtz & Catala, 2001). Analyses of their pulsations will constrain our knowledge of the evolution of angular momentum prior to the main sequence. Marconi & Palla (1998) have studied the radial oscillations of envelope models with a hydrodynamical code including time-dependent convection in order to determine the instability strip for these stars. The time spent in the PMS instability strip for low radial overtones is found very short (10 % of the Kelvin-Helmholtz time $\tau_{\rm KH}$). Further developments in the field would need multisite campaigns to determine whether the PMS and MS stellar oscillations differ in their amplitude and frequency distributions and which processes dominate in the PMS and MS modal selections. Detecting nonradial modes for these stars would provide information on the differences in their inner structures (Suran et al., 2001). Nonradial mode identification will probably be easier as regular frequency spacings are perturbed only at very low frequency. On the other hand, these young stars are fast rotators ($v \sin i \sim 180$ km s^{-1}) and may present magnetic field (Donati et al., 1997) whose effects on oscillation frequencies must be taken into account. Finally we mention the interesting case of an eclipsing double lined spectroscopic binary system, RS Cha, which is composed of two PMS stars with known masses (Andersen, 1991; Palla & Stahler, 2001) in the open cluster η Cha. As was already emphasized by Andersen and by Palla & Stahler, such PMS stars falling in the

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[1] Barban et al. (1999) found oscillations at the level of 1 m s^{-1} in Procyon, while Bouchy & Carrier (2001) detected modes at a level of 35 cm s^{-1} in α Cen A.

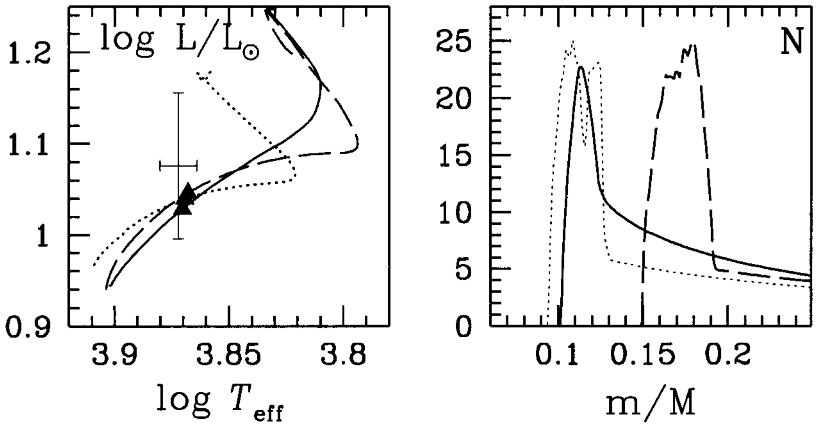

Figure 4. Left: tracks in a HR diagram: without overshooting nor rotation (dotted line); without rotation but an overshoot of 0.2 H_p (long dashed line). The solid line has no overshoot but rotation is included (v = 100 km s^{-1} at the triangle). Right: inner maximum of the normalized Brunt-Väissälä frequency in the inner region of the model located with a triangle (same line style as in left panel).

instability strip are probably variable and as they belong to a well-known binary system, their pulsations are worth to detect and model.

4. Mode identification: nonadiabatic observables

A very difficult but essential field has developed in recent years, namely mode identification which consists in assigning ℓ, m, n values to observed modes.

Multicolor photometry can provide information about ℓ. The intensity perturbation depends on several quantities $(i, \ell, \nu, \epsilon, R, \psi)$ (Garrido, 2000); here i is the inclination angle, ϵ is the intrinsic amplitude, R is a measure of the importance of nonadiabaticity and ψ is the phase lag between maximum temperature and minimum radius. The amplitude ratio A_{b-y}/A_y, for instance, allows to suppress the effects of i and ϵ, hence providing ℓ for each mode given its (R, ψ). (R, ψ) can be computed from models assumed appropriate energy transfer or from three-color observations. Hence comparing both allows to test the convection treatment in outer layers (Garrido et al., these proceedings). Amplitude-phase diagrams discriminate between ℓ's but suffer from some difficulties: the efficiency is strongly dependent on the mode (better for fundamental). These diagrams loose efficiency for hot stars ($T > 8000$ K) (Garrido, 2000) and is α-dependent for cool stars ($T < 7500$ K) (Balona & Evers, 1999). In addition, for fast rotators A_{b-y}/A_y depends on i (Soufi et al., 1998; Balona & Dziembowski, 1999)

Spectroscopic analyses can provide ℓ, m, i as nonradial pulsations generate Doppler shifts and line profile variations (Aerts & Eyer, 2000). Briefly, high ℓ (up to 20) for fast rotators are obtained with the Fourier Doppler imaging technique (Kennelly et al., 1998). Identification of low ℓ ($\ell < 6$) can be obtained with the moment method which also gives m, i but some unrealistic simplifying assumptions must be removed from the theoretical modelling (Balona, 1987; Aerts et al., 1992; Cugier & Daszynska, 2001).

Reliability of these various mode identification techniques requires very high quality data (Paparo & Sterken, 2000), very high quality model atmospheres (Garrido, 2000), an evaluation of the consequences of observational uncertainties but also a deeper theoretical understanding and validations with known cases.

5. Toward seismology: facing the reality

In the young seismological history of δ Scuti stars, there was a first generation of attempts to match the observed frequencies with theoretical ones for a few specific stars: 4 CVn (Breger et al., 1990); 63 Her (Mangeney et al., 1991); GXPeg (Goupil et al., 1993). These types of seismic studies were promising but showed many deficiencies. Remedies had then been to collect much higher quality data, determine very precise stellar parameters, take into account nonstandard processes such as rotation and develop techniques of mode identification.

5.1. Several observational networks and strategies

Focusing on one interesting star: A first strategy is to focus on one specific star and devote several multisite campaigns to this star: FG Vir (DSN, Breger et al., 1998); XX Pyx (WET, DSN, Handler et al., 2000) with the detection of 24 frequencies and 30 frequencies respectively. A large number of frequencies were also detected for other types of δ Scuti stars: evolved: (4 CVn, DSN, Breger et al., 1999b); spectroscopic binary (θ^2 Tau, DSN, Breger et al., 1989; MUSICOS, Kennelly et al., 1998); Algol type system (θ Tuc, Paparo et al., 1996).

Open clusters: Two other networks, STEPHI and STACC, concentrated their efforts in observing several stars in one open cluster. For instance, the STEPHI multisite campaigns observed 7 stars in Praesepe (Hernandez et al., 1998). For the Pleiades, see Suarez (these proceedings). Much fewer frequencies (from 3 to 15) are detected for each star. On the other hand, information such as the chemical composition is available. The STACC multisite campaigns observed several open clusters which led to the detection of a large number of new δ Scuti stars, e.g. NGC 1817 (Frandsen & Arentoft, 1998) (8 δ Scuti stars); NGC 7062 (Freyhammer et al., 2001) (>13 δ Scuti stars).

Simultaneous photometry and spectroscopy: The third strategy, adopted by the Merate group for instance, is to observe one given star from one site simultaneously in photometry and spectroscopy. The combined information brought by fitting the line profile and light curve variations yields several constraints in particular on the inclination angle and thus, the rotational velocity. As an example, studies of X Caeli (Mantegazza et al., 2000) yield 17 frequencies, a rotational velocity of $v \sim 73$ km s^{-1} and the identification of $\ell = 0$ and

$\ell = 1, m = -1$ modes. Other cases are BV Cir (Mantegazza et al., 2001); BB Phe (Mantegazza & Poretti, 1999) and 1 Mon (Balona et al., 2001). These constraints decrease the number of possible model solutions for the star derived from its oscillations.

Monosite photometry or spectroscopy for detection: The fourth strategy keeps on detecting new δ Scuti stars with observations from a single site which are either devoted to that purpose or by accident. For instance, Naini Tal-Cape looks for chemically peculiar variables (Martinez et al., 2001); Koen et al. (1999) detected new δ Scuti stars while looking for λ Bootis stars. The OGLE microlensing survey provided high quality data on high-amplitude δ Scu stars in the Bulge and in the LMC (Poretti, 2001).

5.2. Seismological analyses

The above frequency data sets have then been used to try to derive some information about the stars, for instance FG Vir (Breger et al., 1999a; Viskum et al., 1998); XX Pyx (Handler et al., 2000; Pamyatnykh et al., 1998; Dziembowski et al., 1998); θ Tuc (Templeton et al., 2000; Paparo & Sterken, 2000). The larger number of frequencies allows to search for regular patterns and uniform frequency spacings. Histograms of frequency differences provide the mean density and also, in some easy cases, the rotational splitting. One then deduces for instance that XX Pyx is oscillating in higher overtones than FG Vir while it is younger and hotter. Knowing the mean density restricts the number of possible stellar models. From there on one uses the most updated stellar parameters, models and oscillation codes and compares observed and theoretical frequencies. The difficulties can be seen with the case of FG Vir for which 18 frequencies are observed whereas models predict 30 in the same range (Dziembowski et al., 1998; Guzik, 2000). Even with the conclusion that most modes are axisymmetric (Mantegazza, 2000), mode identification is not unique. These investigations usually conclude that either there is not a unique model and/or not all frequencies can be matched when there is a partial mode identification. The last point is not yet the hint of an incorrect stellar modelling as the discrepancy can still be attributed today to a wrong mode identification.

Seismic analyses in a different spirit have been performed for the Praesepe δ Scuti stars (Michel et al., 1999). The fast rotation of these stars modifies their location in the HR diagram which can be corrected as the stars have the same age. In the absence of mode identification, efforts concentrated on reproducing the radial order range and the width of the instability strip: the observed and theoretical radial order ranges agree when using time dependent convection models but for low mass (cooler) stars, one must either decrease the mixing length parameter or include acoustic emission.

6. Open issues and prospects

Despite obvious progress, we still need to develop further the mode identification techniques, particularly to derive the azimuthal order m. For fast rotators, we must forget about ℓ. The main problem remains our lack of understanding of the observed amplitude distributions and of the processes of modal selection. For instance, 4 CVn is an evolved star with 30 frequencies but models show a much denser theoretical g-mode spectrum: are trapping effects at work ? (Dziembowski, 1997). Amplitude time variations on short time scales and harmonics are observed (Breger, 2000; Arentoft et al., 2001). These can be interpreted as signatures of nonlinear effects: several resonant coupling mechanisms which are likely operating have been identified but a quantitative (i.e. predictive) theory is not yet available (Dziembowski, 1993).

The 3rd generation for the seismology of δ Scuti stars will probably develop with space experiments (MOST 2002; COROT 2004; MONS 2004; Eddington 2007) but results from the 2nd generation work indicate that the targets must be smartly chosen.

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