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# Solar-like oscillations in $\delta$ Scuti stars†

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## Abstract

Model computations of $\delta$ Scuti stars, located in the vicinity of the red edge of the classical instability strip, suggest amplitudes of solar-like oscillations larger than in cooler models located outside the instability strip. Solar-like amplitudes in our $\delta$ Scuti models are found to be large enough to be detectable with ground-based instruments provided they can be distinguished from the opacity-driven large-amplitude pulsations. We anticipate their possible detection in the context of the planned asteroseismic space missions, such as the French mission COROT (COnvection ROtation and planetary Transits). We propose known $\delta$ Scuti stars as potential candidates for the target selection of these upcoming space missions.

## Introduction

The $\delta$ Scuti stars are in general main sequence stars with masses between $1.5\,M_\odot$ and $2.5\,M_\odot$. They are located inside the classical instability strip (IS hereafter) where the $\kappa$-mechanism drives low-order radial and nonradial modes of low degree to measurable amplitudes (opacity-driven unstable modes). Only a small number of opacity-driven modes are observed in $\delta$ Scuti stars (for a review see e.g. Gautschy & Saio 1996), but their amplitudes, which are limited by nonlinear processes, are much larger than stochastically driven intrinsically stable solar-like p modes.

For main-sequence stars with surface convection zones, located outside the IS, model computations suggest all modes to be intrinsically stable but excited

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stochastically by turbulent convection; for models located near the red edge of the IS the predicted velocity amplitudes become as large as 15 times the solar value (Houdek et al. 1999). Moreover, these computations suggest that models located inside the IS can pulsate simultaneously with modes excited both by the $\kappa$-mechanism and by the turbulent velocity field.

Although it is possible from Fig. (13) of Houdek et al. (1999) to conclude that both types of modes can be excited simultaneously in the same star, amplitudes of stochastically excited modes for stars located inside the instability strip were not explicitly carried out by Houdek et al. (1999) and their possible detection were not addressed.

The aim of this paper is to demonstrate that models of stars, located inside the IS and near the red edge, can exhibit both opacity driven modes and solar-like oscillations with sufficiently large amplitudes to be detectable with today's ground-based instruments. Consequently the planned asteroseismology space missions, such as COROT (COnvection ROtation and planetary Transits, Baglin & The Corot Team 1998) or Eddington (Favata et al. 2000), will detect these oscillations even more easily.

## The stellar models

Equilibrium envelope models are computed in the manner of Houdek et al. (1999) using the nonlocal formulation for convection by Gough (1976, 1977, hereafter G'MLT). Integration starts at an optical depth of $\tau = 10^{-4}$ and ends at a radius fraction 0.2. Radiation is treated in the Eddington approximation and the atmosphere is assumed to be gray and plane parallel. In G'MLT formulation two more parameters, $a$ and $b$, are introduced which control the spatial coherence of the ensemble of eddies contributing to the total heat and momentum fluxes ($a$), and the degree to which the turbulent fluxes are coupled to the local stratification ($b$). In this paper we choose $a^2 = 900$ and $b^2 = 2000$ in order to obtain stable modes in the frequency range in which the damping rates exhibit a local minimum. The mixing-length parameter $\alpha$ has been calibrated to a solar model to obtain the helioseismically inferred depth of the convection zone of 0.287 of the solar radius (Christensen-Dalsgaard, Gough & Thompson 1991).

All models assume solar chemical composition and have mass $M = 1.68\,\mathrm{M}_\odot$ and luminosity $L = 11.3\,\mathrm{L}_\odot$, but differ in effective temperature $T_{\rm eff}$, and whether or not acoustic radiation is included in the equilibrium computations. Table 1 lists the fundamental stellar parameters of these models. The models A1, A2 , B1 and B2 are hotter than model C and are located inside the IS and close to the red edge. Models A1 and A2 differ from models B1 and

Table 1: Stellar parameters for the envelope models A1, A2, B1, B2 and C; $R$ is the stellar radius at the photosphere ($T = T_{\rm eff}$), and $\nu_c$ is the acoustic cut-off frequency.

| Model | $T_{\rm eff}$ [K] | $(b-y)_0$ | $R$ [$R_\odot$] | $\nu_c$ [mHz] | acoustic radiation |
|---|---|---|---|---|---|
| A1 , A2 | 6839 | 0.235 | 2.40 | 1.4 | included |
| B1 , B2 | 6839 | 0.235 | 2.40 | 1.4 | neglected |
| C | 6650 | 0.262 | 2.54 | 1.3 | neglected |

Table 2: Acoustic emissivity coefficient $\Lambda$ and Mach-number dependence $\Gamma$ assumed in the acoustic radiation model for the stellar models A1 and A2.

| Model | $\Lambda$ | $\Gamma$ |
|---|---|---|
| A1 | 100 | 5 |
| A2 | 2000 | 7.5 |

B2 by the inclusion of acoustic radiation by turbulence in the envelope calculations (Houdek & Gough 1998). In this model for acoustic radiation in the equilibrium model two more parameters are introduced (Houdek & Gough, 1998): the emissivity coefficient $\Lambda$ and the parameter $\Gamma$ which describes the power-law dependence of the acoustic power emission on the turbulent Mach number. A Mach-number dependence of $\Gamma = 5$ assumes that acoustic emission is dominated by the energy-bearing eddies ; if acoustic emission is predominantly emitted by inertial-range eddies $\Gamma$ has the value 7.5. Table 2 lists the values of $\Lambda$ and $\Gamma$ that are assumed in the models A1 and A2. The values for $\Lambda$ provide for a solar model a similar value for the acoustic flux $F_{\rm ac}$ as the estimates of Stein (1968) and Musielak et al. (1994). For all the models, except for model B2, we assume for the mixing-length parameter the calibrated solar value $\alpha = 2.037$; for model B2 the value $\alpha = 1.5$ is assumed.

Fig. 1 displays the locations of these models in the colour-magnitude diagram. Evolutionary tracks (dashed curves) are shown for models with various masses and are obtained with the CESAM code by Morel (1997) as described by Samadi et al. (2001a). The transformation from luminosity, effective temperature and surface gravity to absolute magnitude $M_{\rm v}$ and dereddened colour indices $(b-y)_{\rm o}$ are obtained from the Basel Stellar Library (Lejeune, Cuisinier & Buser, 1998). The blue and red edges of the fundamental radial modes (solid curves) are calculated in the manner of Houdek et al. (1999). The positions of the observed $\delta$ Scuti stars (filled circles) are taken from Rodriguez et al. (2000):

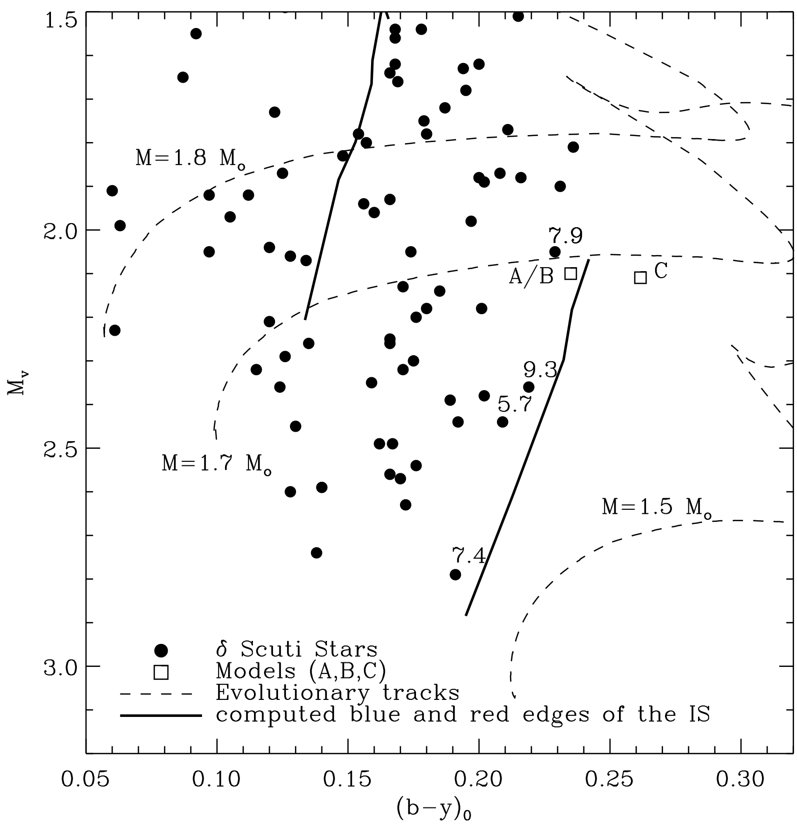


Figure 1: Colour-magnitude diagram: filled circles display the positions of observed $\delta$ Scuti stars from the Rodriguez et al. (2000) catalogue. Squares indicate the positions of the models A1, A2, B1 ,B2 and C (see Tab. 1). Dashed curves show evolutionary tracks for models with masses 1.5 $M_\odot$, 1.7 $M_\odot$ and 1.8 $M_\odot$. Solid curves display theoretical locations of the blue and red edges for the fundamental radial modes according to Houdek et al. (1999). Numbers associated with the symbols indicate apparent magnitudes $V$ for selected observed $\delta$ Scuti stars.

absolute magnitudes, derived from Hipparcos distances and dereddened colour indices were kindly supplied by E. Rodríguez (2001, personal communication; see Rodriguez & Breger 2001, for details).

Table 3: Frequency $\nu$, damping/growth rate $\eta$ and stability coefficient $\omega_{\rm i}/\omega_{\rm r}$ for all overstable radial p modes predicted for the models A1, A2 and B2.

| Model | n | $\nu$ [$\mu$Hz] | $\eta$ [nHz] | $\omega_{\rm i}/\omega_{\rm r}$ $\times 10^{-6}$ |
|---|---|---|---|---|
| | 1 | 123 | -0.03 | 0.25 |
| A1 | 2 | 161 | -0.31 | 1.92 |
| | 3 | 202 | -4.14 | 20.48 |
| | 4 | 244 | -3.90 | 15.97 |
| | 1 | 124 | -0.04 | 0.36 |
| A2 | 2 | 162 | -0.40 | 2.47 |
| | 3 | 203 | -1.27 | 6.25 |
| | 1 | 124 | -0.04 | 0.34 |
| B2 | 2 | 161 | -0.31 | 1.95 |
| | 3 | 203 | -0.83 | 4.09 |

## Stability analysis

The stability computations are as described in Houdek (2000, and references therein). In particular they include the Lagrangian perturbations of the turbulent fluxes (heat and momentum) according to Gough's (1976, 1977) nonlocal time-dependent formulation. Assuming a temporal dependence, $\exp(-{\rm i}\omega t)$, for the pulsations, the complex eigenfrequencies of the modes can be written as $\omega = \omega_{\rm r} + {\rm i}\omega_{\rm i}$, which defines the cyclic pulsation frequency $\nu = \omega_{\rm r}/2\pi$ and the damping/growth rate $\eta = -\omega_{\rm i}/2\pi$. The outer boundary conditions are applied at the temperature minimum, the mechanical boundary condition being consistent with a perfectly reflecting surface; at the base of the envelope, conditions of adiabaticity and vanishing displacement are imposed. In this paper only radial p modes are considered.

For model C all the modes are found to be linearly stable (i.e., $\eta > 0$) as is expected for models lying well outside the IS. This is also found for the hotter model B1. For the model A1 (resp. A2) the first four (resp. three) radial modes, $n$=1,...,4 (resp. $n$=1,2,3), are found to be overstable. With the inclusion of a model for the acoustic radiation in the equilibrium structure the efficacy with which convection transports the turbulent fluxes is decreased (see Houdek & Gough 1998). This leads to a decrease in the turbulent Mach number and to a consequent reduction of the stabilizing influence of the perturbed momentum flux on the mode damping. The driving eventually dominates over the damping leading to overstable modes. Reducing $\alpha$ has a similar effect on mode stability than the inclusion of acoustic radiation in the equilibrium model (see Houdek & Gough 1998, Michel et al. 1999, Houdek 2000). The model B2 was computed with the smaller mixing-length parameter $\alpha = 1.5$, leading to overstable modes with radial orders $n$ =1,2,3.

Table 3 displays the frequency $\nu$ and damping/growth rate $\eta$ for all overstable radial modes ($\eta < 0$) found in the models A1, A2 and B2.

## Excitation rate and amplitude spectrum

Amplitudes of solar-like oscillations result from the balance between damping and stochastic driving by turbulence. The rate at which the turbulence injects energy into the p modes is estimated in the manner of Samadi & Goupil (2001, Paper I hereafter). The rms value of the mode surface velocity, $v_{\rm s}$, is related to the damping rate, $\eta$, and to the rate at which energy is injected into the mode (excitation rate), $P$, by

$$v_{\rm s}^2 = \xi_{\rm r}^2(r_{\rm s})\,\frac{P}{2\,\eta\,I}\,, \tag{1}$$

where $\xi_{\rm r}$ is the radial displacement eigenfunction, $r_{\rm s}$ is the radius at which the surface velocities are measured and which we assume to be 200 km above $T_{\rm eff}$, and $I$ is the mode inertia. The rate of energy injected into a mode is computed according to Paper I and is proportional to

$$P(\omega) \quad \propto \quad \int_0^M \rho\, w^3\, \ell^4 \left(\frac{{\rm d}\xi_{\rm r}}{{\rm d}r}\right)^2 \mathcal{S}(\omega, m)\,{\rm d}m\,, \tag{2}$$

where $\rho$ is the density, $\ell$ is the mixing length, and $w$ is the vertical component of the rms velocity of the convective elements. The function $\mathcal{S}(\omega, m)$ describes approximately contributions from eddies with different sizes to the excitation rate $P$. Detailed expressions for $\mathcal{S}(\omega, m)$ were given in Paper I.

Results for the estimated excitation rate $P$ are depicted in the upper panel of Fig. 2. For the models A1, A2 and B1 the excitation rate $P$ is about one magnitude larger than for model C. This is a result of the larger convective velocities in the superadiabatic boundary layers of the models A1, A2 and B1, which are all hotter than model C. For the models A2 and B2 the efficacy of convection has been reduced severely by either including acoustic radiation in the equilibrium model (A2) or by reducing the mixing-length parameter $\alpha$ to a value much smaller than the calibrated value for a solar model (B2). This results in shallower superadiabatic regions and in larger superadiabatic temperature gradients; pulsation modes in A2 and B2 are therefore predominantly excited at the very top of the convection zone, whereas in the models A1 and B1 the modes are excited over a larger driving region.

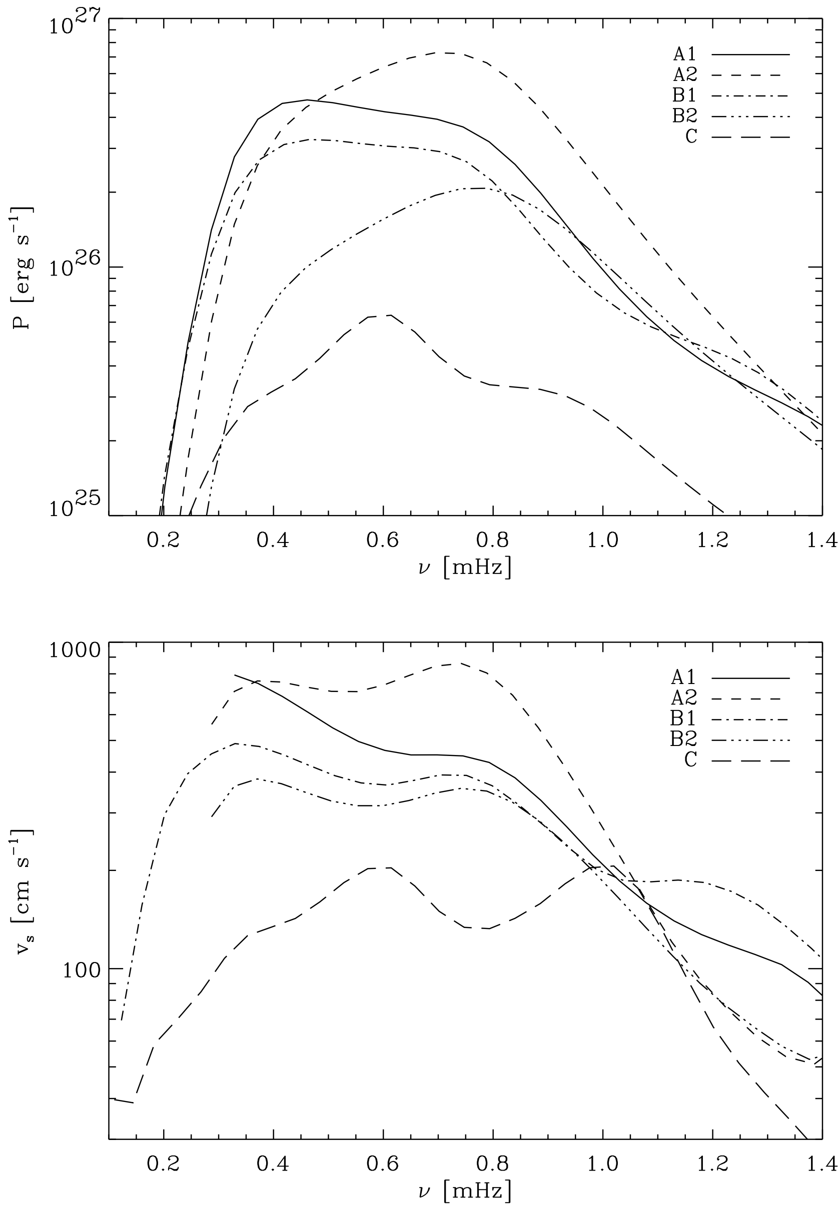


Figure 2: Excitation rate $P$ (upper panel) and estimated velocity amplitudes (lower panel) as a function of frequency for all stellar models.

Table 4: Maximum values of the estimated velocity, $v_{\rm s}$, and luminosity, $\delta L/L$, amplitudes.

| Model | $v_{\rm s}$ [ $\rm ms^{-1}$] | $\delta L/L$ [ppm] |
|---|---|---|
| A2 | 8.6 | 150 |
| A1 | 7.9 | 97 |
| B1 | 4.9 | 101 |
| B2 | 5.5 | 98 |
| C | 2.0 | 84 |

In the lower panel of Fig. 2 the surface velocity amplitudes $v_{\rm s}$ are depicted for all stellar models, computed according to Eq.(1). In the models A1, A2, B1 and B2 the amplitudes of stochastically excited p modes are larger ($\sim 5-9\ \rm ms^{-1}$) than in model C ($\sim 2\ \rm ms^{-1}$). The velocity amplitudes are computed 200 km above the photosphere ($T = T_{\rm eff}$) and do increase by a factor of about two at the outermost meshpoint of the model, i.e. at an optical depth $\tau = 10^{-4}$.

For estimating the luminosity amplitudes the full nonadiabatic luminosity eigenfunctions have to be used. The relative luminosity amplitudes, $\delta L/L$, are linearly related to the velocity amplitudes, i.e. they are proportional to the ratio of the luminosity eigenfunction over the displacement eigenfunction. This ratio is determined by the solution of the nonadiabatic pulsation equations and is independent of a stochastic excitation model (see Houdek et al. 1999). We predict a maximum value of the luminosity amplitude $\delta L/L \sim 97$ ppm for model A1, $\delta L/L \sim 150$ ppm for model A2, $\delta L/L \sim 101$ ppm for model B1 , $\delta L/L \sim 98$ ppm for model B2 and $\delta L/L \sim 84$ ppm for model C. These results are summarized in Table 4.

## Observational constraints for detecting solar-type oscillations

There have been recent reports on the possible detection of solar-type oscillations in $\alpha$ Cen (HD 128620) by Bouchy & Carrier (2001), in $\beta$ Hydri (HD 2151) by Bedding et al. (2001) and in Procyon A (HD 61421) by Martic et al. (1999, see also Barban et al. 1999), who obtained spectroscopic surface velocity measurements of these bright stars (the apparent magnitude $V = 2.80$ for $\beta$ Hydri, $V = 0.34$ for Procyon and $V = -0.1$ for $\alpha$ Cen) from the ground. The maximum values of the observed peak-velocity amplitudes are of the order $\sim 35\ \rm cms^{-1}$ for $\alpha$ Cen, $\sim 50\ \rm cms^{-1}$ for $\beta$ Hydri and $\sim 50\ \rm cms^{-1}$ for Procyon. Current ground-based instruments are able to detect oscillations with velocity amplitudes of the order predicted for our models A1, A2 and B1, B2, but only for stars with an apparent magnitude $V$ of less than $\sim 3-4$ (Bouchy, personal communication). The HARPS (High-Accuracy Radial-velocity Planetary Search) project (Bouchy & Carrier 2001), for example, will be able to detect oscillations with our predicted velocity amplitudes for stars with an apparent magnitude smaller than $\sim 4-5$. This detection threshold is still too small for detecting solar-type oscillations in currently known $\delta$ Scuti stars located near the red edge of the IS, particularly in view of the fact that most of the currently known $\delta$ Scuti stars are even fainter. For example, the apparent magnitudes of known $\delta$ Scuti stars located nearest to the red edge (see Fig. 1) are between $V = 5.7$ and $V = 9.3$.

Future space missions with instruments dedicated to asteroseismology, however, will be able to detect solar-like oscillations in $\delta$ Scuti stars: the forthcoming space project COROT (Baglin & The Corot Team 1998), for example, will reach a noise level of $0.7$ ppm (Auvergne & The Corot Team 2000) for a star with an apparent magnitude of $V = 6$, using photometric measurements. Therefore, in stars with similar magnitudes, COROT will be able to detect oscillation amplitudes as small as $\sim 3$ ppm, a value which is similar to that measured in the Sun. The instrument on COROT will be limited by the photon noise only for stars with magnitudes larger than $V \simeq 9$: i.e., for a star with magnitude $V \simeq 8$ the detection threshold will be $\sim 5$ ppm. This threshold is small enough to detect and measure many solar-like oscillations in $\delta$ Scuti stars which are similar to the $\delta$ Scuti models considered in this paper.

## Conclusion

We studied oscillation properties in $\delta$ Scuti stars located near the observed red edge of the classical instability strip. Such stars can pulsate with both opacity-driven modes and intrinsically stable stochastically driven (solar-like) modes. The estimated velocity amplitudes of the stochastically driven modes in our $\delta$ Scuti models are found to be larger than in cooler and pulsationally stable models lying outside the IS. This result supports the idea that solar-like oscillations in $\delta$ Scuti stars may be detected.

Including a model for the acoustic radiation in the equilibrium model results in a cooler red edge and does effect the properties of the excitation rate of p modes (see also Houdek & Gough 1998, Houdek 2000); in particular the pulsation amplitudes become larger and are predicted to be largest for a model with the largest acoustic flux $F_{\rm ac}$ (i.e., model A2). Moreover, for the $\delta$ Scuti models considered in this paper, overstable modes were predicted only if either acoustic emission in the mean stratification was included or if the mixing-length parameter was reduced to a value smaller than suggested by a calibrated solar model.

A potential target star should neither be too cool (i.e., no opacity-driven modes) nor too hot (i.e., stochastically excited modes with amplitudes too small to be detectable). We quantify this with the illustrative case of our $\delta$ Scuti models with a mass $M = 1.68\,\mathrm{M}_{\odot}$ and we identify the following $\delta$ Scuti stars from the Rodriguez et al. (2000) catalogue, located near the red edge, as potential candidates for the target selection of upcoming observing campaigns: HD57167, HD14147, HD208999 and HD105513.

Although the amplitudes of the solar-type oscillations, predicted in our $\delta$ Scuti models, are large enough to be detected from ground, today's ground-based instruments will detect such oscillations only in brighter $\delta$ Scuti stars with an apparent magnitude of up to $V \sim 3-4$ (Bouchy 2001, personal communication). However, new ground-based observing campaigns, such as the HARPS project (Bouchy & Carrier 2001) will be able to detect stochastically excited oscillations in $\delta$ Scuti stars with an apparent magnitude of up to $V \sim 4-5$. Unfortunately, there are no such bright stars in the Rodriguez et al. (2000) catalogue which are located near the red edge, although some bright stars near the red edge may have opacity-driven modes with amplitudes too small to be detectable with today's ground-based instruments and are therefore not classified as $\delta$ Scuti stars.

The forthcoming space missions for asteroseismology, such as COROT and Eddington will be able to detect solar-like oscillations in faint $\delta$ Scuti stars. The large instrument on the Eddington spacecraft will measure stellar oscillations with amplitudes as small as $1.5$ ppm in stars with an apparent magnitude of $V \simeq 11$ assuming an observing period of 30 days. Moreover, Eddington's large field of view will allow it to monitor a large number of stars simultaneously. This will be helpful for detecting and classifying new $\delta$ Scuti stars and for measuring the location of the red edge of the IS with greater precision than it was possible before.

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