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Pulsation, Rotation and Flares in A Stars

Invited talk

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Abstract. New observations of *Kepler* δ Scuti stars show that our understanding of pulsation in these stars is incomplete. A large fraction of A and B stars exhibit rotational modulation in light, suggesting that spots exist in stars with radiative envelopes. Flares are seen in some A stars, as may be expected if starspots are present. Differential rotation shear increases from M to F but decreases for A stars; it reaches a maximum among the γ Doradus variables. Current views of stars with radiative envelopes may need to be reviewed in the light of these observations.

Keywords. Stars: early-type, oscillations, spots, flares, rotation.

1. Introduction

The *Kepler* satellite has provided almost continuous photometry of stars over a period of four years with a cadence of 30 min. I have inspected the light curves and periodograms of over 20 000 of the brightest *Kepler* stars and classified them according to variability type. This report presented a summary of recent findings concerning pulsation and rotation in A stars. Many of the results are surprising, and do not follow what might be expected on the basis of long-held views on the envelopes of stars with radiative atmospheres.

2. The Problem of the δ Scuti Stars

Prior to *Kepler*, it was taken for granted that δ Scuti stars only pulsated in high frequencies ($\nu > 5\,\mathrm{d}^{-1}$), in agreement with models where driving is through the opacity κ mechanism in the He II ionisation zone. Low frequencies ($\nu < 5\,\mathrm{d}^{-1}$) were seen in a few δ Sct stars which were then called δ Sct/γ Dor hybrids. The γ Doradus stars lay on the cool edge of the δ Sct instability strip; the hybrids seemed to straddle the two instability regions.

From the beginning of the *Kepler* mission it became clear that this view was wrong. Grigahcène *et al.* (2010), already showed that the hybrids are distributed uniformly across the instability strip. There are very few δ Sct stars without low frequencies, making the term 'hybrid' redundant. On the other hand, γ Dor stars are still distinguished as a separate class since they do not pulsate with frequencies above $5\,\mathrm{d}^{-1}$ and are confined to cooler end of the instability strip ($6500 \lesssim T_{\rm eff} \lesssim 7500\,\mathrm{K}$; see Fig. 1).

Recent work has shown that several mechanisms may be responsible for driving pulsations in the δ Sct stars. The well-known κ mechanism alone does not lead to a red edge. The top of a convection cell not only transports heat to the layer above, but also transfers momentum. This transfer of momentum acts as a pressure, referred to as 'turbulent pressure'. The turbulent pressure term, in general, acts to drive pulsations. In the deep interior of a convective zone, turbulent kinetic energy dissipation (the thermodynamic coupling between convection and oscillations) acts to damp pulsations. In order

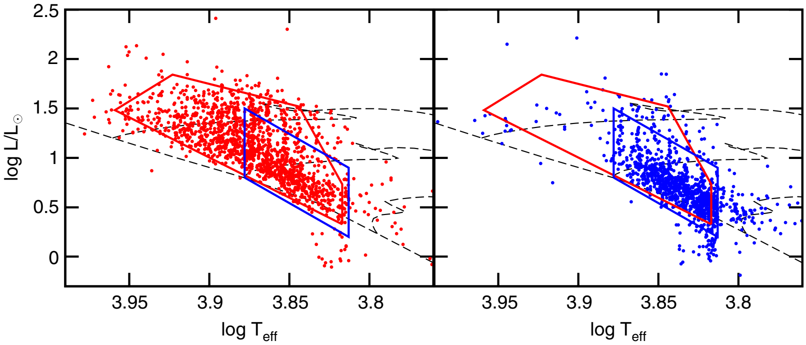

Figure 1. The theoretical H–R diagram showing the *Kepler* δ Scuti stars (*left*) and their approximate instability region (polygon), and the *Kepler* γ Doradus stars (*right*) and their instability region (polygon). The dashed line is the zero-age main sequence and evolutionary tracks for stars with 1.2, 1.6 and 2.0 $M_\odot$.

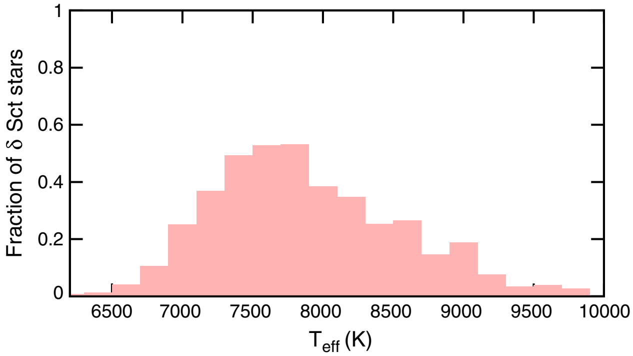

Figure 2. Fraction of δ Scuti stars as a function of effective temperature.

to account properly for those additional terms, it is necessary to use a time-dependent perturbation theory because the convection turn-over time-scale is comparable to, or longer than, typical pulsation periods.

According to the time-dependent convection model of Houdek (2000), the damping of pulsations at the red edge of the δ Sct instability strip appears mostly to be due to fluctuations of the turbulent pressure which oscillates out of phase with the density fluctuations. However, in the models of Xiong (1989) and Dupret *et al.* (2005), turbulent pressure driving and turbulent kinetic energy dissipation damping cancel near the red edge and stability is determined by the perturbations of the convective heat flux. All models are able to predict the red edge, but further research is necessary to identify the correct processes that define the location of the cool edge of the classical instability strip. A more detailed discussion can be found in Houdek & Dupret (2015).

In a recent paper, Xiong *et al.* (2016) have been able to reproduce the low frequencies right across the instability strip by the use of a particular non-local time-dependent convection theory. They conclude that δ Sct and γ Dor stars should be considered as a single type of pulsating star. The difference in frequency ranges are explained by the interplay between the driving and damping terms described above.

Unfortunately, none of the current theories allows for the fact that not more than half of the stars in the δ Sct instability strip actually pulsate (Balona & Dziembowski 2011), as shown in Fig. 2. Since the *Kepler* observations allow detection of pulsation amplitudes

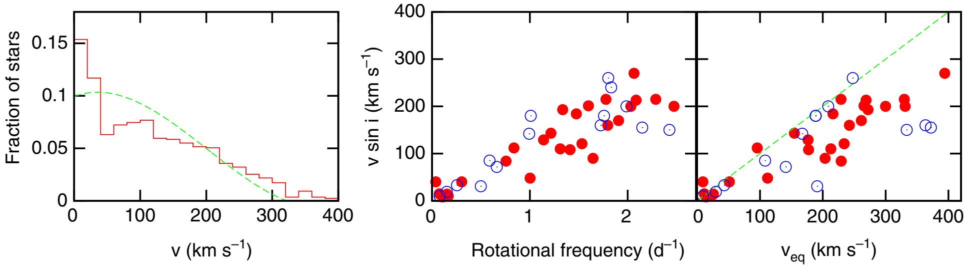

Figure 3. *Left:* Distribution of equatorial rotational velocities derived from the *Kepler* photometry and radii of 875 A stars (histogram), compared with that derived from $v \sin i$ measurements of field A stars (dashed line). *Centre:* Observed $v \sin i$ values of *Kepler* stars as a function of their photometric frequencies. Filled circles are A0–A9 stars; open circles are B5–B9 stars. *Right:* $V \sin i$ for the same stars as a function of equatorial rotational velocity derived from the photometric period and stellar radius. The dashed line has unit slope.

as low as a few micromagnitudes, it is difficult to argue that pulsations are present but undetectable. There seems to be an unknown mechanism which damps the instability in some stars but not in others with the same stellar parameters. Another inexplicable factor is that, given several δ Sct stars with approximately the same stellar parameters, the pulsation frequencies and amplitudes that are observed are completely different (see Fig. 8 of Balona *et al.* 2015). These observations are difficult to understand in terms of the current view of the outer stellar envelopes of early-type stars.

3. Spots and Flares

Soon after the first release of *Kepler* data it became evident that a significant fraction of A stars showed peaks at frequencies roughly corresponding to their expected rotational frequencies. Indeed, the light-curves strongly resembled those of cool stars known to have starspots (Balona 2011). A more complete analysis of the low-frequency variations in *Kepler* A-type stars (Balona 2013) showed that about 40% of A stars exhibit a low-frequency peak and its harmonic. The distribution of equatorial rotational velocities, obtained from the photometric frequencies and the estimated stellar radii of 875 A-type stars, closely matches the distribution expected from the spectroscopic projected rotational velocities of field A-type stars (Fig. 3).

Recent spectroscopic observations of A stars in the *Kepler* field, mostly by Niemczura *et al.* (2015), have enabled the photometric frequencies to be compared directly to their projected rotational velocities ($v \sin i$), as shown in the two right panels of Fig. 3. There can be no doubt that the photometric periods are the same as the rotation periods. The number of B stars observed by the *Kepler* and K2 missions are not very large, but it seems that rotational modulation is also common among the B stars (Balona 2016).

The simplest explanation is that the rotational modulation is due to starspots. Indeed, time-frequency diagrams of early A-type stars show that their frequencies and amplitudes vary with time, as found in cool stars with spots (Balona 2017). The approximate sizes of the spots can be estimated from the amplitude of rotational modulation on the assumption that spots are circular and completely dark. The sizes of spots on A-type stars are about the same as in other stars (left panel of Fig. 4). From visual classification of the ∼20 000 *Kepler* stars, it appears that the fraction of main-sequence stars with spots is much the same across the H–R diagram (right panel of Fig. 4).

The discovery that some A stars in the *Kepler* field show flare-like events is even more surprising (Balona 2012). It is natural to expect the flares to originate in a cool companion, since most A-type stars are probably double or multiple systems. Indeed,

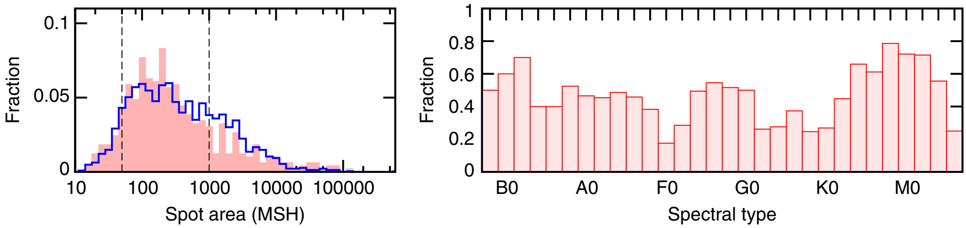

Figure 4. *Left:* Distribution of spot sizes in micro-solar hemispheres for A-type stars (filled histogram), and for all stars combined (line). The two vertical dashed lines correspond to typical sunspot sizes at solar maximum and the largest sunspot group ever observed. *Right:* Fraction of main-sequence stars in the *Kepler* field of a given spectral type which may be classified as rotational variables (i.e. spotted stars).

Pedersen *et al.* (2017) have found that most of the flaring A-type stars are spectroscopic binaries, and find no compelling evidence to suggest that the flares originate in the A-type stars themselves. If the *Kepler* measurements of an A-type star were to be contaminated by the proximity of a cool star, the measured effective temperature would not be that of an A star but that of an F or G star. In that case the star would not even appear on the list of flaring A stars. Pedersen *et al.* (2017) confirm that the flare stars are indeed A-type stars.

The fact that an A-type star might have a cool companion does not prove that the origin of the flare is the cool star, but neither can one assume that it is the A star. The fact that A-type stars have spots removes the argument that they cannot have surface magnetic fields and therefore cannot flare. Since it is not possible to resolve the stellar discs optically, some other independent evidence is required to clarify this matter.

An M- or K-type companion is about 50–100 times less luminous than an A-type star. The flare amplitude originating in a cool companion should therefore, on average, appear to be about 50–100 times smaller when observed together with the A-type star. From a study of long-cadence *Kepler* data, the mean flare amplitude in 51 A-type stars is about the same as in *Kepler* K–M stars (Balona 2015). That could be taken as an indication (but not a proof) that the flares originate in the A-type stars.

Flares appear to be seen in 2.8% of all main-sequence A-type stars (Balona 2015). Using the same criterion for detecting flares, it was found that 12.8% of K–M stars flare. The larger fraction among cool stars may simply be due to the fact that it is more difficult to detect flares in A-type stars because their brightness is so much higher in the blue and UV where most of the flare emission occurs.

4. Differential Rotation

Meridional circulation arises as a result of the thermal imbalance caused by the temperature difference between the pole and the equator in a rotating star. The interplay between meridional circulation, convection and the Coriolis force produces differential rotation. Differential rotation of main-sequence dwarfs is predicted to vary mildly with rotation rate, Ω, but to increase strongly with effective temperature, $T_{\rm eff}$. Differential rotation has been measured by different techniques on less than 100 stars, a sample too small to determine its dependence on both $T_{\rm eff}$ and Ω.

The large number of stars in the *Kepler* field with photometric rotational modulation enables the differential rotation shear, $\Delta\Omega$, to be estimated. Balona & Abedigamba (2016) used time-frequency diagrams of 2562 M–A stars to measure the rotational frequency spread. By using 82 stars similar to the Sun, the statistical relationship between frequency spread and $\Delta\Omega$ can be calibrated (assuming that those stars have about the

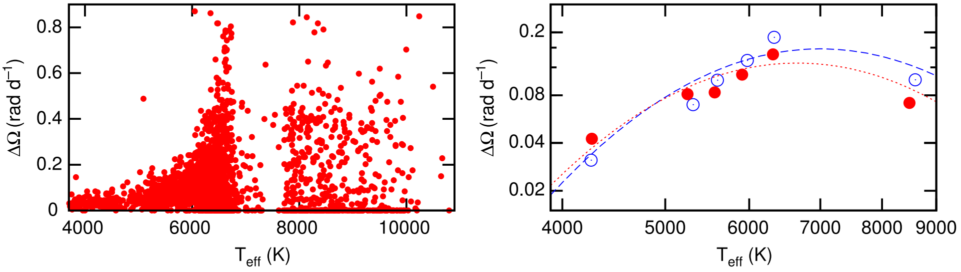

Figure 5. The differential rotation shear, ΔΩ, as a function of effective temperature for *Kepler* main-sequence stars. *Left:* Measurements for all 2562 stars (the gap is due to the omission of γ Dor stars). *Right:* Relationship for stars with rotation periods in the range 4.3–6.8 d (open circles) and 6.8–10.3 d (filled circles). The curves show the empirical calibration in terms of $T_{\rm eff}$ and Ω.

same differential rotation shear as the Sun). In that way the relationship between ΔΩ and both $T_{\rm eff}$ and Ω can be determined (Fig. 5). The theories of Küker & Rüdiger (2007) and Kitchatinov & Olemskoy (2012) predict correctly the observed variation with $T_{\rm eff}$ at constant rotation period, but there are discrepancies between theory and observation in the relationship between ΔΩ and Ω at constant $T_{\rm eff}$.

In those theories, the A stars were not considered. Nevertheless, Fig. 5 suggests that the dependence of ΔΩ on $T_{\rm eff}$ continues smoothly from the F stars to the A stars. In other words, the break that one might have expected in the transition between convective envelopes in the cool stars to radiative envelopes in the A stars is not present.

Stars within the γ Dor instability strip have been omitted, which accounts for the gap in measurements shown in the left panel of Fig. 5. In most cases it is not clear whether the multiple peaks in these stars are due to pulsation or differential rotation. It is interesting that rotational shear attains its maximum value precisely in the region of the γ Dor stars. Clearly, the possibility that one or more peaks in the periodogram are of rotational origin needs to be taken into account, not only for γ Dor stars but probably also for Slowly Pulsating B-type variables.

5. Conclusion

In current models of stellar pulsation, there is no reason why all stars in the δ Sct instability should not pulsate, but the *Kepler* results show that the fraction of pulsating stars does not exceed 50%. Furthermore, stars with similar parameters should have similar pulsation frequencies, but observations show large differences in the frequencies and amplitudes of stars with similar effective temperatures and luminosities. The presence of low frequencies in the vast majority of δ Sct stars still remains a problem. Although the introduction of effects such as turbulent pressure and turbulent kinetic energy dissipation are important, the theory is clearly incomplete.

The detection of spots on a considerable fraction of A and B-type stars suggests that small-scale magnetic fields are common in stars with radiative envelopes. At this stage we do not have an explanation of how such fields may be generated. (Spruit 2002) suggested that mass motions resulting from differential rotation may replace convection in the dynamo theory and could generate a magnetic field in stars with radiative envelopes. It is possible that these mass motions, if they exist, may also have an important effect on pulsational stability. *Kepler* observations show that differential rotation is indeed present in at least some A-type stars.

Flares are seen in some A-type stars, but whether or not they originate in the A star itself remains an open question. It is known that flares are associated with spots in the

Sun and in cool stars. If one is of the opinion that A-type stars do not flare, it is necessary to explain why that correlation breaks down for A stars.

This new perspective on A and B-type stars shows that current views on stars with radiative envelopes may need to be revised. This revision will have clear implications not only for pulsational stability and the origin of surface magnetic fields, but also for the role of diffusion in A-type stars.

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