SuperWASP observations of pulsating Am stars


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ABSTRACT

We have studied over 1600 Am stars at a photometric precision of 1 mmag with SuperWASP photometric data. Contrary to previous belief, we find that around 200 Am stars are pulsating δ Sct and γ Dor stars, with low amplitudes that have been missed in previous, less extensive studies. While the amplitudes are generally low, the presence of pulsation in Am stars places a strong constraint on atmospheric convective, and may require the pulsation to be laminar. While some pulsating Am stars have been previously found to be δ Sct stars, the vast majority of Am stars known to pulsate are presented in this paper. They will form the basis of future statistical studies of pulsation in the presence of atomic diffusion.

Key words. asteroseismology – stars: chemically peculiar – stars: oscillations – stars: variables: delta Scuti – techniques: photometric

1. Introduction

In the region of the Hertzsprung-Russell (HR) diagram where the Cepheid instability strip extends across the main sequence, there is a complex relationship between stellar pulsation and atmospheric abundance anomalies that is not fully understood. This region ranges from the early A stars to mid-F stars in spectral type, and from the zero age main sequence to the terminal age main sequence in luminosity. Found here are the strongly magnetic chemically peculiar Ap and Fp stars, the non-magnetic metallic-lined Am stars, the rarer metal-deficient magnetic chemically peculiar Ap and Fp stars, the non-magnetic δ Sct stars, γ Dor stars and rapidly oscillating Ap (roAp) stars. Much has been written about these stars and their physics, which we briefly summarise here. For more detailed discussions see Joshi et al. (2006), Kurtz & Martinez (2000) and Kurtz (1989, 1978, 1976).

Most stars in the main-sequence region of the instability strip are normal abundance δ Sct stars with relatively high rotational velocities – usually v sin i ≥ 100 km s^{-1}. A large fraction of A stars are Am stars, peaking at around 50 per cent at A8, but Am stars are believed either not to pulsate as δ Sct stars, or may do so with much smaller amplitudes than the normal abundance δ Sct stars. Am stars are mostly found in short period binary systems with orbital periods between 1–10 d, causing synchronous rotation with v sin i ≤ 120 km s^{-1} (Abt 2009); a few single Am stars with similar slow rotation are known.

The magnetic Ap stars are rarer, constituting less than 10 per cent of the A stars. They have very strong global magnetic fields and are often roAp stars with high overtone p mode pulsations with much shorter periods than the δ Sct stars. No Ap star is known to be a δ Sct star. Our physical understanding is that atomic diffusion – radiative levitation and gravitational settling – stabilises the slowly rotating Ap and Am stars so that low overtone p modes are not excited; particularly important in this context is the gravitational settling of helium from the He ionisation zone where the κ-mechanism drives the pulsation of δ Sct stars (see Aerts et al. 2010). Otherwise, the more rapidly rotating stars remain mixed because of turbulence induced by meridional circulation and are excited by the κ-mechanism (Turcotte et al. 2000).

The understanding of the relationship of the long-established δ Sct stars to the more recently discovered γ Dor stars is currently in flux. Previously, the δ Sct stars were known as p mode pulsators, while the γ Dor stars were known as g mode pulsators. The instability strips for these classes of stars partially overlap, and some “hybrid” stars were discovered with pulsation in both p modes and g modes. A striking case is that of HD 8801, which is an Am star that shows both δ Sct and γ Dor p-mode and g-mode pulsation (Henry & Fekel 2005).
Hybrid stars that show both p modes and g modes are of particular interest asteroseismically because the p modes characterise the conditions primarily in the outer part of the star, while the g modes test the core conditions. Now with data from the Kepler Mission, which is obtaining nearly continuous data for over 150,000 stars for 3.5 y, mostly with 30-min cadence, but for 512 stars with 1-min cadence (Gilliland et al. 2010), the Kepler Asteroseismic Science Consortium (KASC) is studying numbers of δ Sct stars and γ Dor stars at μmag precision. It is becoming clear that hybrid stars are common and may be the norm, so that the classes of δ Sct and γ Dor stars are merging (Grigahcène et al. 2010). Interestingly, the latter authors find a possible correlation among the hybrid stars and Am spectral classification.

The Kepler Mission through KASC will model individual Am stars that are δ Sct pulsators with data of such high precision that new insight into the physics of the relationship between atomic diffusion and p mode pulsation will be obtained. But Kepler has a limited number of Am stars in its 105 deg² field-of-view. Another complementary source of information is to look at the statistics of pulsation in Am stars over the entire sky. That is now possible with the highly successful SuperWASP planetary transit-finding programme (Pollacco et al. 2006) that has surveyed a large fraction of both the northern and southern skies. There now exists in the SuperWASP archive over 290 billion photometric measurements for more than 30 million stars. These light curves encompass many types of stars, including the A stars in general, and Am stars in particular.

In this paper we have selected Am stars from the Renson & Manfroid (2009) catalogue of peculiar stars for which we have at least 1000 data points in SuperWASP light curves. While we do not detect pulsation in all of our programme stars, for around 200 metallic-lined stars out of over 1600 tested we find δ Sct pulsation. This is contrary to previous understanding that Am stars are constant in brightness. The reason we have gained this new understanding is that there has been no previous survey of so many Am stars, and previous studies have not all reached the SuperWASP detection threshold of only 1 mmag.

Many Am stars therefore do pulsate, generally with lower amplitude than normal abundance δ Sct stars. This amplitude difference is still to be understood in terms of atomic diffusion reducing pulsation driving for the slowly rotating Am stars, but there is not a complete lack of pulsation. That, has implications for turbulence in the diffusive layers and may require that the pulsation be laminar. Some striking examples of metallic-lined stars with relatively high pulsation amplitude (these are rare) address this question further, such as HD 188136 (Kurtz 1980; Wegner 1981) and HD 40765 (Kurtz et al. 1995). More constraints on the physics of the interaction of pulsation and atomic diffusion may also be found in stars that show no δ Sct p modes or γ Dor g modes at precisions of μmag. Some such A stars are known in the CoRoT and Kepler data sets, but in-depth studies have not yet been made, hence discussions of these have yet to be published.

The combination of the all-sky mmag precision of SuperWASP with the μmag precision of CoRoT and Kepler on selected stars, calls for new attempts to model the physics of the interaction of pulsation, rotation and atomic diffusion in the A stars.

2. Observations

The WASP project is surveying the sky for transiting extrasolar planets (Pollacco et al. 2006) using two robotic telescopes, one at the Observatorio del Roque de los Muchachos on the island of La Palma in the Canary Islands, and the other at the Sutherland Station, South African Astronomical Observatory (SAAO). Both telescopes consist of an array of eight 200-mm, f/1.8 Canon telephoto lenses and Andor CCDs, giving a field of view of 7.8′ × 7.8′ and pixel size of around 14″. The observing strategy is such that each field is observed with a typical cadence of the order of 10 min. WASP provides good quality photometry with a precision exceeding 1 per cent per observation in the approximate magnitude range 9 ≤ V ≤ 12.

The SuperWASP data reduction pipeline is described in detail in Pollacco et al. (2006). The aperture-extracted photometry from each camera on each night are corrected for primary and secondary extinction, instrumental colour response and system zero-point relative to a network of local secondary standards. The resultant pseudo-V magnitudes are comparable to Tycho V magnitudes. Additional systematic errors affecting all the stars are identified and removed using the SysRem algorithm of Tamuz et al. (2005). The final light curves are stored in the WASP project’s searchable archive (Butters et al. 2010).

3. Am star selection and analysis

We have selected Am stars from the Renson & Manfroid (2009) catalogue of peculiar stars for which we have data in the WASP archive and when individual light curves have at least 1000 data points (i.e. for a single camera and during a single season). Any stars known, or found, to be eclipsing binary systems were excluded from the analysis. Stars were also rejected when two approximately equal brightness stars were within the 3.5-pixel (=50") SuperWASP photometry aperture. However, unresolved close pairs in DSS images (separation <2") and systems with fainter companions (≥2 mag) were retained.

For each individual light curve, periodograms were calculated using the fast computation of the Lomb periodogram method of Press & Rybicki (1989) as implemented in the Numerical Recipes routine (Press et al. 1992). Spectral window functions were also calculated, in order to identify peaks which had arisen due to the gaps in the observations. The periodograms were examined for any evidence of variability. Stars were rejected if the false alarm probability of the strongest peaks exceeded 0.1 (Horne & Baliunas 1986). The remaining stars were examined in more detail using the Peri04 program (Lenz & Breger 2005). For stars in which variability was confirmed, frequencies continued to be selected so long as their amplitude was >4 times the average background of the pre-whitened residuals (Breger et al. 1993). Formal uncertainties on frequencies and amplitudes were obtained from the least-squares fitting using the method of Montgomery & O’Donoghue (1999).

Of the 1620 Am stars initially selected, a total of 227 (14% of the total) have been found to pulsate. The remaining 1393 stars were deemed as “not found to pulsate”, since low-level pulsation could be present below the SuperWASP detection limits. Table 1 provides a summary of the pulsating Am stars. The individual periodograms and phase-folded lightcurves are presented in Fig. 1.

4. Stellar parameters

To place stars on the HR diagram we require values of $T_{\text{eff}}$ and log $L$. For stars with $uvby$ photometry in the Hauck & Mermilliod (1998) catalogue, we used the $u'vyb\beta\epsilon$ code of Moon (1985) to obtain de-reddened indices, and the $(b-y, c_0)$ grids of Smalley & Kupka (1997) to determine $T_{\text{eff}}$ and log $g$. For stars with only $uvby$ photometry the above procedure was used but without the de-reddening step. For stars without $uvby$ photometry, Geveva photometry from Rufener (1988) was used.
5. Am stars in Kepler field

The sky coverage of the SuperWASP survey overlaps with a large fraction of the Kepler field. For Am stars with light curves in both the Kepler Public archive and the SuperWASP database we have compared the frequencies and amplitudes. This allows us to evaluate the detection limits of SuperWASP. Of the 10 stars with both Kepler and SuperWASP data, four have clear pulsations with amplitudes ≥1 mmag (Table 2), while the other six stars have amplitudes below the SuperWASP detectability limit.

The \texttt{PSRO04} analysis (Table 3) shows good agreement above the nominal SuperWASP 1 mmag amplitude limit. There is a suggestion that the amplitudes found using SuperWASP lightcurves are slightly higher than those from Kepler. In addition, the SuperWASP frequency can differ from the “true” frequency by a small integer number of 1 d\(^{-1}\) aliases. The comparison also shows that it is possible with SuperWASP data to detect frequencies slightly below the 1 mmag level (Fig. 2).

6. Discussion

The pulsating Am stars (see Fig. 3) are concentrated within the fundamental radial mode red and blue edges of Dupret et al. (2005). This is in agreement with that found by Balona et al. (2011) for Am stars within the Kepler field. These studies show that pulsating Am stars are concentrated in the cooler region of the instability strip. Hot Am stars do not appear to pulsate at the precision of the Kepler data.

The standard interpretation of the Am phenomenon is that atomic diffusion – radiative levitation and gravitational settling – in the outer stellar envelope gives rise to the observed atmospheric abundance anomalies. For a typical mid-A star, \(T_{\text{eff}} \sim 8000\) K, there are two thin convection zones in the outer envelope. The atmosphere itself is a convection zone a few thousand km thick where ionisation of H drives the convection. Deeper in the atmosphere, at \(T \sim 50\,000\) K, the ionisation of He also creates a thin convection zone, where the \(\kappa\)-mechanism drives \(\delta\) Scf
pulsation. It has long been clear that some Am stars and related types do pulsate, particularly the marginal Am stars (labelled spectroscopically as Am: stars), the evolved Am stars (δ Del or ρ Pup stars), and some more extreme cases, such as HD 188136 (Kurtz 1980; Wegner 1981) and HD 40765 (Kurtz et al. 1995).

The pulsation modes that we observe in Am stars are low radial order, low spherical degree p modes. The surface of the star is an anti-node. With the low radial order, the vertical wavelength is long compared to the depth of the envelope above the He ii ionisation zone. With the decrease in density with height in the atmosphere, conservation of kinetic energy density means that the pulsation amplitude increases with height in the atmosphere, or conversely, decreases with depth.

In Am stars, the microturbulence velocity is also peculiar, as it is generally much higher than that of chemically normal stars. This high microturbulence arises from large velocity fields in the stellar atmosphere (Landstreet 1998), which are even supersonic for some Am stars. We do not really know what causes these large velocity fields to develop exclusively in Am stars and how chemical peculiarities and velocity fields coexist. The results shown by Landstreet et al. (2009) suggest that there is a connection between $T_{\text{eff}}$ and the velocity fields, peaking at around $T_{\text{eff}} \sim 8000$ K, although we do not know what happens for cooler Am stars.

Atomic diffusion occurs in the radiative zone below the turbulent outer convective layer, which is far below the observable

Fig. 2. Comparison between the KIC00604 periodograms from Kepler (left) and SuperWASP (right) for four Am stars with pulsations detected by SuperWASP (see Table 3 for details of frequencies identified).
blue edges of the instability strip (Dupret et al. 2005). The large cross indicates the typical uncertainties in log $T_{\text{eff}}$ and log $L$. The dots are the δ Sct stars from the catalogue of Rodríguez et al. (2000).

Fig. 3. HR diagram showing the location of Am stars. The filled circles are the Am stars which were found to pulsate, while the open circles are the Am stars which were not found to pulsate. The solid lines indicate the location of the ZAMS and the fundamental radial mode red and blue edges of the instability strip (Dupret et al. 2005). The large cross indicates the typical uncertainties in log $T_{\text{eff}}$ and log $L$. The dots are the δ Sct stars from the catalogue of Rodríguez et al. (2000).

atmosphere. In this radiative layer there must be no turbulence at the diffusion velocity, which is of the order of $10^{-4}$ — 1 cm s$^{-1}$. The photometric amplitudes found in Am stars are consistent with atmospheric pulsation radial velocity amplitudes of a few km s$^{-1}$. Taking into account the decrease in pulsation amplitude with depth – largely because of the increase in density, but also because of the radial wave function – the pulsation velocity in the radiative layer where atomic diffusion is most important in Am stars is still of the order of a km s$^{-1}$. With such pulsations in a layer where atomic diffusion is operating at sub-cm s$^{-1}$ velocities, it must be that the pulsation is laminar; i.e., producing no turbulence at the sub-cm s$^{-1}$ level.

With the results from the Kepler mission (Balona et al. 2011) and our results from SuperWASP we conclude that the loss of helium by gravitational settling from the He ii ionisation zone reduces driving, but does not suppress it entirely. Thus Am stars can pulsate as δ Sct stars, but typically with relatively low amplitudes compared to normal abundance δ Sct stars. Some Am stars show no pulsation whatsoever at Kepler μmag precision. It has yet to be shown whether this lack of pulsation can also occur in the more rapidly rotating normal abundance stars in the δ Sct instability strip. Study of this question is in progress with Kepler data. As was concluded for the individual cases of HD 188136 and HD 40765, we may now state in general: in Am stars the pulsation must be laminar, not generating turbulence to mix away the observed effects of atomic diffusion in the outer atmosphere.

The Fm δ Del subclass are evolved Am stars above the main-sequence, many of which have been found to show variability (Kurtz 1976). Not unexpectedly, many stars classed as Fm δ Del are found to be pulsating in the WASP data, but clearly not all. Of the 227 Am stars that we found to be pulsating 55 are classed as Fm δ Del: 24% of the Am stars found to pulsate. This compares to a total of 186 Fm δ Del stars out of the 1620 Am stars investigated using WASP data, around 11% of the sample. Therefore, 30% of the Fm δ Del stars have been found to pulsate, compared to just 12% of other Am stars. Thus pulsation amplitude either grows in Am stars as they evolve, or some non-pulsating Am stars begin pulsating as they move off the main sequence. This is likely to be a consequence of the driving region moving deeper into the star where the helium abundance is higher than in the main sequence He ii ionisation zone (see Turcotte et al. 2000 for theoretical discussion).

The location of the pulsating Fm δ Del stars in the HR diagram is shown in Fig. 4. There is a tendency for the pulsating Fm δ Del stars to be located toward the cooler (and/or) slightly more evolved parts of the instability strip, whereas the non-pulsating Fm δ Del stars are distributed more uniformly. The frequency-amplitude diagram (Fig. 5) shows that the Fm δ Del stars occupy the same regions as the other Am stars, but with an absence of high-frequency ($\gtrsim 20$ d$^{-1}$) pulsations; this is not surprising, given that they are cooler and more evolved than average δ Sct stars.

Several factors are thought to play a role in the development of pulsating Am stars, but stellar rotation is probably one of the most important. Charbonneau & Michaud (1991) showed that Am chemical peculiarity develops in stars that rotate slower than...
90 km s\(^{-1}\) and that the He \(\text{ii}\) ionisation zone deepens with decreasing rotation. This was later confirmed by more advanced diffusion model calculations by Talon et al. (2006) and observationally by Fossati et al. (2008), who found a correlation between Am chemical peculiarities and \(v \sin{i}\) in Am stars belonging to the Praesepe open cluster. The vast majority of the Am stars already known to pulsate have a rather large \(v \sin{i}\), between 40 and 90 km s\(^{-1}\), thus avoiding the He \(\text{ii}\) ionisation zone sinking too deep into the star and therefore allowing the development of pulsation driven by the \(\kappa\)-mechanism. On the other hand, for the very slowly rotating pulsating Am stars, the pulsation could be laminar. It is therefore likely there are two different mechanisms driving pulsation in Am stars.

Our results show a wide variety of pulsations, from singly periodic to complex multiperiodic, and also some examples of what appear to be hybrid \(\gamma\) Dor/\(\delta\) Sct pulsators. This is similar to the range of behaviour seen in normal abundance \(\delta\) Sct stars, as can be seen in the study of \textit{Kepler} data by Grigahcène et al. (2010). Those authors reclassified pulsation types with the following scheme:

- \(\delta\) Sct: frequencies above 5 d\(^{-1}\);
- \(\delta\) Sct/\(\gamma\) Dor hybrid: most frequencies above 5 d\(^{-1}\), but some low frequencies present;
- \(\gamma\) Dor: frequencies lower than 5 d\(^{-1}\); and
- \(\gamma\) Dor/\(\delta\) Sct hybrid: most frequencies lower than 5 d\(^{-1}\), but some high frequencies present.

Our results are summarized in Table 4 and the individual classes for each star are given in Table 1. The majority of the pulsators we found are \(\delta\) Sct stars, with the remaining quarter split between \(\gamma\) Dor stars and mostly \(\delta\) Sct/\(\gamma\) Dor hybrids. Given that the SuperWASP data are affected by daily aliases and systematics at low frequencies, the true number of stars with \(\gamma\) Dor pulsations may indeed be higher. However, given that Am stars are thought to be members of binary systems and tidal effects slow the stellar rotation rate, it is possible that some of the low-frequency signatures found in the SuperWASP data are due to ellipsoidal effects in close binaries. Assuming a rotation limit of \(v \sin{i} \leq 120\) km s\(^{-1}\) for an Am star and a radius of 1.5 \(R_\odot\), the shortest period for a binary system containing a tidally-synchronised Am star is \(\sim 0.6\) d. Close binary systems with dissimilar components have two maxima and minima per orbital period, and this value dominates over the orbital value in periodograms. Hence, frequencies \(< 3.3\) d\(^{-1}\) may have arisen due to ellipsoidal variations in close binaries. Thus, we caution that some of the stars presented in Table 1 could have erroneously been classified as having \(\gamma\) Dor pulsations. In addition, it is possible that long-period pulsations in close binaries could be tidally excited (Handler et al. 2002).

It is clear from examination of the \textit{Kepler} data set that the \(\delta\) Sct stars show frequencies ranging from nearly zero d\(^{-1}\) up to 100 d\(^{-1}\); some stars even show the full range, including frequencies between the \(g\) mode and \(p\) mode ranges seen in models. These intermediate frequencies are unexplained at present. It is clear that the \(\delta\) Sct stars are complex pulsators that show \(g\) modes, \(p\) modes, mixed modes and many nonlinear cross terms. Whether there are differences between abnormal abundance, slowly rotating Am stars that are \(\delta\) Sct stars and the more rapidly rotating, normal abundance \(\delta\) Sct stars is yet to be determined. The objects we present here from SuperWASP greatly increases the number of pulsating Am stars for statistical study of this question.

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### Table 4

The number of pulsating Am stars and percentage in each of the four pulsation classes as defined by Grigahcène et al. (2010).

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<tr>
<th>Pulsation Class</th>
<th>Number</th>
<th>Percentage</th>
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<tr>
<td>(\delta) Sct</td>
<td>169</td>
<td>75</td>
</tr>
<tr>
<td>(\delta) Sct/(\gamma) Dor</td>
<td>23</td>
<td>10</td>
</tr>
<tr>
<td>(\gamma) Dor</td>
<td>30</td>
<td>13</td>
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<tr>
<td>(\gamma) Dor/(\delta) Sct</td>
<td>5</td>
<td>2</td>
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Fig. 1. SuperWASP periodograms for the pulsating Am stars (top) and corresponding lightcurves folded on the principal frequency (below). The lightcurves have been binned in 0.01 phase steps and phase 0.0 corresponds to the time of maximum light.
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