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A-Type Stars as a Unique Challenge in Time-Domain Studies

WORKSHOP 5

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Abstract. As photometric standards, A-Type stars have proved to be extremely useful; this is particularly true of Vega, the fundamental photometric standard. However, the identification of at least some main-sequence A-type stars as small-amplitude variables, while of interest as an issue of fundamental astrophysics, needs to be understood if they are to continue to be used as photometric standards. Flaring and Rossby waves are proposed in the literature as possible explanations, as was discussed during a well-attended Workshop debate. This report summarises the discussion, and suggests future investigations.

Keywords. Stars: early-type, stars: oscillations, stars: activity

1. Introduction

A-type main-sequence (MS) stars are unique, showing periodic variations on time-scales ranging from minutes to centuries. As discussed below, variations are caused by different physical processes, including pulsation, rotation and multiplicity; they manifest themselves through observables such as photometric brightness, spectral line strength and shape, radial velocity, as well as magnetic field strength and orientation. The diversity in time-scales over which variability needs to be followed and characterised, along with diagnostics and techniques to be used to that effect, makes A-type stars particularly well suited to illustrate a range of challenges in time-domain astronomy. Most daunting among those challenges is to identify A-type stars that are *constant* enough to be used as photometric standards in the era of space-based photometry.

Space-based missions such as *Kepler* (Borucki *et al.* 2010) and *K2* (Howell *et al.* 2014) have provided, and continue to provide, photometric data of unprecedented precision when compared with ground-based photometry. In particular, space-based photometry obtained over many months of nearly continuous observing provides light-curves from which stars previously understood to be constant are identified as very small-amplitude variables. The quality of *Kepler* data allowed Uytterhoeven *et al.* (2011) to present the first general characterisation of the pulsational behaviour of MS A–F type stars. While pulsation in MS A-type stars is of interest insofar as it supports asteroseismic studies, it is also crucial that it be properly understood in view of the important role that MS A-type stars have as photometric standards.

The Workshop saw a lively debate on the variability of MS A-type stars, and A-type stars in general, and this report tries to summarise the discussions. First we highlight the importance of the debate by briefly reviewing the role of MS A-type stars as photometric standards. Then we discuss A-type star variability caused by starspots, flares and Rossby waves.

2. Photometric Standards

The success of Johnson & Morgan's (1953) UBV photometric system and its adoption of the bright A0 V star Vega as having $V = 0.03$, $(B - V) = 0.00$ and $(U - B) = -0.01$ confirmed its well-established status as the fundamental photometric standard. Several determinations of the absolute spectral energy distribution of Vega were attempted by comparing monochromatic flux measurements with laboratory sources at near ultraviolet, optical and infrared wavelengths. Oke & Schild (1970) provided an absolute spectral energy distribution for Vega from 3300 to 10800 Å as earlier determinations exhibited discrepancies of as much as 10%. Hayes & Latham (1975) improved the atmospheric extinction corrections and derived an improved absolute spectral energy distribution for Vega. Of course it is preferable to have an absolute spectral energy distribution which does not depend on corrections for atmospheric extinction, and for that reason Bohlin & Gilliland (2004) used the Space Telescope Imaging Spectrograph to provide absolute spectrophotometry of Vega from 0.17 to 1.10 μ.

A shell around Vega which manifests itself as an infrared excess (Selby *et al.* 1983, Blackwell *et al.* 1983, Harvey *et al.* 1984, Aumann *et al.* 1984) now casts doubt on the suitability of Vega as a fundamental photometric standard at wavelengths longer than $\sim 1\,\mu$. For longer wavelengths, Cohen *et al.* (1992) have established a network of standard stars based on A-star models of Vega and Sirius, an approach which prompted Bohlin (2014) to provide space-based absolute spectrophotometry of Sirius as well as Vega. Bohlin *et al.* (2014) give a short review of absolute flux calibration from the ultraviolet to the mid-infrared, describing techniques and recent developments.

3. Variability

The use of A-type stars as photometric standards, and Vega as the fundamental photometric standard, follows from the belief that these are not active stars, or indeed not intrinsic variables. Any variability detected among the normal A-type stars would be of immediate interest because of their contribution to the establishment of standard photometric systems and to the absolute flux calibrations of those systems. Koen's (2001) tentative identification of pulsations in early A-type stars, based on Hipparcos epoch photometry, resulted in further space-based photometry being anticipated with considerable interest.

Balona (2011) examined Quarter 0 and Quarter 1 *Kepler* light curves of more than 9000 A–F stars, mostly obtained in the long cadence mode with exposure times of 29.4 minutes. The majority of A–F stars were found to vary with frequencies of $< 5\,\mathrm{d}^{-1}$ and low amplitudes of 40–150 ppm. As there was at that time no known mechanism which could lead to low frequency pulsations in A stars, Balona (2011) investigated rotational modulation as a possible explanation and concluded that the light variations in A-type stars may be due to starspots or to other co-rotating structures.

Using the full four-year *Kepler* dataset, Balona (2017) found a high correlation between projected rotational velocities and photometric frequencies in a sample of thirty late-B to mid-A stars. Moreover, time-frequency diagrams showed stochastic variations in all respects similar to those of spotted cool stars. Balona therefore proposed starspots, or some other co-rotating feature, to be the rule rather than the exception among A-type stars and the origin of their light variability. Starspots could imply the presence of substantial localised magnetic fields, as discussed in more detail below, but chemical surface inhomogeneities or 'chemical weather' may be an alternative explanation.

Kochukhov *et al.* (2005) and Hubrig *et al.* (2006), for example, detected variations in mercury lines (and those of some other elements) in the spectra of HgMn stars where magnetic fields are weak (Makaganiuk *et al.* 2012) or tangled (Kochukhov *et al.* 2013).

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Kochukhov *et al.* (2007) attributed such variations to chemical surface inhomogeneities; such processes, if active in other A-type stars, would account for a correlation between photometric frequencies and projected rotation speed. If 'chemical weather' in the atmospheres of A-type stars bore some resemblance to terrestrial weather as Kochukhov *et al.* (2007) argue, it would also be responsible for stochastic photometric variability.

Concern that Vega was being used as a fundamental photometric standard star but might itself be a variable goes back at least as far as Fath (1935) and contemporary studies cited therein. Observations suggesting that Vega is a small-amplitude variable have also been discussed by Fernie (1981) and Engelke *et al.* (2010). Bohlin *et al.* (2014) do not agree, however, with the conclusion of Engelke *et al.* that Hipparcos photometry shows Vega to be a variable, and saturation of the pulse-counting electronics in the image dissector photomultiplier tube was regarded as a more probable explanation.

If Vega is a small amplitude variable, a possible explanation could be the co-rotating structures (starspots) which Böhm *et al.* (2015) discovered. In a star like Vega, the origin of rotational modulation of surface structures must be different from the chemically-peculiar Ap/Bp/HgMn stars. With a weak magnetic field and a high rotation rate, the atmosphere would not be stable enough for chemical anomalies to develop through atomic diffusion. If the weak magnetic fields observed in Vega are responsible for starspots, they should be brighter than the photospheric average because dark spots only occur when the magnetic field is strong enough to limit convective heat transport within them.

Petit *et al.* (2017) used Doppler imaging to reconstruct a time-sequence of three maps of the visible photosphere of Vega. While a number of surface features are seen in all three maps, others seem to evolve over the time-span of the observations, suggesting changes that can affect the Vega surface on a time-scale of days or less. Although it is tempting to attribute starspots to Vega's weak magnetic field, which Vidal *et al.* (2018) suggested could have a tidal origin, further investigation is required.

4. Stellar Flares

Stellar flares are dramatic increases in brightness over almost the whole electromagnetic spectrum. A rapid increase in brightness is followed by a slow decline, the time-scale typically ranging from a few minutes to several hours. While stellar flares are usually associated with M-dwarfs (UV Ceti variables), they are also well-studied in the Sun. Energy released by the reconnection of magnetic field lines in the outer solar atmosphere accelerates energetic particles into deeper atmospheric layers, resulting in a solar flare seen as emission from X-rays to radio waves (Benz & Güdel 2010). Although flares in active M-dwarfs may be as much as 10^3 more energetic than solar flares (Güdel & Nazé 2009), they are understood to form effectively in the same way as in the Sun.

Although what constitutes a flare is perhaps not as well-defined as it should be, Balona (2012) was guided by the above-mentioned description in his examination of *Kepler* light-curves for nearly 2000 A-type stars, and detected flares in 19 of them. The energy released in an A-star flare was estimated by Balona to be $\sim 10^{36}$ ergs, which is difficult to understand as A-type stars have weak magnetic fields. A comparison with energies released in cool-star flares, also observed by *Kepler*, led Balona (2012) to conclude that flares attributed to the 19 A-type stars do indeed originate in those stars and not in a visual or physical cool companion.

Balona (2013) identified additional A-type stars in the *Kepler* field which show flares, and concluded that A-type stars are active and, like cooler stars, have starspots and flares. On considering flare stars across the Hertzsprung–Russell Diagram, Balona (2015) found the proportion of MS stars which flare to be independent of effective temperature, but energies released during a flare were strongly correlated with stellar luminosity and radius. Furthermore, flare stars were found to have larger spots and higher rotation rates

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than non-flare stars. While rotation plays a role in generating flares, Balona (2015) noted that the influence may be indirect; any possibility that it and differential rotation have a *direct* role does need further investigation.

Pedersen *et al.* (2017) re-examined critically Balona's (2012) claim to have identified flares in *Kepler* light-curves of A-type stars, arguing that for stars to flare they have to have a sufficiently deep outer convection zone, strong large-scale magnetic fields or strong radiatively driven winds; normal A-type stars are understood to have none of those and therefore should not flare. In cases where Pedersen *et al.* obtained spectra of Balona's (2013) targets, they were confirmed to be A-type stars and some were spectroscopic binaries. Alternative explanations for the observed flares were found in at least 19 of the 33 A-type stars for which Balona found flaring, and Pedersen *et al.* did not identify a convincing target supporting the conclusion that A-type stars flare. However, a weakness in the Pedersen *et al.* analysis is that they declined to address Balona's (2015) finding of a strong correlation between energies released during a flare and stellar luminosity and radius.

Van Doorsselaere *et al.* (2017) developed an automated flare detection and characterisation algorithm which they applied to raw *Kepler* (Quarter 15) light-curves. A further 24 A-type stars in which flares were detected, plus those which Pedersen *et al.* (2017) disqualified as flaring A-type stars, were also recovered by the Van Doorsselaere *et al.* study. A consequence of the latter is that it would be premature to dismiss the possibility of flaring in A-type stars.

5. Rossby Waves

Platzman (1968) reviewed early work on Rossby waves in the context of meteorology. In rotating stars, global normal modes of Rossby waves (Papaloizou & Pringle 1978, r-modes) couple with the spheroidal motion caused by the Coriolis force to produce temperature perturbations and consequently stellar variability. Saio *et al.* (2018) provided evidence, and supporting theory, for global Rossby waves in upper MS stars. In amplitude-spectra of spotted B to early A stars, Saio *et al.* found groups of r-mode frequencies that were symmetric (with respect to stellar equators) just below the frequency of a structured peak, which they suggest represented an approximate stellar rotation rate.

Similar amplitude-spectra for spotted A-type stars were obtained from *Kepler* data by Balona (2017, his Figure 7) where he considered the broad spread of peaks, which Saio *et al.* identified as r-mode frequencies, to be a consequence of strong differential rotation and abundant solar-like spots. The sharp structured peak which Saio *et al.* considered to represent an approximate stellar rotation rate was characterised by Balona (2017) as fully resolved, and caused by reflection from an orbiting Jupiter-sized planet.

By their nature, Rossby waves must be expected in the amplitude-spectra of rotating stars, and their amplitudes will clearly be dependent on rotation speed. The interpretation by Saio *et al.* (2018) of the amplitude-spectra of rotating A-type stars on the MS corresponds, in a natural way, with a variability that would appear to be co-rotating with the star. A possible confusion with starspots or other co-rotating features in the stellar photosphere could then occur in an obvious way. Current stellar models (Kallinger & Matthews 2010) suggest that A-type stars on the MS have a thin convection zone, and do not therefore form starspots.

6. Future Directions

In many cases stellar models, and their convection zones in particular, are reliant on Böhm-Vitense's (1958) mixing-length theory (MLT), which has a free parameter (the mixing length) for which a calibration is required. One of many attempts to replace MLT was that of Pasetto *et al.* (2014), who presented a self-consistent, scale-free convection (SFC), analytical formulation starting from a conventional solution of the Navier-Stokes/Euler equation (in effect the Bernoulli equation for a perfect fluid) expressed in a non-inertial reference frame co-moving with convective elements. MLT and SFC comparisons (Pasetto *et al.* 2016) were encouraging, good agreement being found for MS models. But as (Arnett *et al.* 2015) pointed out, stars are much more complex than such simplified one-dimensional models. When computer-power becomes adequate, and well-resolved three-dimensional simulations of whole stars for evolutionary time-scales have been computed, a better understanding of convection in A-type MS stars should become available. Until then, it would be premature to assert that A-type MS stars do not flare or have starspots because their convection zones are not sufficiently extensive.

As mentioned above, the study by Van Doorsselaere *et al.* (2017) suggested that further work is needed to establish whether A-type MS stars flare. The 33 A-type flare stars which Balona (2012, 2013) identified, plus the additional 24 which Van Doorsselaere *et al.* (2017) found, should in due course be observed by the Large Synoptic Survey Telescope (Tyson 2002, LSST). The higher resolution which the LSST cameras will achieve would identify M dwarf flare stars observed in the same *Kepler* pixels as the A-type stars which Balona and Van Doorsselaere *et al.* have declared to be flare stars; the origin of the flares could then be established with more confidence, although LSST would not necessarily resolve all objects contaminating a $3''.98 \times 3''.98$ *Kepler* pixel.

Rossby waves also produce light variations in stars which are rotating rapidly; they result from temperature and pressure variations in the photosphere, and a corresponding radial-velocity perturbation should also be expected. It would therefore be of some interest to estimate the Rossby wave contribution to the line-profile variations in Vega which Böhm *et al.* (2015) observed. That latter discovery of starspots on Vega would seem to have been secured through Doppler imaging by Petit *et al.* (2017), but it would (for example) be worthwhile to investigate whether any underlying physics distinguishes transient and consistently recovered surface features in the Petit *et al.* maps. Could the transient features be due to spots, and could those seen consistently in all three maps be a manifestation of Rossby waves?

While the Bohlin (2014) flux calibration based on Sirius and Vega remains the best available flux standard, its limitations need to be explored by studying Sirius in the way that Böhm *et al.* (2015) and Petit *et al.* (2017) studied Vega. The importance of doing so is emphasised by the detection by Petit *et al.* (2011) of a weak surface magnetic field on Sirius A. Almost as important is the need to extend the Böhm *et al.* and Petit *et al.* studies to the 18 new A-type flux standards which Allende Prieto & del Burgo (2016) have proposed.

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