Discovery of spots on hot stars requires major revision of stellar physics

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It has long been thought that starspots are not present in the hot A and B stars because magnetic fields cannot be generated in stars with radiative envelopes. Space observations show that a considerable fraction of these stars vary in light with periods consistent with the expected rotation periods. Here we show that the photometric periods are the same as the rotation periods and that starspots are the likely cause for the light variations. This unexpected discovery has wide-ranging implications and suggests that a major revision of the physics of hot stellar envelopes is required.

It is accepted that the outer envelopes of main sequence stars with effective temperatures hotter than about 7000 K are in radiative equilibrium. The lack of convection in the outer layers precludes the operation of the dynamo mechanism which is believed to be necessary to generate surface magnetic fields[1]. Indeed, measurements in two bright A stars, Vega and Sirius, indicate global magnetic fields of less than 1 G, which is weaker than that of the Sun[2]. For this reason, photospheric activity such as starspots and flares, are not expected in A and B stars.

This picture of quiescent radiative envelopes, in which diffusion and gravitational settling can proceed relatively undisturbed, has been successful in accounting for peculiar A and B stars. This process, operating in the absence of a magnetic field and in the absence of mixing by convection or rotational circulation, is generally accepted as the explanation for the metallic-lined Am stars[3]. The same process operating in the presence of a strong global magnetic field, is thought to be responsible for the patches of anomalous abundances in the chemically peculiar Ap and Bp stars[3]. The kilogauss global magnetic fields in Ap and Bp stars are presumed to be of fossil origin[4].

For cool stars with convective envelopes, a magnetic field in conjunction with a stellar wind exerts a torque on the ejected matter, resulting in a steady loss of angular momentum. On the other hand, hotter stars with radiative envelopes do not experience loss of angular momentum. This explains the steep increase of rotation rate between main-sequence stars with convective and radiative envelopes. Should it be found that spots are present in stars with radiative envelopes, just as they are in cool stars with convective envelopes, the ideas described above will almost certainly require revision.

Photometric observations of very high precision from space, particularly by the *Kepler* and *TESS* missions, have gradually revealed a picture which is at odds with our current understanding of stars with radiative envelopes. Pulsational driving in the δ Scuti stars, which have effective temperatures in the range 6500–9000 K, is thought to be a result of the κ opacity mechanism operating in the HeII ionization zone. Models predict pulsation modes with frequencies greater than about $6\,\mathrm{d}^{-1}$. However, the first *Kepler* observations revealed that a large fraction of δ Scuti stars also pulsate in numerous low frequency modes[5], in conflict with model predictions. It is now known that at least 98 percent of δ Scuti stars contain low frequencies[6]. The huge disparity in pulsation frequency distributions among δ Scuti stars with the same effective temperature and luminosity and the fact that less than half of the stars in the instability strip actually pulsate[6] also present serious challenges. Another problem is the presence of δ Scuti pulsations in stars which are much hotter than predicted (the Maia variables[7,8]).

The problem involving stellar pulsation among the A stars is a severe challenge, but this is further compounded by *Kepler* observations which suggest that a large fraction of A and B stars vary with periods which are consistent with their rotation periods[9–11], suggesting the presence of starspots. Until then, starspots were believed to be present only in cool stars with convective envelopes.

Because of the disruptive implications of these results, it is necessary to show beyond reasonable doubt that the period derived from the light variation is the same as the rotation period. One way is to compare the equatorial rotational velocity, v, derived from the photometric period and an assumed radius, with the projected rotational velocity, $v\sin i$, which is derived from spectroscopy. Because of the unknown inclination angle, i, such a comparison needs to be made statistically using a large sample of stars. Unfortunately $v\sin i$ measurements are not available for most A and B stars observed by *Kepler* and *K2*. A comparison using 30 stars with effective temperatures in the range 8300-12000 K[12] supports the identification of the photometric period with the rotation period. A similar study using *TESS* observations of B stars comes to the same conclusion[11], but both these studies involve small numbers of stars.

An entirely different test can be made by comparing the distribution of v, obtained from space photometry, with the distribution obtained from $v\sin i$ in a different set of stars with the same effective temperature and luminosity ranges. The assumption is that the distribution of rotational velocities does not depend on the location in the sky from where the stars are selected. An added advantage of the method is that it tests the distribution of rotational velocities and not just the trend of v with $v\sin i$. Application to 875 *Kepler* A stars indicates that the photometric period is the same as the rotation period[9].

The advent of *TESS* has greatly increased the sample of A and B stars in which these tests can be made. The data used in this study comprises light curves from the full four-year *Kepler* mission, from the *K2* mission and from sectors 1–11 of the *TESS* mission. The total number of

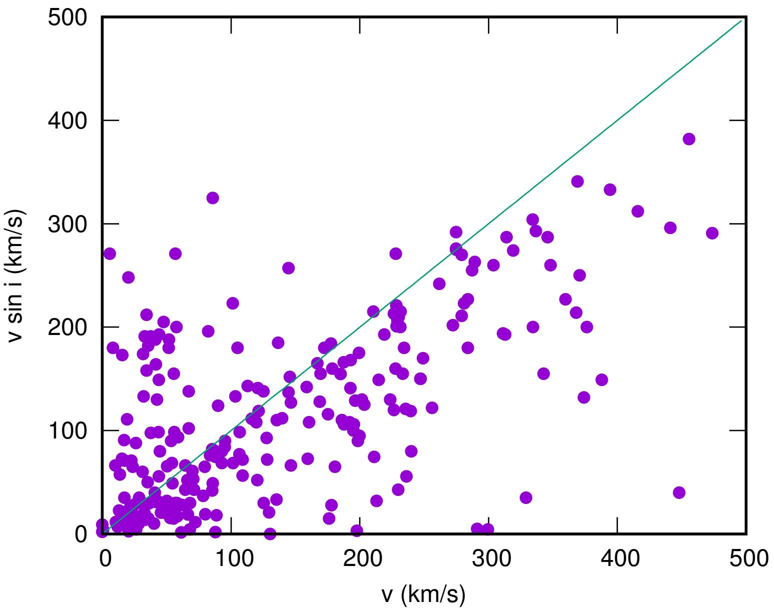

Figure 1: The projected rotation velocity, $v \sin i$, as a function of the equatorial rotation velocity, v, estimated from the photometric period for stars with effective temperatures $T_{\text{eff}} > 8000\,\text{K}$. The straight line is $\sin i = 1$.

stars of all spectral types (but mostly hotter than 6000 K) is over 51000. The first step is to classify the variability type of each star by visual inspection of the periodogram and light curve. The classification technique is described elsewhere[11]. Stars identified as possible rotational variables were noted for further analysis and the period and amplitude measured. This results is 2734 stars with known photometric periods and with effective temperatures greater than 7000 K. Using *Gaia* DR2 parallaxes[13,14], the distance of each star can be determined. From the effective temperature and the bolometric correction[15], and using an interstellar extinction model[16], the stellar luminosity can be derived and hence the radius is found. The equatorial rotational velocity, v, is derived from the stellar radius and the photometric period,

In Fig. 1 a comparison between $v \sin i$ and v is made for 251 stars with $T_{\text{eff}} > 8000\,\text{K}$. The temperature limit was chosen to minimise contamination by stars in which surface convection may still be present. Since $v \sin i$ cannot exceed v, the points are expected to lie below the $\sin i = 1$ line in the figure, which they do. Since most of the stars would be observed at high angles of inclination, a trend between $v \sin i$ and v is expected, which is the case. The increase in scatter at low velocities is explained by the fact that the relative error in the velocities increases rapidly at slow rotation rates[11]. The significance of the correlation between v and $v \sin i$ is such that the probability of such a correlation occurring by chance is less than 10^{-4}. This is an upper limit because the relationship between the two quantities is more complex. The photometric period can be equated to the rotation period with a very high degree of confidence.

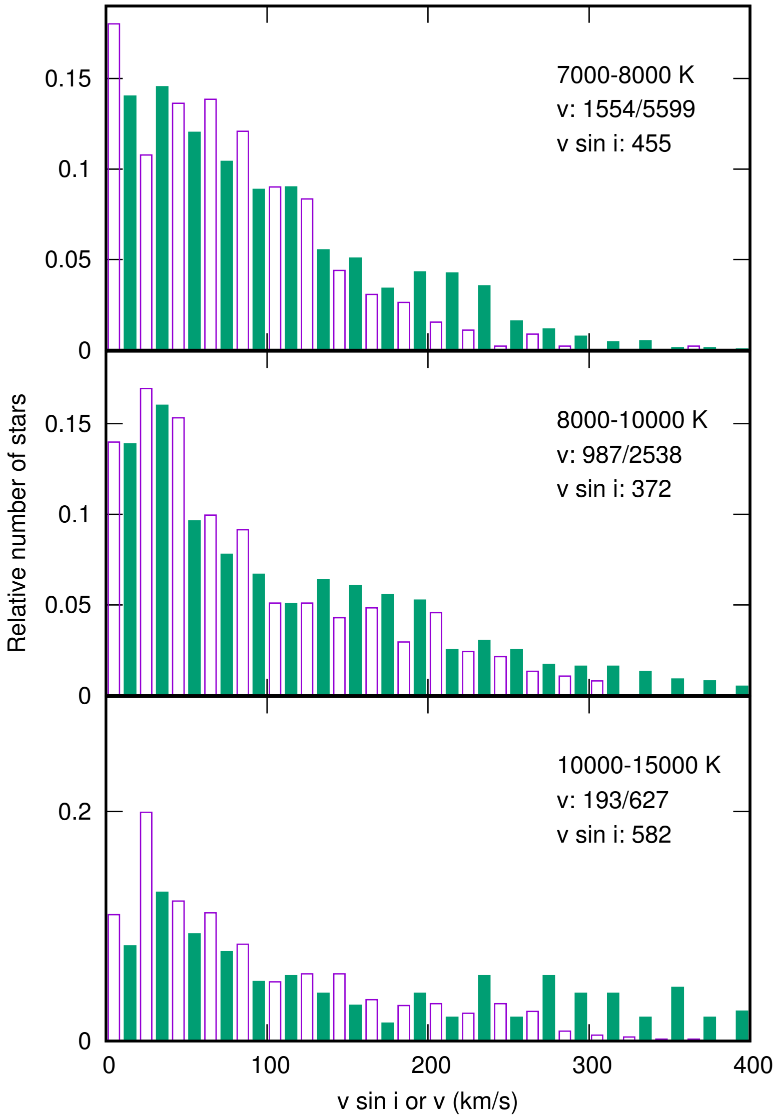

Figure 2: Distribution of projected rotation velocities, $v \sin i$ (empty boxes) and equatorial rotation velocities (filled boxes) for stars in different ranges of effective temperature (labelled in degrees K). The fraction after the v is the number of rotational variables and the total number of stars in the particular range of effective temperature. The number after $v \sin i$ is the number of stars used in the $v \sin i$ distribution.

From a catalogue of projected rotational velocities[17,18], the distribution of $v \sin i$ can be found for main sequence stars in any given effective temperature range. A comparison of v and $v \sin i$ distributions for various ranges of effective temperature is shown in Fig. 2. There are too few stars hotter than 15000 K for a meaningful analysis. It is clear that there is very good agreement between the two distributions for each temperature range.

It should be noted that photometric periods longer than 10 d are difficult or impossible to determine from space photometry owing to the limited time range of the observations. The number of stars is therefore underestimated at low velocities for the v distribution. Another source of bias is the use of radii derived from the luminosity and effective temperature. The equatorial radius will be larger, and so v will be larger, as the rotation rate increases. For these reasons, it is not expected that the distribution of v derived from $v \sin i$ by deconvolution (assuming random orientation of the axes of rotation) will fully agree with the distribution derived from the photometry.

Both tests leave little doubt that the photometric period is the same as the rotation period. The fraction of stars that are rotational variables among the A and late B stars is in the range 0.20–0.40. For cooler stars the fraction is somewhat higher, 0.40–0.60. In any case, it is clear that rotational variables are very common among all main sequence stars.

While these results show that a co-rotating structure is a common feature in hot stars, one could postulate that this might be different from a sunspot and might not necessarily involve a local magnetic field. Some form of standing wave might be responsible, for example. Just such an idea has recently been proposed to account for a peculiar feature in the periodogram of A stars. In about 15 percent of *Kepler* A stars the periodogram shows a broad hump with a closely-spaced sharp peak at slightly higher frequency[9]. It was originally suggested that the broad hump is due to differential rotation and the sharp peak a result of reflection effects from a planet in a synchronous orbit[19]. However, it now seems that the broad peak may be a result of Rossby waves, while the sharp peak is due to rotation[20]. The idea that the spots in most A and B stars are a result of Rossby waves does not seem to be likely on two counts. Firstly, the sharp peak is in any case identified as the rotation peak in this explanation. Secondly, the majority of periodogram peaks are sharp. Rossby waves are multiple modes which are expected to lead to a broad peak in the periodogram.

Some A stars also appear to flare[9,21,22]. The question of flares in A stars has been disputed on the grounds that most of these stars are spectroscopic binaries or their light curves contaminated by fainter stars in the same aperture[23]. This, of course, could well be true, but is irrelevant to whether these stars flare or not. It is necessary to resolve the stellar disks in order to prove that a flare is associated with any given star in a binary or multiple system. The argument that it is the A stars that flare, and not a physical or visual companion, comes from the fact that these flares attain energies never seen in cool flare stars[9,22]. Indeed, a flare on an M dwarf orbiting an A or B star would be undetectable even by space photometry.

The presence of starspots similar to those on the Sun in A and B stars implies the presence of strong localized magnetic fields. As in the Sun, one would expect flares to occur as a result of re-connection of flux lines. Strong localized magnetic fields would not be detected by current techniques and the global stellar field may well be as low, or even lower, than in the Sun. It is thus reasonable to suppose that the observed flares are a natural consequence of localized magnetic fields which are presumed to be associated with starspots.

The problems regarding the δ Scuti stars mentioned above cannot be resolved by applying our current understanding of radiative envelopes. It may be the case that surface convection is present in all stars including A and B stars. This opens up the possibility of finding a solution in terms of convective instability.

It has been suggested that magnetic fields produced in subsurface convection zones could appear on the surface[24,25]. Thus localized magnetic fields could be widespread in those stars with sub-surface convection. Magnetic spots of size comparable to the local pressure scale height are predicted to manifest themselves as hot, bright spots. However, this mechanism will not work in all A and B stars and predicts ranges in effective temperature where spots will not be present, which is not the case. Another idea is that differential rotation in the A and B stars may be sufficient to create a local magnetic field via dynamo action[26–28]. It is important that these ideas be further pursued.

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Acknowledgments

I thank the South African National Research Foundation for financial support. Funding for the *Kepler* mission is provided by the NASA Science Mission directorate. Funding for the *TESS* mission is provided by the NASA Explorer Program. I thank the *TESS* and TASC/TASOC teams for their support of the present work. This work has made use of data from the European Space Agency (ESA) mission *Gaia*, processed by the *Gaia* Data Processing and Analysis Consortium (DPAC). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the *Gaia* Multilateral Agreement.