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Chapter 7: Comparison of solar and stellar flares

Solar and Stellar Flares and their Effects on Planets
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Flare stars across the H-R diagram: a clue to the origin of the corona

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Abstract. *Kepler* observations show that starspots and superflares are present in A stars. An analysis of *Kepler* short-cadence data shows that the relative number of A/F flare stars is only a factor of four smaller than K/M flare stars, which can be explained as a selection effect. The average maximum flare amplitude does not depend much on spectral type, which is to be expected if the size of the active region scales in proportion to the stellar radius. The presence of starspots and superflares in A stars suggests that these stars have magnetic fields. However, X-ray observations show that A stars do not possess coronae. I therefore conclude that convection in the stellar envelope is a necessary condition for the formation of the corona. A magnetic field may be necessary to enable coronal heating.

Keywords. stars: flare, stars: coronae, stars: spots

1. Introduction

Ground-based optical observations show that stellar flares occur mostly in M dwarfs and are typically 10–1000 times more energetic than solar flares (Güdel & Nazé 2009). Optical flares are also seen in some RS CVn variables, which are detached binaries typically composed of a chromospherically active G or K star. Observations indicate that the spectrum of a stellar flare has a continuum resembling that of an A- or B-type star (Kowalski *et al.* 2012, Melikian 2014). The closest solar counterparts to stellar flares are the rare white-light solar flares.

For our purposes we define a "flare star" as a star in which at least one flare has been observed. Optical observations from the *Kepler* spacecraft have shown that flare energies are 10^2–10^6 higher than large solar flares. Because of their very high energies, they have been called "superflares". A large solar flare has an amplitude of only around 200 ppm in whole-disk white light observations, so that the Sun would not be recognized as a flare star even in the most precise photometric observations from space.

The *Kepler* data consists of practically continuous photometry of over 100 000 stars over a four-year period. Each observation has an exposure time of 30 min (long-cadence mode: LC). The long exposure time prohibits detection of short-lived flares and greatly lowers the amplitude of flares lasting for less than an hour or two. Short-cadence (SC) exposures, which are of 1-min duration, are more suitable for the study of stellar flares. However, SC data are available for only about 5000 stars and the time coverage is usually limited to only a few months.

Walkowicz *et al.* (2011) identified 373 flare stars from about 23 000 cool dwarfs in the *Kepler* field. Balona (2012) discovered superflares in 52 solar-type stars and, surprisingly, in 19 A stars as well. The number of B stars in the *Kepler* field is too small to allow the possible detection of B-star flares. The search for superflares in the *Kepler* data was extended to 148 solar-type stars by Maehara *et al.* (2012). Superflares were found on a further 279 G stars by Shibayama *et al.* (2013). All these searches employed, almost entirely, LC mode. Balona (2015) examined the light curves of stars in the *Kepler* field for which SC data are available and found 209 flare stars. These observations provide a unique set of flare data of micro-magnitude precision and good time resolution which is unlikely to be repeated for many years to come. A surprising result from this study is that the relative number of flare stars is probably similar for all spectral types. The fact that most known flare stars are cool stars with K/M spectral types seems to be a selection effect.

The detection of superflares on A stars (Balona 2012, 2013, 2015) is of particular significance because these stars have radiative envelopes and are not expected to possess magnetic fields and associated activity. It is natural to assume that flares on A stars occur not on the A star itself, but on a presumed cool companion. However, this possibility is easy to refute (see below). Starspots also seem to be present in A stars (Balona 2013) as well as B stars (Balona, Baran,Daszyńska-Daszkiewicz & De Cat 2015), further undermining the generally held opinion that B and A stars are not active.

In this paper we summarize the generally accepted understanding of the occurrence of starspots and flare stars among various spectral types. We suggest that this paradigm may need to be modified as a result of the *Kepler* data. In particular, these findings seem to imply that convection in the outer layers is a necessary condition for the formation of stellar coronae.

2. Spots on A and B stars

Among the greatest surprise in the *Kepler* data was the fact that A and B stars appear to have co-rotating features which we call "starspots" by analogy with sunspots. Evidence for starspots in A and B stars comes directly from periodic variability of the light curve. In most A stars observed by *Kepler*, the periodogram shows a distinctive peak at a low frequency. In 875 A stars observed by *Kepler* (about 40 percent of the total number of A stars), the harmonic of this frequency is also present. Examples are shown in Fig. 1 for a sample of hot A stars. The light curve thus shows almost sinusoidal, low-amplitude, variability which is most simply interpreted as a rotational effect.

Detection of low-frequency monoperiodic variability certainly suggests rotational modulation, but to prove that rotation is responsible requires that the photometric period be the same as the rotational period. The distribution of equatorial rotational velocities for main sequence A stars can be obtained from spectroscopic line-broadening measurements of the projected rotational velocity, $v \sin i$. Here v is the equatorial velocity and i the inclination of the rotational axis to the line of sight. Values of $v \sin i$ for large numbers of field main-sequence A stars have been catalogued by Glebocki & Stawikowski (2000). Hence the distribution of $v \sin i$ can be determined. The distribution of true equatorial velocities can be found on the assumption that the axes of rotation are randomly distributed.

Since the presumed rotation periods are known from the *Kepler* light curves, the equatorial rotational velocities can be estimated from the stellar radii. It turns out that the stellar radius is one of the quantities derived from ground-based multicolour photometry of stars in the *Kepler* field and is listed in the *Kepler Input Catalogue* (KIC, Brown *et al.* 2011). Although the error in the radius is large, this is compensated by the large number of A stars with known periods. As a result, the distribution of equatorial rotational velocities, v, can be found with good accuracy. If the hypothesis that the photometric period is the rotation period is correct, the distribution of v found from the *Kepler* photometric

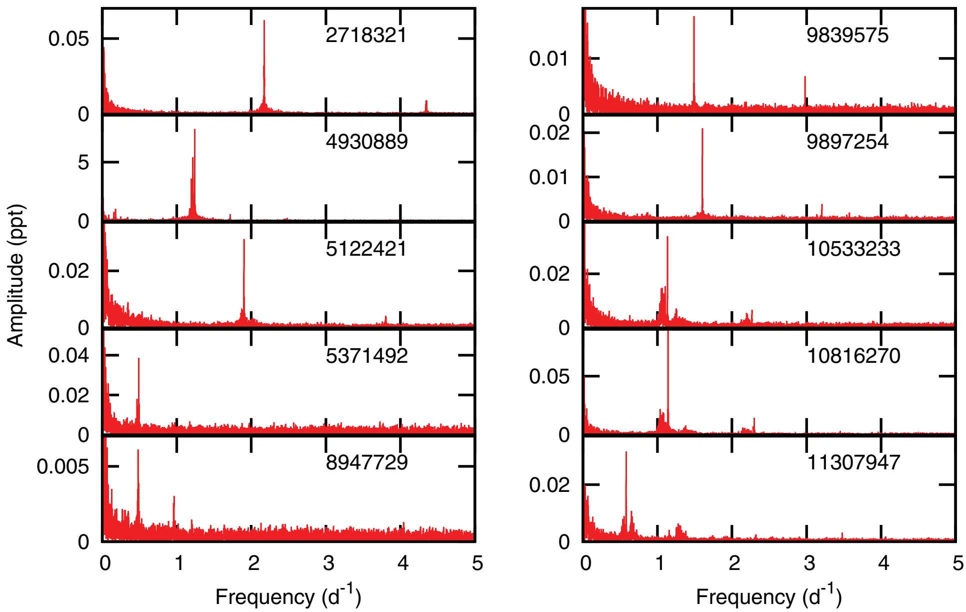

Figure 1. Examples of a periodograms of hot A-type stars showing the low-frequency peak and its harmonic. The KIC number of each star is shown.

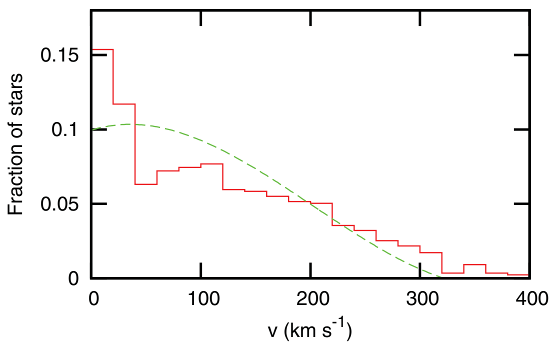

Figure 2. Distribution of equatorial rotational velocities, v, derived from stars with a low-frequency peak and harmonics (histogram). The curve is the distribution of equatorial rotational velocities for A-type field stars derived from $v \sin i$ assuming random orientation of the rotational axes.

period should agree with the distribution of v from spectroscopic $v \sin i$ measurements of field A stars.

Fig. 2 shows a comparison of the two distributions. It is evident that they agree, in spite of the difference in the way they were obtained. It is clear that the photometric variation of the *Kepler* light curves is due to rotation. We can therefore claim that the presence of spots on A stars has been established beyond reasonable doubt. Spots on B stars have been suspected for a long time (Degroote *et al.* 2011). The number of B stars in the *Kepler* data is too small to perform a similar analysis, but rotational modulation is suggested by the appearance of harmonics (Balona, Baran, Daszyńska-Daszkiewicz & De Cat 2015).

Confirmation of the existence of starspots on the A star Vega was recently obtained by Böhm *et al.* (2015) using high-dispersion spectroscopic observations. Very recently,

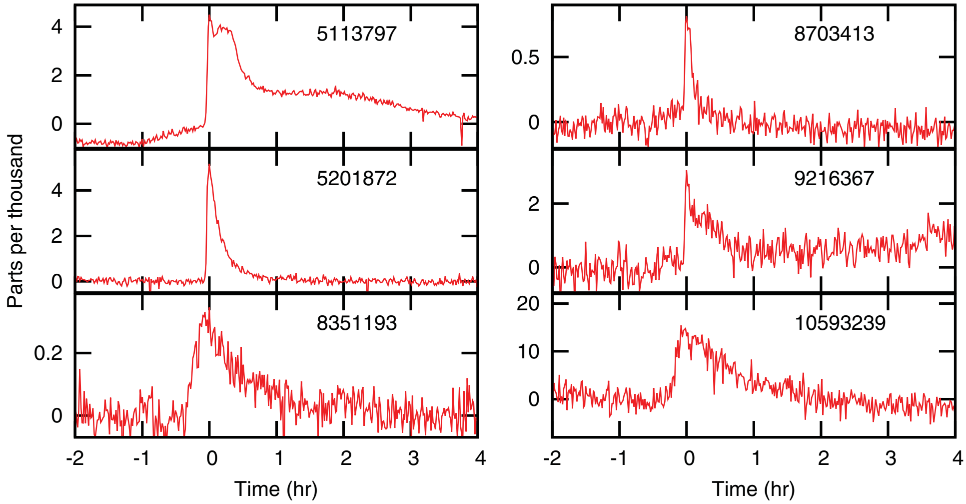

Figure 3. Examples of flares in A stars observed in short-cadence mode. KIC numbers are indicated.

the discovery of a magnetic field and starspots on an A-type pulsating δ Scuti star was announced (Neiner & Lampens 2015).

3. Flares on A stars

Examples of flares detected in the short-cadence *Kepler* observations of A stars are shown in Fig. 3. Out of the 424 A stars observed in SC mode, flares can be seen in 10 stars (2.4 per cent). Many more flare stars have been detected in LC mode (51 stars out of 1833), though the reality of some of these flares is questionable because of the poor time resolution. Nevertheless, the presence of flares in A stars is undeniable, though they could possibly be attributed to a cool companion rather than the A star itself.

The problem with attributing the flares on A stars to a cool companion is that a K or M dwarf companion would be about 100 times less luminous than the A-star primary. A flare on the supposed companion would thus be reduced in intensity by a factor of about 100 compared relative to the flare intensity on an isolated cool star. The average flare amplitude of the largest flares on isolated K/M stars observed by *Kepler* is about 3000 ppm. Taking this amplitude to be typical of the largest flares on a K/M companion, we expect the observed amplitude in the presence of the A star primary to be about 30 ppm. This is below the noise level for most *Kepler* stars. In other words, a large flare on a cool companion to an A star will be undetectable in the *Kepler* data.

A different way of visualizing the problem is shown in Fig. 4. In this figure we show the average peak flare amplitude for stars of different spectral types (points) together with error bars. Suppose we take a K star with a large flare of typical amplitude (as observed by *Kepler*) and introduce it as a companion to a non-flaring main sequence star. The flare amplitude of the two components observed as a single star is shown as the solid line. For A stars, the deviation is two orders of magnitude, and several standard deviations from what is observed. This shows beyond doubt that the A star must play an active role in generating the flare.

The *Kepler* observations are by no means the first time a flare has been detected on an A star. Schaefer (1989) reported cases of several B and A stars where strong flares may have been observed. Wang (1993) detected a flare on the A5/8V star BD+47 819

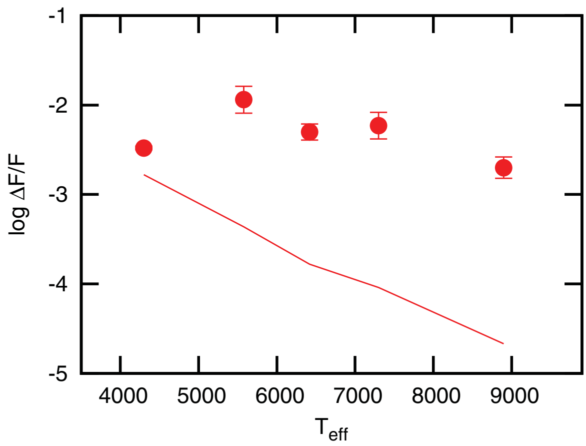

Figure 4. The average peak flare intensity derived for *Kepler* stars within a given effective temperature range (points) compared with the flare intensities calculated for a non-flaring star with a cool flare companion (line). One standard deviation error bars in flare intensities are shown.

using photographic techniques. Miura *et al.* (2008) detected an intense X-ray flare on the A1 IV/V star HD 161084. The peak X-ray luminosity amounts to 10^{32} erg s^{-1} which is much larger than the X-ray luminosity of an ordinary late-type main-sequence star, indicating that the flare probably originates in the A-star itself rather than on a hidden late-type companion. Robrade & Schmitt (2011) detected a large X-ray flare in the A0p star IQ Aur with temperatures up to $\approx 10^8$ K and a peak X-ray luminosity of $\approx 3 \times 10^{31}$ erg s^{-1}. The flare has a decay time of less than half an hour, originates from a rather compact structure and is accompanied by a significant metallicity increase. The X-ray properties of IQ Aur cannot be described by wind shocks only and require the presence of magnetic reconnection. Bhatt *et al.* (2014) found X-ray flares in two late-B stars belonging to the young open cluster NGC 869. Pye *et al.* (2015) found an X-ray flare in HD 31305 (A0) from the XMM-Newton serendipitous source catalogue.

4. The relative numbers of flare stars of different spectral types

The vast majority of flare stars observed from the ground are M dwarfs. The white light continuum during M dwarf flares has long been known to resemble that of an A or B star (Kowalski *et al.* 2012, Melikian 2014). Flares are therefore easily detectable using U or B band optical filters which greatly enhance the contrast between the flare and the M star continuum. The contrast decreases for stars of earlier spectral type. Moreover, a flare of the same energy is more easily visible in a cool dwarf than in a hotter star because the luminosities of cool dwarfs are so much lower. These effects tend to reduce the visibility of flares on K, G, F and A stars making them very difficult or impossible to detect them from the ground.

Because the *Kepler* passband is very broad, it offers no particular advantage for detection of flares in M dwarfs. Nevertheless, in order to be detected with similar amplitudes, flares in hotter, more luminous, main sequence stars need to have larger energies. Fig. 4 shows that, in fact, the typical maximum flare amplitude does not change much with spectral type. This means that either we are detecting only the rarer, most energetic, flares on these hotter stars or that flare energies increase with increasing stellar luminosity.

Table 1. The total number of stars, N, and the number of flare stars, $N_{\rm flare}$ within a given effective temperature or spectral type range as determined from short-cadence *Kepler* data. The last column is the percentage of flare stars within the given range.

Type	$T_{\rm eff}$	N	$N_{\rm flare}$	Percent
K+M	3000–5000	561	57	10.16
G	5000–6100	2018	99	4.91
F	6100–7600	1617	41	2.54
A	7600–10000	424	10	2.36

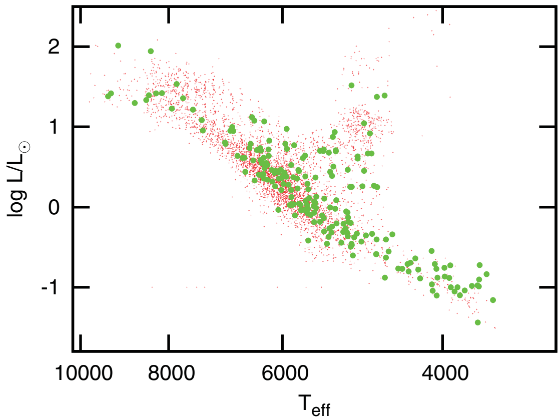

Figure 5. Theoretical H-R diagram for *Kepler* flare stars (large filled circles) observed in short--cadence mode using stellar parameters in the *Kepler Input Catalogue*. The small dots are stars which were examined but no flares detected.

It is interesting to investigate how the relative number of flare stars varies with spectral type. For this purpose, Balona (2015) searched for flares in 4758 stars observed by *Kepler* in SC mode. These data are unbiased in terms of target selection and should offer a good indication of the relative number of flare stars as a function of spectral type. In Fig. 5 the 209 flare stars observed in SC mode are shown as large filled circles in the theoretical H-R diagram. It is evident that while there is certainly a trend for most flare stars to be cool dwarfs, the number of hotter flare stars is not very much lower.

We can count the number of flare stars within a given range of effective temperature and divide by the total number of stars within the same $T_{\rm eff}$ range to obtain the fractional number of flare stars for each spectral type. The small number of B stars in the *Kepler* field does not allow detection of flares on these stars. Table 1 shows the result. The drop in relative numbers of flare stars from 10.2 per cent for K/M stars to 2.4 per cent for A stars is not unexpected given the severe selection effects described above. Allowing for selection effects, would imply that the true fraction of flare stars probably does not change very much with spectral type.

5. Magnetic fields in radiative envelopes

It is well-known that the rotation rate of a star plays an important role in inducing flares. For example, Notsu *et al.* (2013) and Shibayama *et al.* (2013) find that the average flare frequency increases with rotation among solar-type stars. This effect is usually attributed to age. Rapidly-rotating stars are younger, have more effective dynamos and are therefore more active. In fact, age and rotation are strongly correlated and it is not possible to separate the two effects. Moreover, it is not really clear whether the same

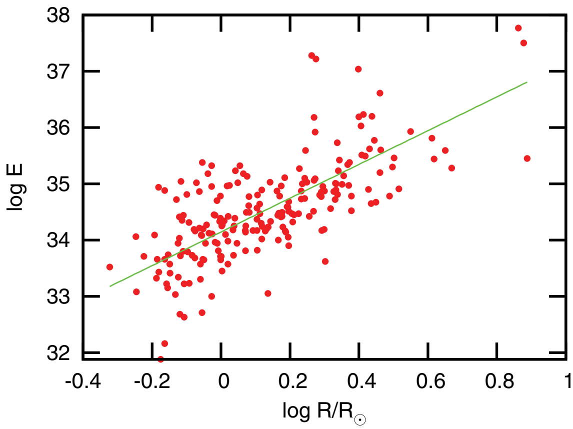

Figure 6. The median flare energy, (E, in ergs) as a function of stellar radius, R. The straight line is $\log E = 3\log R/R_\odot + 34.14$, indicating that the flare energy is proportional to R^3.

reasoning can be applied to A stars which have no convective dynamo action according to current ideas.

To understand the role of rotation in inducing flares, it is necessary to understand how magnetic fields can be generated in stars with radiative envelopes. A theory of dynamo action in radiative envelopes which requires rotation has been developed by Spruit (1999, 2002) and Maeder & Meynet (2004). In this theory a magnetic instability in the toroidal field wound up by differential rotation replaces the role of convection in closing the field amplification loop in conventional dynamo theory.

The widths of the rotation peak in periodograms of *Kepler* A stars are broader than they should be, which suggests different rotation rates for spots at different latitudes (Balona 2013). The implied differential rotation is similar to that seen on the Sun. It is therefore possible that a radiative dynamo could power magnetic fields in A stars. At the same time, twisting of field lines in differentially-rotating layers could replace convection as the source of magnetic reconnection.

There are three very well observed rapidly-oscillating Ap stars in the *Kepler* field. In spite of the fact that these roAp stars were observed for almost four years in SC mode, no flares were detected. No flares were detected in any other known Ap star in the *Kepler* field either. Ap stars, in general, have very strong kilogauss dipolar magnetic fields. Their rotational light curves show no sign of differential rotation. While this by no means proves that differential rotation is a key factor in generating flares in A stars, it at least offers some support for the idea.

6. Energetics of stellar flares

The energy stored in a magnetic field of magnitude B is approximately $E = L^3B^2/8\pi$ where L is the size of the magnetically active region. If stellar flares are a result of magnetic reconnection, then the flare energy release should be closely related to the magnetic field strength and some characteristic length, L. If one supposes that the magnetic field strength, B, is much the same for all stars, one expects the flare energy, E, to be proportional to the volume of the active region, L^3.

Fig. 6 shows $\log E$ as a function of the stellar radius, $\log R/R_\odot$. The slope has a value close to 3, suggesting that the loop length, L, is proportional to the stellar radius. In other words, the larger the star, the larger the size of the active region or loop length and the larger the flare energy. This may explain why the average maximum flare amplitude does not change much with spectral type (Fig. 4). Suppose that $L = \alpha R$, where α is a constant of proportionality. Then we may write $\log E = 3 \log R/R_\odot + \log C$ with $C = \alpha^3 R_\odot^3 B^2/8\pi$. The straight line in Fig. 6 is $\log E = 3 \log R/R_\odot + 34.14$. This leads to $B \approx 32\alpha^{-\frac{3}{2}}$ G. Since the value of α is of the order unity, the implied field strength is some tens of gauss, which seems a reasonable value.

We may therefore conclude that the magnetic reconnection model could account for the increase of flare energy with luminosity if the size of the active region also increases in proportion to the stellar radius. The required magnetic field strength is consistent with typical field strengths found in main sequence stars. The fact that the observed global magnetic fields in normal A stars are typically less than 1 G (Lignières *et al.* 2009, Petit *et al.* 2011) probably implies that the magnetic fields on these stars are of complex topology with mixed polarities, as in the Sun.

7. Convection as a necessary condition for the corona

The solar corona, which has a temperature in excess of 10^6 K, emits most of its radiative output at soft X-ray wavelengths. Although the source of coronal heating is not fully understood, it is thought to be of magnetic nature. The discovery of X-ray emission from many thousands of solar-type stars is taken as direct evidence for the presence of stellar coronae.

Berghoefer *et al.* (1996) lists all O and B stars in the *Yale Bright Star Catalogue* (Hoffleit & Jaschek (1964)) which are detected by the ROSAT all-sky X-ray survey. Similarly, Huensch *et al.* (1998) lists A, F, G and K stars in the *Yale Bright Star Catalogue* detected by ROSAT. We can compare the number of X-ray detections, N_X, relative to the total number of stars, N, of a particular spectral type. The distribution of N_X/N is shown in Fig. 7.

Fig. 7 shows that stars in the spectral range B1–A9, which have radiative envelopes, are relatively inactive. X-ray activity increases sharply for stars cooler than A9 or hotter than B1. The X-ray activity for stars cooler than A9 can be attributed to the presence of convection and dynamo-generated magnetic fields which are responsible for heating the corona. For stars earlier than B1, the X-ray emission is attributed to shocks in the radiatively-driven stellar winds. Note that while the X-ray activity for B1–A9 stars is small, it is not zero. It is generally thought that this residual activity arises from unseen cool companions. This may well be the case, but the possibility that part of the activity may be due to stochastic X-ray emission from flares should not be excluded.

The above scenario agrees with the generally-accepted view that only stars with convective envelopes can generate magnetic fields, which explains why the A9–B1 stars do not have coronae. However, if A stars do have magnetic fields as, as suggested by starspots and flares, this explanation cannot be complete. The observations indicate that only stars with convective envelopes possess coronae and the presence or absence of a magnetic field is not relevant to the existence of coronae. It appears that while a magnetic field may be necessary for effective heating of the corona, the corona itself cannot be formed unless convection is present in the outer layers of a star.

8. Conclusions

Analysis of *Kepler* photometry shows that starspots are present in A and B stars and that superflares are seen on A stars. The implication is that upper main sequence stars possess magnetic fields in spite of the fact that they have radiative envelopes.

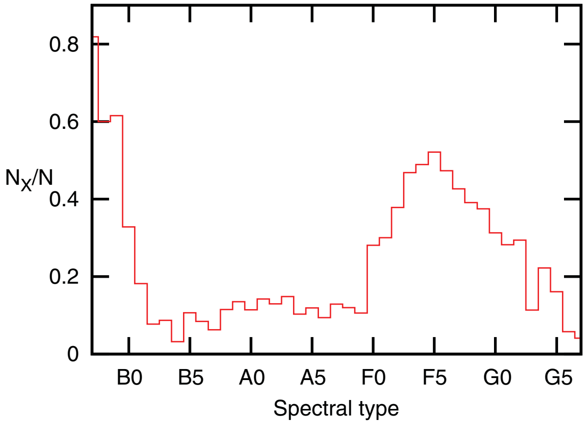

Figure 7. Relative numbers of X-ray active stars N_x/N in the *Bright star catalogue* as a function of spectral type. Note the x-ray "hole" between B1 and F0.

Presumably, these magnetic fields have complex polarity (tangled field lines) like the Sun, which means that the overall global field is very weak, as observed. The radiative dynamo theory (Spruit 1999; Spruit 2002; Maeder & Meynet 2004) may offer a possible explanation for the existence of magnetic fields in radiative envelopes. In this theory, differential rotation replaces convection as the energy source for generating magnetic fields.

The relative number of flare stars is high in K/M dwarfs and drops for hotter stars. However the total drop is only a factor of four and can be mostly explained as a selection effect. It is much easier to detect flares of the same energy on a low-luminosity cool dwarf than on a high-luminosity A star. Moreover, the A-type continuum of a flare is more easily seen in a cool dwarf than in an A star. The true relative number of flare stars is probably much the same for all spectral types.

Kepler observations show that the relative flare amplitude does not change much with spectral type. Since the stellar luminosity along the main sequence increases from M to A stars, this implies that flare energies increase in about same proportion. The observations indicate that the flare energy is actually proportional to the stellar volume. This can be understood if the size of the active region increases with the size of the star.

If magnetic fields are ubiquitous across the main sequence, and if magnetic fields are responsible for the formation of stellar coronae, then all stars should have coronae. X-ray observations show that this is not the case: only stars with convective envelopes possess coronae. This suggests that convection is a necessary condition for the formation of the corona. However, a magnetic field may be required to transport the mechanical energy of convection to the upper atmosphere, thereby heating the corona.

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