Flare stars across the H-R diagram

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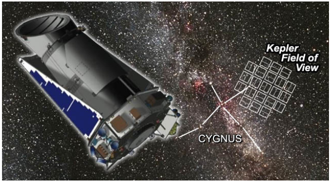
Main results of flare stars observed by *Kepler*

- Flares occur in M, K, G, F and A stars (very few B stars observed).
- Flare stars may be common over the whole spectral range.
- Flares tend to occur mostly in rapidly rotating stars.
- Flare energies increase with increasing stellar radius.
- No support for interacting magnetospheres in RS CVn binary model.

The Kepler spacecraft



- Continuous photometry of over 100 000 in a broad optical band (4000–9000 Å).
- Sampling time of 30 min (long-cadence mode) over 4 years.
- Sampling time of 1 min (short-cadence mode) over a few months.

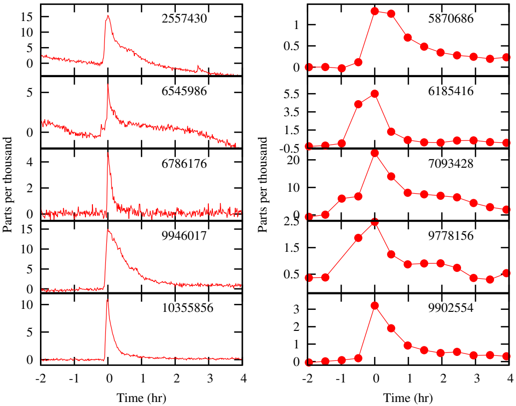
The Kepler input catalogue

- Prior to launch, the *Kepler* field was observed with multicolour photometry.
- For each star, the $T_{\rm eff}$ and radius was derived by a modeling process.
- Each star can therefore be approximately placed in the H-R diagram.

The data

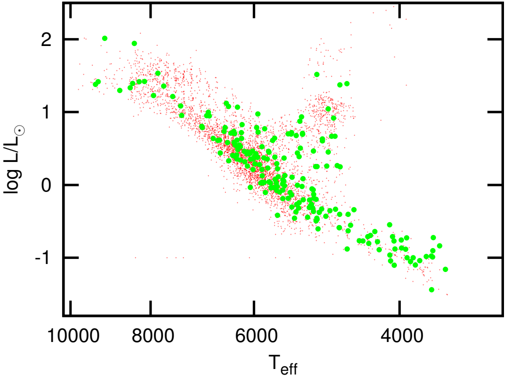
- Raw light curves of about 20 000 stars brighter than 12th mag were visually inspected.
- Each star classified according to variability type and possible flares noted.
- Eliminated all “flares” which are simultaneous in different stars.
- Omitted all “flares” which did not have the characteristic impulsive phase.
- Avoided noisy stretches in the *Kepler* data.

Examples of flares: short- and long-cadence



We use only short-cadence data.

H-R diagram of flare stars - short cadence



Flares occur even in hottest stars!

Flares in hot stars

- Flares in A stars are unexpected.
- This indicates that something is wrong with current understanding.
- This offers a perhaps important insight into the roles of convection and magnetism in generating the corona.

Current view on incidence of flare stars and presence of corona

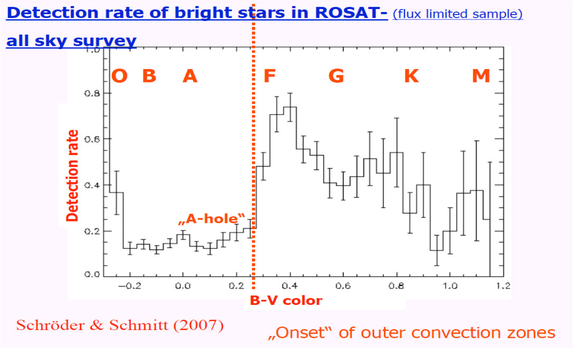
Stars cooler than granulation boundary ($T_{\rm eff} \lesssim 7500\,{\rm K}$):

- Convection $\rightarrow$ magnetic fields $\rightarrow$ spots $\rightarrow$ flares.
- Convection/magnetic fields $\rightarrow$ corona $\rightarrow$ X-ray emission.

Stars hotter than granulation boundary ($T_{\rm eff} \gtrsim 7500\,{\rm K}$):

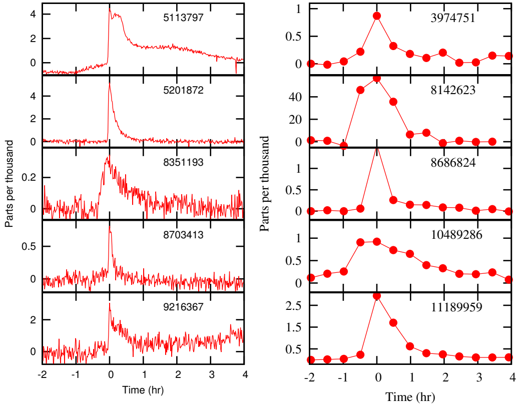
- No convection $\rightarrow$ no magnetic fields $\rightarrow$ no spots $\rightarrow$ no flares.
- No convection/magnetic fields $\rightarrow$ no corona $\rightarrow$ no X-ray emission.

X-ray detections supports current view

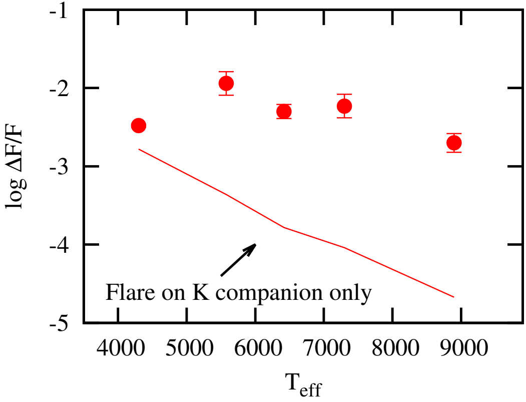


X-ray "hole" for A stars shows that A stars do not have coronae, as expected.

Flares in A stars



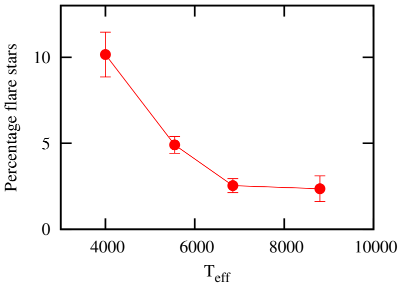
Flares in A stars are not due to a cool companion



Kepler would be unable to detect a flare on a K/M companion to a non-flaring A star.

Percentage of flare stars as a function of $T_{\rm eff}$

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



Selection effects

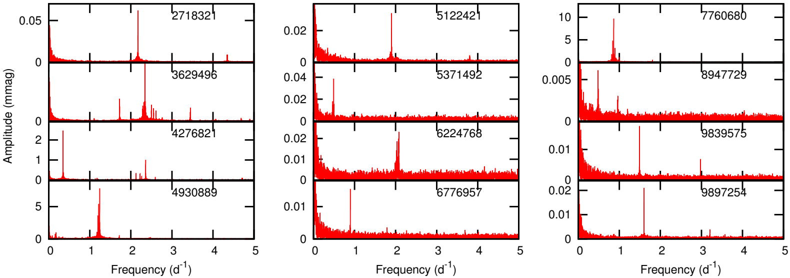
- A flare of a given energy will have a lower amplitude and more difficult to detect on an A star than on a cool star.

- Stellar flares in K/M dwarfs have A- or B-type continuum (Kowalski et al 2013). It is easier to detect such flares on cool stars than on hot stars.

Above selection effects tend to give decrease in flare star numbers from M $\rightarrow$ A, as observed. It is possible that the relative number of A-type flare stars is not very different from the relative number of K/M flare stars.

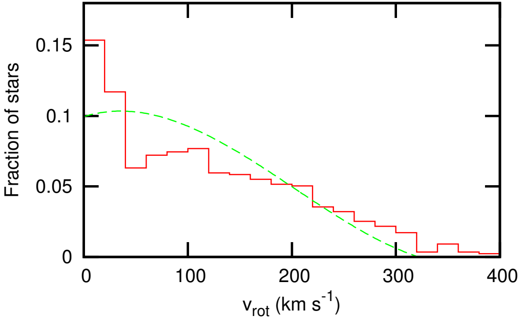
Flares seem to be a general property of all stars and not just cool dwarfs.

Rotational modulation in A stars



- Most *Kepler* A-stars show an isolated low-frequency peak.
- Very often the harmonic can be detected.
- Strongly suggests rotational modulation due to star spots.

Distribution of equatorial rotational velocities



Distribution of v_e from *Kepler* photometry (histogram) agrees with distribution of v_e for field A stars (dashed curve).

Revised view on incidence of flare stars

A stars have spots and flares. A stars therefore have magnetic fields (but no coronae).

It seems that the presence or absence of X-ray emission (coronae) is independent of the presence of a magnetic field.

On the other hand, X-ray emission stops when convection stops, therefore:

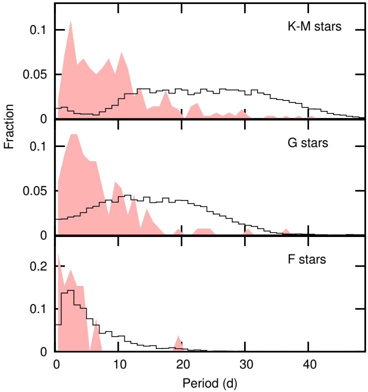
- Convection may be necessary condition for the development of a corona.
- Magnetism may play a role in heating, but does not seem to be primary cause of corona.

What are these flares?

Flares observed by *Kepler* are white-light flares. White-light solar flares are rare.

Stellar white-light flares may involve processes different from normal solar flares.

Flare stars rotate rapidly



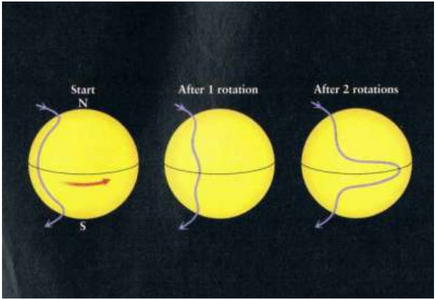
Rotation periods from *Kepler* light curves.

Why is rotation so fundamental in causing flares?

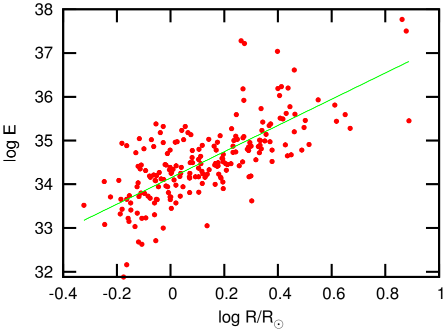
Rapid rotation $\rightarrow$ young star $\rightarrow$ activity.

BUT

Perhaps rotation itself plays a role in promoting flares. Perhaps differential rotation is efficient at twisting magnetic fields over very large distance scales.



Flare energy scales with stellar size

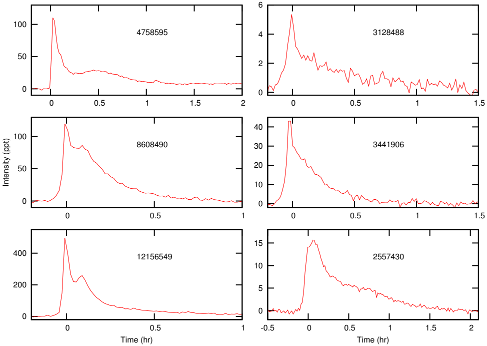


Fractal nature of magnetic reconnection?

Why do larger stars have more energetic flares?

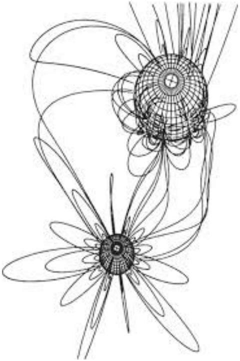
- Energy in magnetic field is given by $E = \frac{L^3 B^2}{8\pi}$
- Larger stars $\rightarrow$ larger L $\rightarrow$ larger E for a given B.
- Observed relation gives $B \approx 30\,\mathrm{G}$ assuming $L \propto R_{\rm star}$

Flare shapes



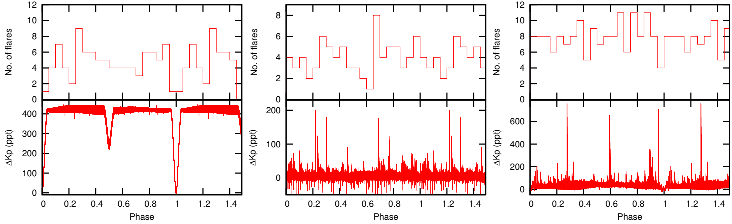
More than 30% of flares have bumps or change in decay rate.

Interacting magnetosphere model for RS CVn stars



Model for reconnection in magnetic field connecting components of RS CVn binary can be tested by looking at flaring rate as a function of orbital phase.

Flares in eclipsing binaries



No obvious correlation of flaring rate with phase. Interacting magnetoshere model not supported.

Conclusions

- Flares common in M – A stars.
- Flares, spots on A stars $\rightarrow$ convection necessary for a corona.
- Rapid rotation promotes flares (differential rotation twisting?).
- The larger the star, the more energetic the flare ($B \approx 30\,\mathrm{G}$).
- Inter-star reconnection not supported for flares in close binaries.

We need to understand solar white-light flares to understand stellar flares.