Flare stars across the H-R diagram

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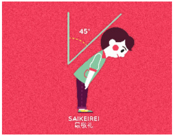
S A Astronomical Observatory

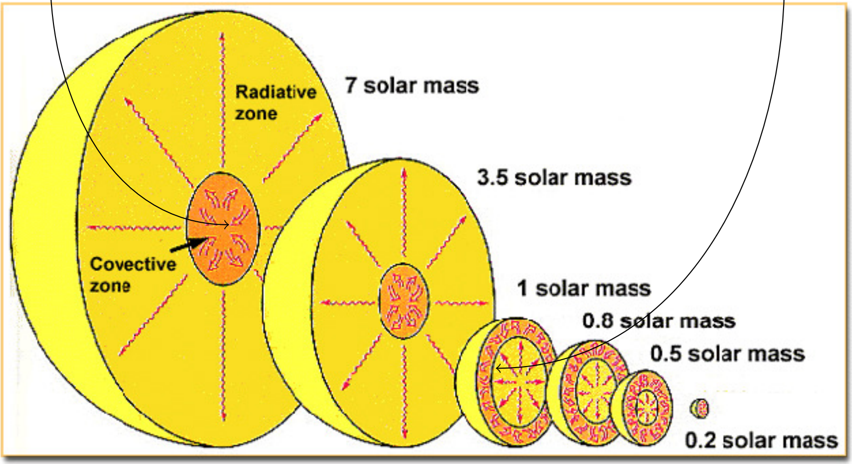
Thank you for inviting me!



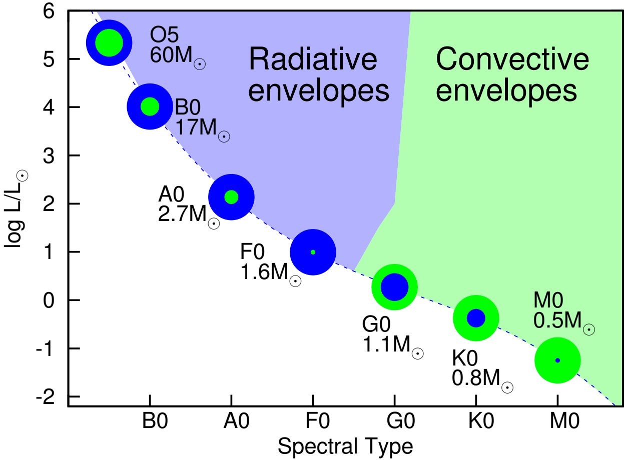
Convective envelopes in stars

CNO cycle

Ionization of H & He



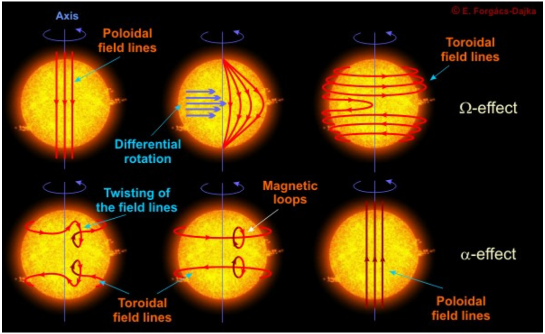
Convective envelopes in stars



The solar dynamo

- Convection → moving conductor → electric current → magnetic field.
- Stars with convective envelopes are thus expected to have surface magnetic fields.

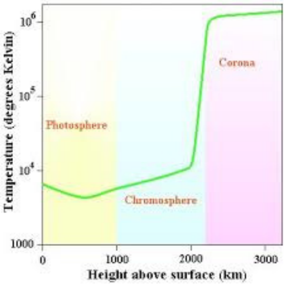
Solar cycle – 11 yr periodic re-configuration of magnetic field:

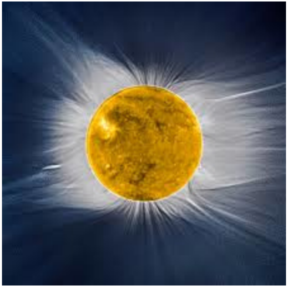


Convection also implies a corona

Magnetic fields extend from the photosphere to space.

- Turbulence due to convection moves magnetic field lines.
- Magnetic waves increase in amplitude with height above photosphere due to lower gas density.
- This heats the gas high above the photosphere to above 10^6 K, forming the corona.





High temperature of corona emits X-rays

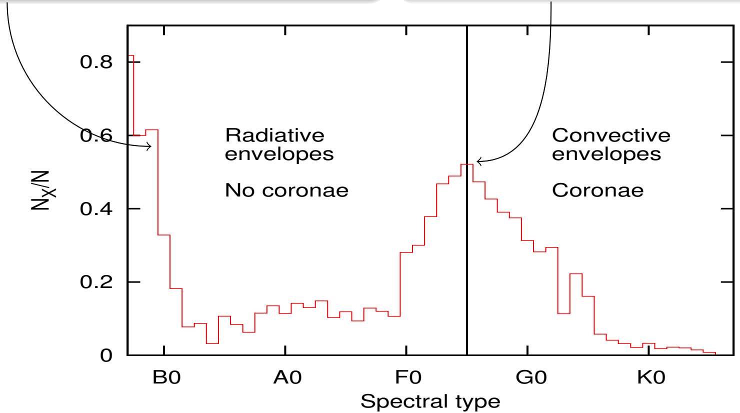
X-ray detection in 6000 brightest stars:

Very hot stars:

Shocks in radiatively-driven wind → X-ray emission.

Cool stars:

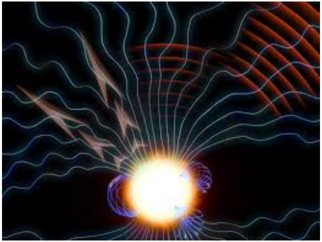
Surface convection + magnetic field → hot corona → X-rays.



Convection also implies a stellar wind

- Because gas in the corona is a very good heat conductor, it extends to large distances from the Sun.
- The weak gravity and high temperature means gas can escape supersonically into space, forming a stellar wind.

Convection $\rightarrow$ acoustic waves + magnetism $\rightarrow$ heating of upper atmosphere $\rightarrow$ corona $\rightarrow$ stellar wind.

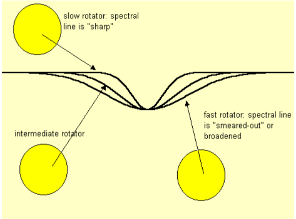


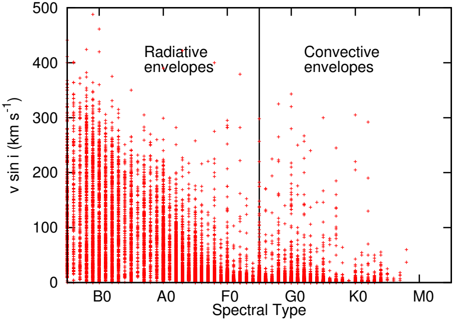
Stellar wind removes angular momentum

- Convection leads to corona and wind.
- The wind coupled to the magnetic field leads to a slow loss of angular momentum. Star rotates more slowly with time.

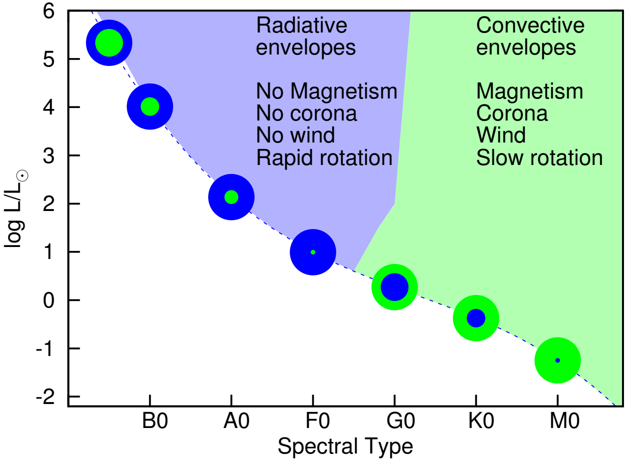
Stars with convective envelopes rotate slowly.

Stars with radiative envelopes retain initial rotation.



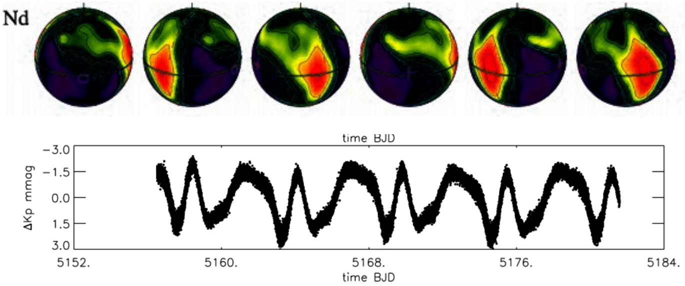


Convection, magnetism, coronae, wind and rotation



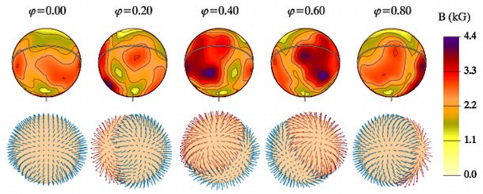
Exception: the Ap/Bp stars

- About 2–5% of A/B stars show overabundances of Sr, Cr, Eu, Pr, Nd and other rare-earth elements: the Ap or Bp stars.
- Over-abundances occurs in spots on the surface, giving rise to periodic light variations as a result of rotation.
- Rotation of Ap/Bp stars is slow (2d to $>$70yr).



Kilo-gauss magnetic fields in Ap/Bp stars.

- Rotation of Ap/Bp stars is slow (2d to >70yr).
- They have very strong (0.5–30 kG) global dipole magnetic fields.
- But they have radiative envelopes.

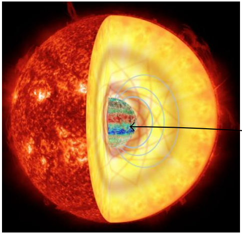


Where does the large magnetic field come from?

They are born that way (a “fossil” field). Loss of angular momentum occurred in the pre-main sequence phase (convective envelope).

Magnetic field trapped in convective core

For stars with radiative envelope and convective core (A, B stars), dynamo action generates very strong magnetic fields trapped in the core.

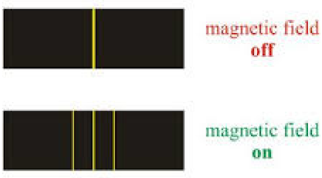


Strong magnetic field trapped in core

However, magnetic fields cannot rise to surface. Radiative envelopes still implies no magnetic field.

Indicators of magnetic field

The Zeeman effect measures global magnetic field strength. Needs high dispersion. Ineffective for local fields of mixed polarity. Requires high dispersion, high S/N.

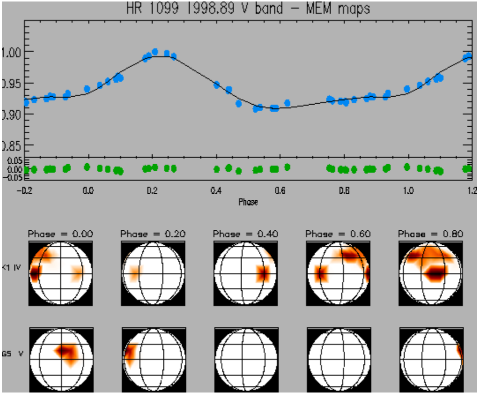


Stellar activity (starspots, flares) are indirect indicators of a magnetic field.

Current paradigm predicts that stars cooler than F5 are active, stars hotter than F5 are inactive.

We can test this by looking for starspots and/or flares in A and B stars.

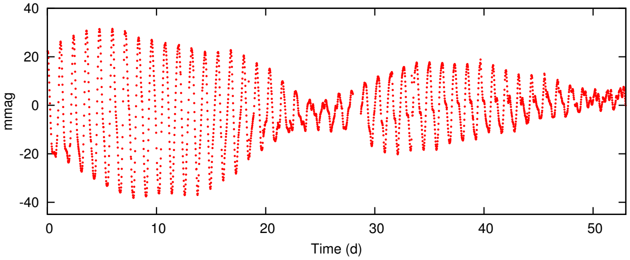
Magnetic field slows down convection, reduces gas pressure. Therefore gas cooler than surrounding.



Starspot leads to light variation with period equal to rotation period.

Detection of starspots

Over 500 stars are known to have spots from ground-based observations. All are cool F, G, K, M stars. Typical light curve:

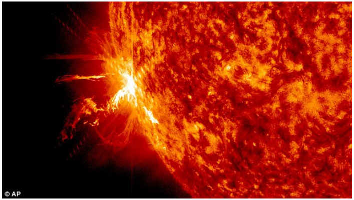


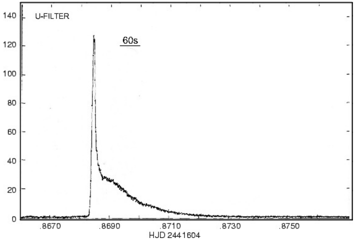
Variable amplitude due to change in spot size. Different spots may have slightly different periods owing to differential rotation.

Starspots indicate a local magnetic field.

Stellar flares

Stellar flares emit mostly in the U band and are most easily detected in M dwarfs.

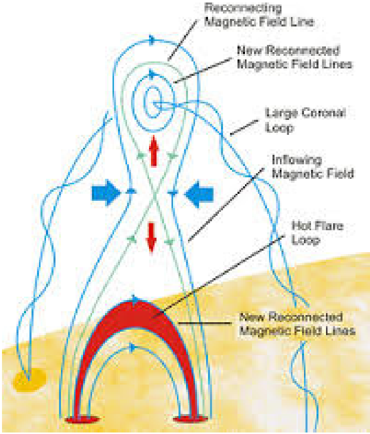




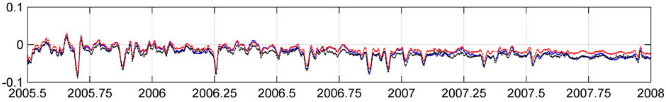
Ground-based optical observations only tell us about the most energetic flares in the coolest stars.

Stellar flares are powered by magnetic re-connection

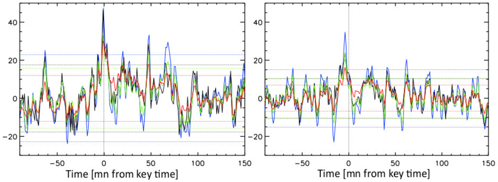
Flare energy comes from re-connection of magnetic field lines:



Flares indicate a local magnetic field.



Sunspot amplitude is typically less than 0.1% (1 mmag) over the Sun's rotation period of 27 d.



Total amplitude of large (X-class) solar flare is typically 40 ppm.

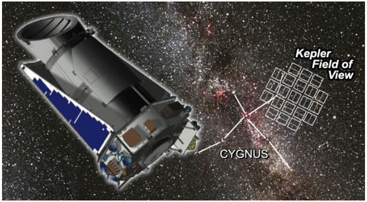
The Sun is very constant when observed as a star.

Problems with detecting starspots and stellar flares

- Very difficult to detect spots in hot stars due to poor contrast. Amplitude becomes smaller as temperature increases ($\frac{\Delta L}{L} \propto 4\frac{\Delta T}{T}$). That is why only very large spots in cool stars are detected.
- Very difficult to detect flares on hot stars due to lower flare amplitude. Flare amplitude gets smaller as temperature increases ($\frac{\Delta L}{L} \propto \frac{\Delta E}{L}$). That is why only large flares in very cool stars have been detected.
- Need photometric precision in ppm and long-term stability.

Observation from space is the only solution.

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.
- Ground-based muticolour photometry allows $T_{\rm eff}$ and $\log L/L_{\odot}$ to be estimated for all stars.

The Kepler data

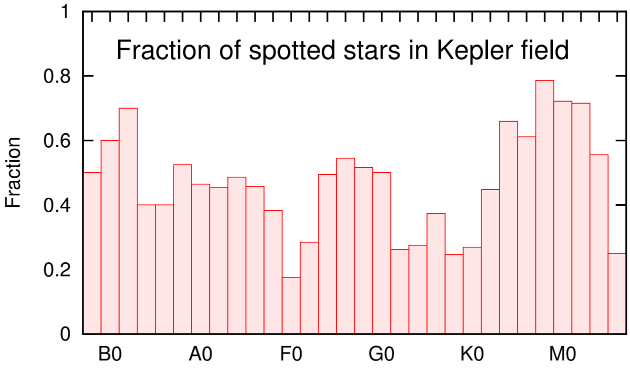
- Visually examined light curves and periodograms of all 20000 stars with $m > 12$ mag with a precision of 10-100 ppm.
- Classified each star according to its variability type.

Catalogue of 20 000+ stars:

KIC	Type	RA	Dec	sl	Kepmag	Log(T)	Log(L)	Log(g)	[Fe/H]	Teff	Radius	Cont	Remarks
1430353	SPB/ROT	19:23:46	37:01:26	l	12.391	4.0320	2.2991	3.6530	-0.1220	10765.0	4.07	0.003	
1430590	DSCT	19:24:02	37:01:54	l	9.721	3.8296	1.2075	3.6590	-0.0190	6755.0	2.94	0.161	F0V
1431474	SPOT	19:24:55	37:04:06	l	13.521	3.8225	0.7491	4.0340	-0.1610	6645.0	1.79	0.180	FLARE
1431794	-	19:25:11	37:00:03	l	12.386	3.8519	1.0013	3.9300	-0.2010	7111.0	2.09	0.067	
1432149	GDOR	19:25:29	37:05:57	sl	11.223	3.8615	0.9815	3.9910	-0.1400	7269.0	1.96	0.047	
1433628	-	19:26:45	37:02:25	l	12.166	3.8075	0.7124	4.0040	-0.1940	6419.0	1.84	0.036	
...	...	...	...	...	...	...	...	...	...	...	...	...	...

- A large number of stars have light curves which can be attributed to spots.
- Flares seem to occur on many stars.

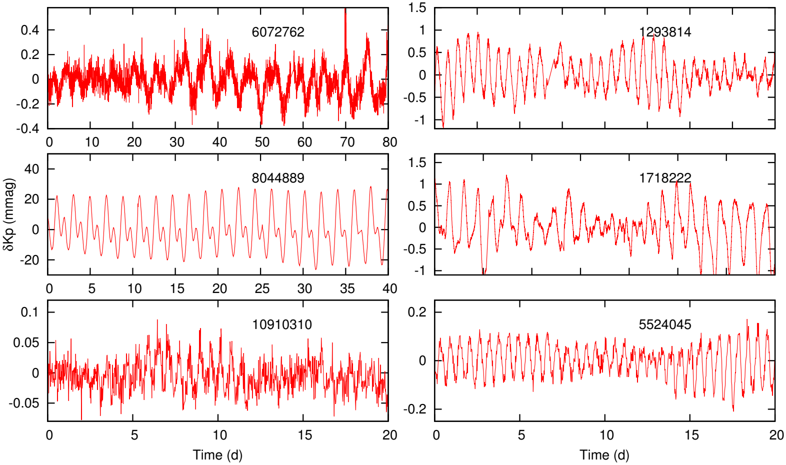
Fraction of Kepler stars with spots



Spots seem to occur in stars of all spectral types!

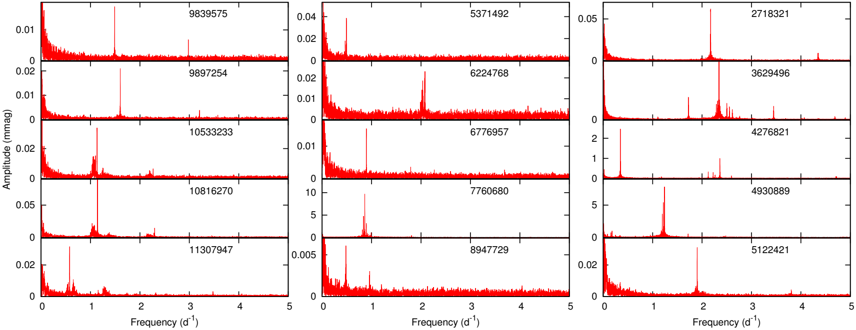
Variability in Kepler A stars

Examples of light curves of spotted A stars:



Rotation periods of Kepler A stars

Periodograms of 875 stars (40% of all A stars) show low-frequency peak and harmonic.

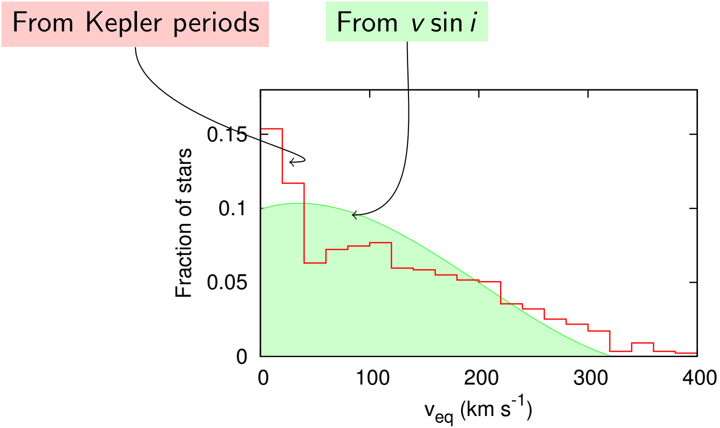


How do we know this is the rotation period?

- Measure period, P, from the light curve.
- Obtain radius, R, from KIC (multicolour photometry).
- Calculate equatorial rotational veocity $v = 2\pi R/P$.
- Compare with expected v for A stars as determined statistically from projected rotational velocity, $v \sin i$.

Rotational velocity distribution of Kepler A stars

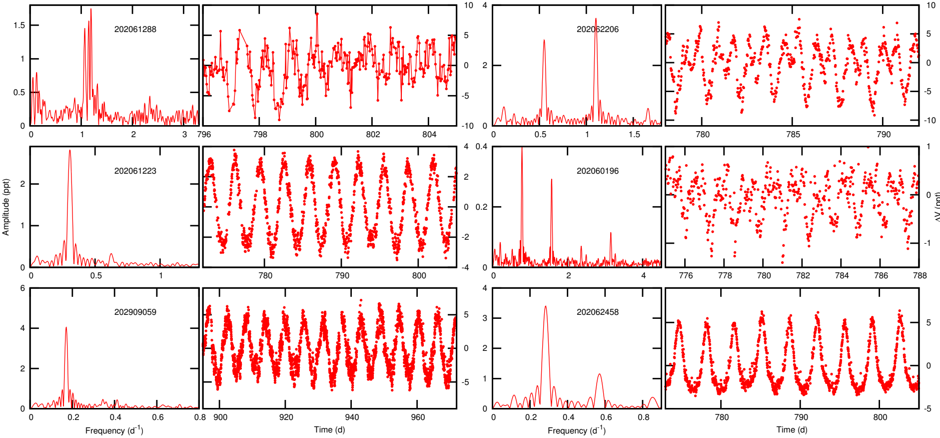
Equatorial rotational velocities from light period and radius agrees with that of field A stars from spectroscopic $v \sin i$.



It seems that about half of all A stars have spots!

Rotational variability in Kepler B stars

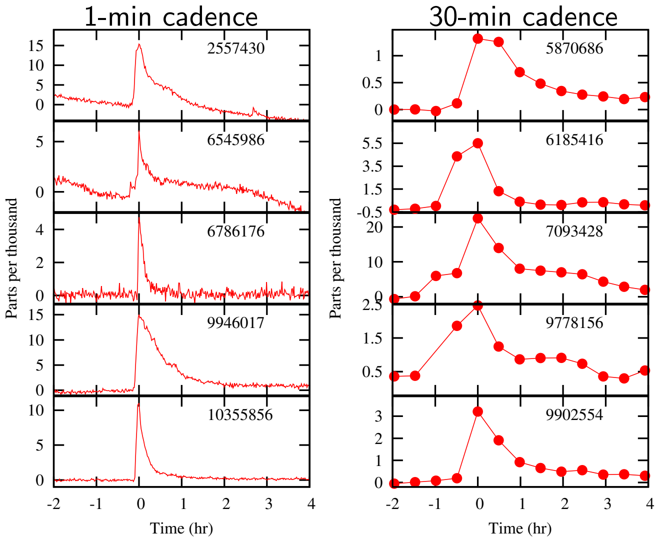
From the Kepler and K2 data we can also see that 30-40% of B stars have spots as well.



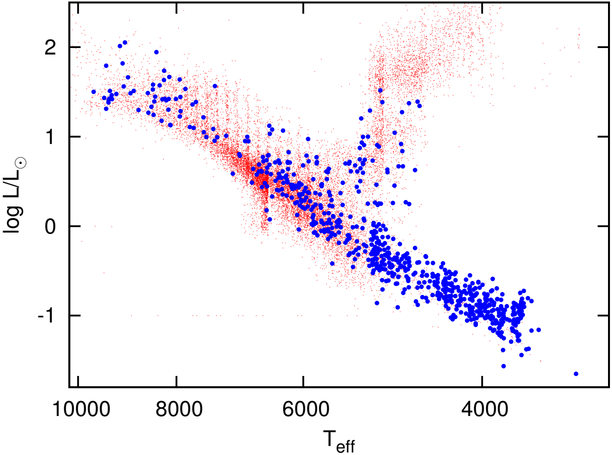
Flare stars in Kepler

- Inspection of 20000 Kepler stars brighter than 12 mag show that many do flare.
- Not too surprising if these are M, K, G or late F stars.
- But A stars also flare!
- Too few B stars to study flares.
- List of all flares detected in all short-cadence Kepler data (3140 flares in 209 stars): *VizieR Online Data Catalog: 2015yCat..74472714B*.

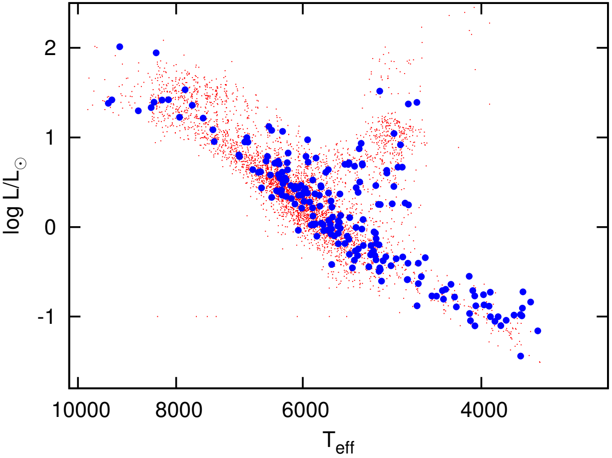
Examples of A-star flares: short- and long-cadence



H-R diagram of flare stars - long cadence



H-R diagram of flare stars - short cadence



Flares occur even in hottest stars!

Can flare be explained by a cool companion?

- Maybe flares in A stars actually occur on a binary K/M companion.
- Because K/M stars are 50-100 times less luminous than A stars, observed flare amplitude should be 50-100 times smaller.

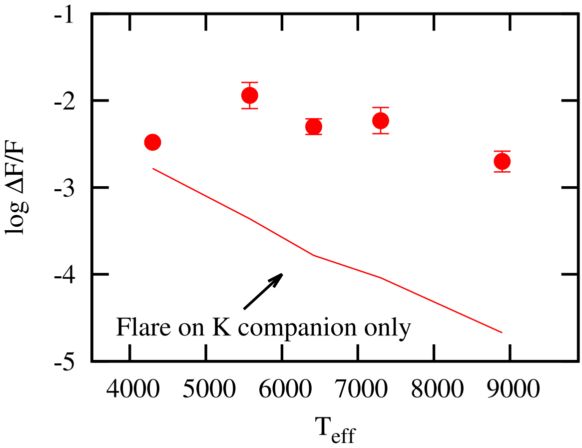
Why flares in A stars cannot be due to a cool companion

- Measure amplitude of largest flare in 373 K/M Kepler dwarfs.
- Measure amplitude of largest flare in 35 A stars.

Average amplitude in K/M dwarfs $\approx$ average amplitude in A dwarfs.

Flare is on A star, NOT on a cool companion!

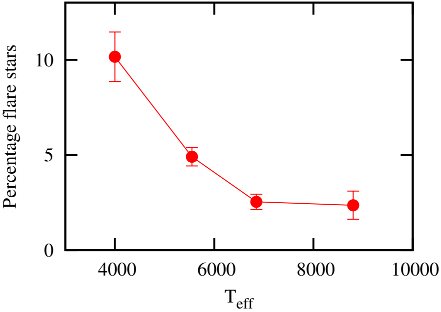
Flare amplitudes for M to A stars



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

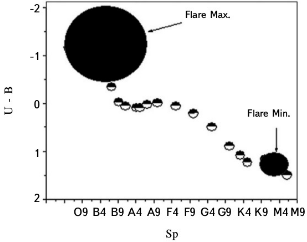
Percentage of flare stars as a function of T_{eff}

Type	T_{eff}	N	N_{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



Incidence of flares is similar for all spectral types

- A flare of the same energy will be easier to detect on a star of low luminosity (cool star).
- Because a stellar flare emits mostly in the U band, it is easier to detect on a cool star.



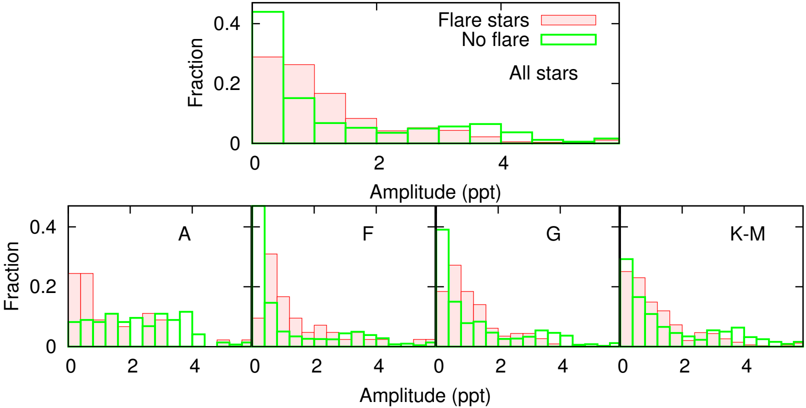
These two selection effects may fully account for the 4-fold decrease in flare incidence from K/M to A stars.

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

Flares and spot sizes

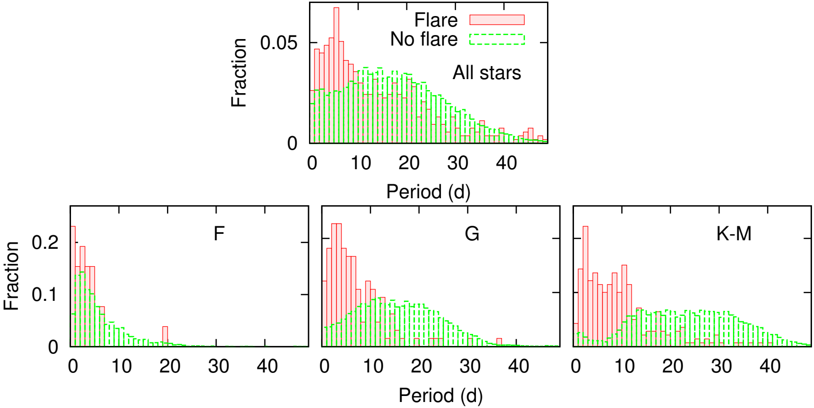
- The light amplitude is related to the spot size.
- One can study the relationship between the incidence of flares and spot size.

Do large flares imply large spots?



There is a slight tendency for flare stars to have somewhat larger spots than non-flare stars.

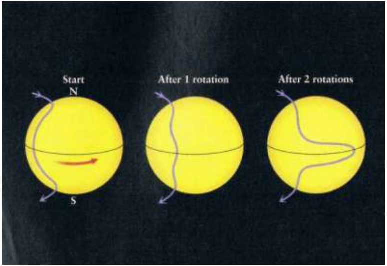
Does incidence of flaring depend on rotation?



Flares are ceratinly more likely on rapidly-rotating stars.

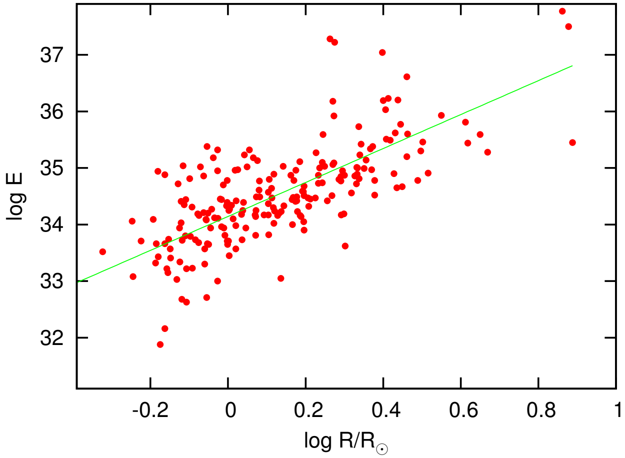
Why is rotation so fundamental in causing flares?

- Perhaps rapid rotation → large differential rotation → twists magnetic fields → magnetic re-connection and flares.
- The fact that X-ray luminosity increases with rotation rate may be a result of the increased flare rate.



Flare energy and stellar radius

Flare energy increases with stellar radius: $\log E = 3 \log R/R_\odot + 34.14$.

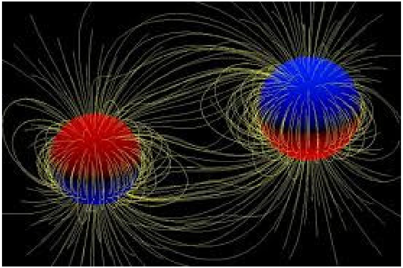


Why flare energy increases with stellar radius

- Energy released by re-connection in magnetic field B with loop length L is $E = \beta\frac{L^3B^2}{8\pi}$ or $\log E = 3\log L + 2\log + \log\frac{\beta}{8\pi}$, where $\beta < 1$ is the fraction of released energy.
- Suppose that $L = \alpha R$ $(0 < \alpha < 1)$ and $B \approx$ constant for all stars.
- Then $\log E = 3\log R/R_\odot + \log C$ with $C = \alpha^3\beta R_\odot^3 B^2/8\pi$.
- The straight line fit gives $C = 34.14$, which gives $B \approx 32/\sqrt{\alpha^3\beta}$ G.
- Since $\alpha^3\beta \ll 1$, we estimate $B \approx$ a few hundred or a thousand gauss.

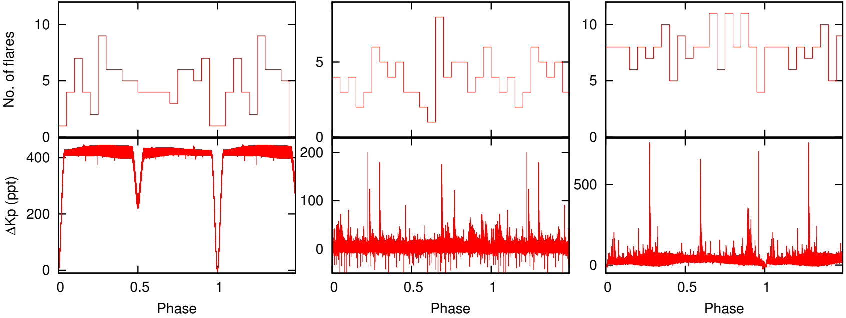
Flares in close binaries

- There is an idea that flares in close binaries (RS CVn stars) may arise from reconnection of magnetic loops *connecting the two stars*.
- This will allow for a large energy release (larger magnetic volume).
- Can this be verified from Kepler observations?



Light curves of three flaring eclipsing binaries

There are three cases of eclipsing binaries with flares.

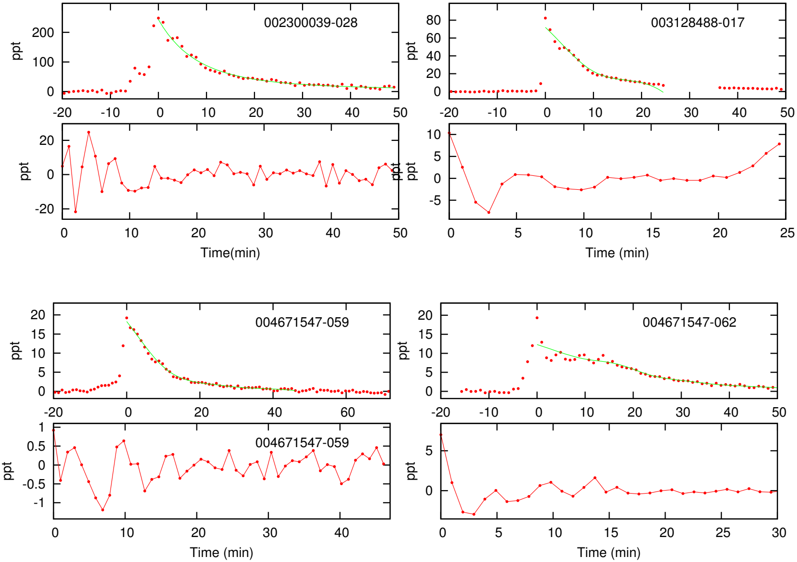


No obvious correlation of flaring rate with phase. Interacting magnetoshere model not supported.

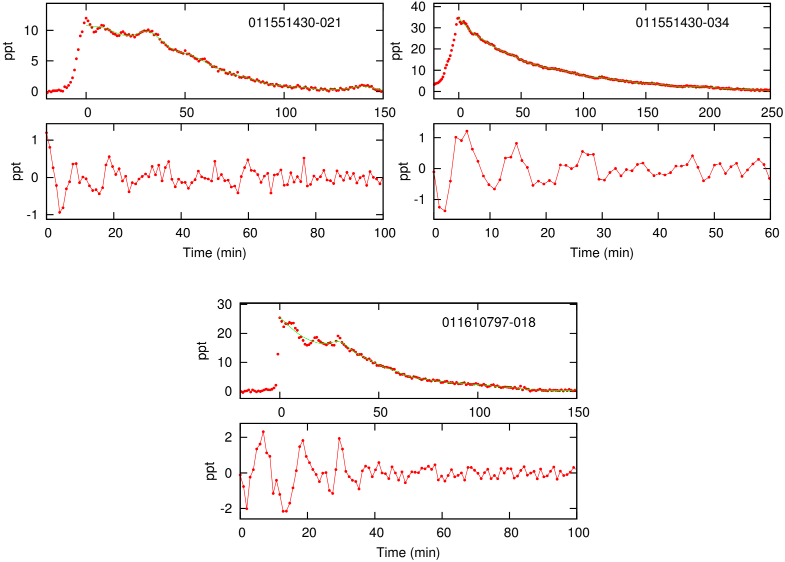
Flare oscillations

- Oscillations in stellar flares may tell us something about physical conditions in flare loops.
- Searched for oscillations in 3140 flares observed in SC mode.
- Used wavelets to search for possible periods.
- Found possible oscillations in 7 flares.
- Periods do not correlate with any physical parameter.
- No starquakes detected.

Flare oscillations

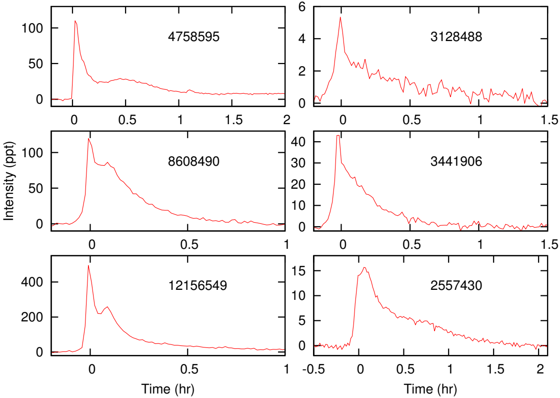


Flare oscillations



Why do so many flares have bumps?

About 30% of flares have a distinct bump or rate discontinuity on the decay branch.



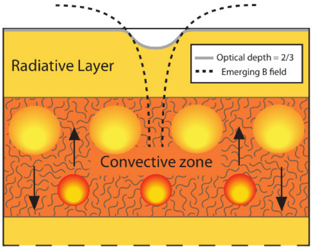
Some thoughts

How can a magnetic field be generated in an A or B star?

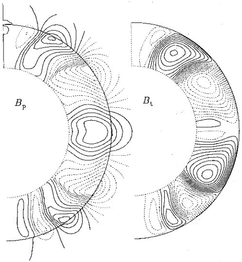
Can we say anything on how the corona is formed or heated?

Generation of magnetic fields in hot stars

Dynamo action in sub-surface convective zone (Braithwaite & Spruit 2015)?



Dynamo action in radiative envelope by means of differential rotation (Spruit 2002)?



Coronal heading: acoustic or magnetic field?

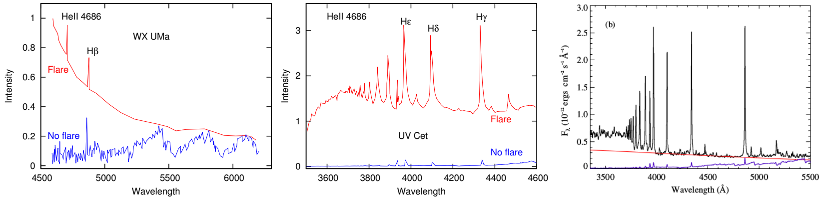
- Stars earlier than F5 have magnetic fields but no coronae.
- Stars later than F5 have magnetic fields and coronae.
- Therefore formation of corona does not depend on presence of magnetic field.

Two deductions regarding coronal heating:

- We can rule out mechanical energy due to convection, on its own, as a source of coronal heating.
- Surface convection is essential in forming a corona.

Stellar flares are **White Light** flares

Stars: WX UMa, UV Cet, YZ CMi:



- How is $\approx 10^4$ continuum created? (Kowalski et al: high-energy electron beam + chromospheric compression; Reep & Russell: Alfvenic wave heating of chromosphere?).
- How can we explain A star flares? A stars have no coronae. Do they have a chromosphere?

Future prospects

- Need more studies of the Sun-as-a-star to compare stellar flares with solar flares.
- TESS (to be launched in 2017) offers prospects for further stellar flare optical observations.
- Will offer more opportunities to study rotation and flares in all types of stars.

Conclusions

- Starspots and flares show that A and B stars have surface magnetic fields.
- Current paradigm that stars with radiative envelopes are inactive and without magnetic fields needs to be revised.

Thank you!