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Chapter 10: New frontiers in solar and stellar flares and research programs

Solar and Stellar Flares and their Effects on Planets
Proceedings IAU Symposium No. 320, 2015
A.G. Kosovichev, S.L. Hawley & P. Heinzel, eds.

doi:10.1017/S1743921316000351

Synergy Between Solar and Stellar Flares: Challenges and Perspectives

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Abstract. I will review the current status of stellar flare observations and models, highlight similarities and differences with solar flares, and plead for additional data and insight from the "Sun as a Star".

Keywords. Stars, Flares

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1. Introduction

I have been charged with reviewing the current synergy between solar and stellar flare observations (and possibly models), outlining some challenges and perspectives. Probably the biggest challenge will be covering that topic in the allotted 20 minutes! As one of the last talks at this conference, I will try to also highlight some of the previous results that have been presented this week; readers can refer to other papers in this proceedings for details.

2. Challenges

The first and perhaps largest challenge in comparing solar and stellar flares is the enormous difference in the types of data that are obtained. When observing the Sun, you can observe every tree in the forest, and indeed almost every leaf on every tree. A huge variety of solar flare phenomena are visible with exquisite spatial resolution and high time resolution especially in the high energy (X-ray) regime. It is possible to observe coronal mass ejections and measure particle fluxes in-situ. And nearly continuous monitoring by a fleet of satellites over the past several decades has resulted in volumunious databases that record the context (e.g. magnetic field structure) and evolution (e.g. two-ribbon arcades) of a huge number of flares.

However. There are a few missing elements in the solar flare record, and unfortunately these are almost precisely the elements that make up the bulk of stellar flare observations: to wit, broadband optical and near-ultraviolet photometry and broad wavelength coverage optical and near-ultraviolet spectroscopy. Flares on low mass stars are characterized by their optical light curves (typically in blue bandpasses from the ground, but in a broad white-light ∼4000-8000Å wide filter with Kepler from space) and by spectra showing significant blue and near-ultraviolet continuum emission and strong, broad hydrogen Balmer, Ca II and He emission lines in the optical and near ultraviolet. Such optical spectra have not been obtained on the Sun in any quantity since the 1980s when photographic plates were replaced by digital detectors. The connection between solar and stellar flare phenomena since that time has thus relied on inference and proxies rather than direct comparison of similar data.

A recent development that has been addressing this issue is the ROSA photometric instrument (Jess *et al.* 2010) on the NSO Dunn Solar Telescope (DST), which has continuum filters in the blue and near-ultraviolet that sample both to the red (near 4170Å) and blue (near 3500Å) of the Balmer jump. The same set of filters is available on ULTRACAM, a high-speed stellar photometer (Dhillon *et al.* 2007). Recent work by Mathioudakis, Kowalski and others has tried to connect e.g. Balmer continuum behavior between solar and stellar flares using these instruments (Kowalski *et al.* 2011). Kowalski *et al.* (2015a) have also resurrected the old Horizontal Spectrograph at the DST to take NUV/blue spectra over a large (several hundred Å) wavelength range during a small solar flare.

A second challenge is the difference in mass, surface temperature, rotation velocity, and evolutionary state of typical flare stars, which tend to be lower mass, cooler, faster rotators and younger than the Sun. On the stellar side there are many detailed observations, both photometric and spectroscopic (though admittedly with lower time resolution than on the Sun), of flares on M dwarfs where the contrast of the flare radiation with the underlying cool photosphere makes optical observations quite feasible. Observing flares on solar-type (G and K) stars, on the other hand, is much more difficult since these stars flare much less often and the contrast (in the optical) of the flare radiation with the quiet underlying star is much lower.

Thus, until a few years ago when Kepler was launched, we were typically in a situation of comparing a few Å of solar flare data centered on particular coronal or chromospheric emission lines with photometry and spectroscopy covering thousands of Å and probing primarily chromospheric and photospheric radiation from flares on active M dwarfs. Synergy was therefore limited, although certainly some progress was made, culminating most recently in the stellar flare atlas of Kowalski *et al.* (2013) and new radiative hydrodynamic models (Kowalski *et al.* 2015b) drawing on the solar flare analogy to explain many features of M dwarf flare radiation. I will discuss these results briefly below, but see also paper by Kowalski in these proceedings for additional perspective on this work.

Kepler, a satellite which provided continuous monitoring for nearly four years of >100,000 solar-type stars (and including a few thousand M dwarfs), has been a huge boon for stellar physics, and in particular for observing stellar flares. The relatively rare flare events on G stars have been spectacularly revealed through this long term monitoring, resulting in the identification of so-called “superflares”, with energies up to 10^4 times the most energetic observed solar flares (e.g. Shibayama *et al.* 2013). Several talks, including those by Shibata, Maehara and Nogami have discussed the G-star superflares at this meeting. Thus we are able to confirm that the strong optical continuum emission previously seen from M dwarf flares is not confined only to flares on low mass stars, but also occurs on solar-type stars that are likely younger and more active than the Sun. The superflare light curves look like a scaled up version of a classical M dwarf flare, with a typical fast rise and rapid decay (impulsive phase) followed by a longer decay (gradual phase). Drawing on all the work connecting M dwarf flares to solar flares, we therefore assume that the superflares are simply very energetic versions of solar flares. This leads us to conclude that solar flares may have significant optical continuum radiation, which is very hard to detect against the bright background, but which may be an important contribution to the overall energy budget (Fletcher *et al.* 2007; Kretzschmar 2011), (and see also papers in these proceedings by Kleint, Berlicki, Fletcher, Milligan). Thus, a challenge extended to the solar community is to develop instrumentation that can obtain spectra of the near-ultraviolet and optical wavelength region of white-light kernels during flares on the Sun. And by spectra, I mean at least 1000Å of wavelength coverage!

3. Perspectives

3.1. *Connection between flares and starspots and the underlying magnetic field*

A particularly interesting result from our recent paper on M dwarf flares in Kepler (Hawley *et al.* 2014, hereafter H14) is the lack of a temporal relationship between starspots and flares. The active M dwarf GJ 1243 has a 0.6 day rotation period and exhibits an approximately sinusoidal flux variation of about 3% (peak-to-trough) as it rotates, indicating the presence of a stable, long-lived starspot (or starspot group). Kepler observed this star for 11 months in the short cadence (1 minute exposure time) mode, and the data reveal ∼6000 flares. A 10 day segment of the light curve showing the starspot variation and many flares is illustrated in the 5th panel (orange line) of Figure 1. In H14, we examined a 2 month segment of the light curve, and folded it on the period as shown in the top panel of Figure 2. It is clear that the starspot is very stable over this time frame (red line shows median), and flare excursions are seen at all phases. The second and third panels of Figure 2 show that the number of flares and the energy of flares are not correlated with the starspot phase. We also found that the waiting time distribution of the flares during this two month period did not show a characteristic ramp up and ramp down as seen in single solar active regions (e.g. Wheatland 2010) but instead was well fit by a single exponential above a wait time of 30 minutes (see figure 13 in H14). These observations led us to suggest that the flares did not originate from the dark starspot region but instead were occurring in many smaller active regions distributed approximately uniformly across the stellar surface. These smaller active regions would be frequently flaring (and the flares would overlap in time) so there would be no waiting time effect from any individual region, and they would be constantly rotating in and out of view, thus not causing any rotational modulation of the light curve.

In another paper in our series on flares in Kepler, Lurie *et al.* (2015) found a similar result for the two components of the M dwarf binary GJ 1245AB, i.e. that the flares did not correlate with the rotational modulation in either star. We are presently extending the Kepler sample to analyze earlier type G and K stars with short cadence data, as shown in Figure 1, which depicts 10 day segments of the light curves for two G stars (top two panels, purple/blue), two K stars (middle two panels, cyan/green) and two M stars (bottom two panels, orange/red). It is clear that the previous M dwarf results are borne out in this larger sample. Stars with no starspot have flares. Stars with significant starspot modulation have no flares. There is no apparent correlation between the starspot amplitude and the flare rate. Figure 3 shows the distribution of flares with time for the G star illustrated in the top panel of Figure 1. It is clear that there is no relationship between the relative brightness of the star (as the starspot rotates in and out of view) and the times of the observed flares.

Drawing on several talks here at IAU symposium 320 and at the Focus Meeting 13 (Brightness Variations of the Sun and Sun-like Stars) held last week at this same IAU General Assembly, it appears that a connection can be made between starspots, flares and the underlying magnetic topology. In particular, Berdyugina (this meeting) described polarimetry observations that indicate a large filing factor of small scale (mixed polarity) magnetic field, and Wedemeyer (this meeting) found that M dwarfs show complicated magnetic field structure in 3D MHD simulations. Previous observations using Zeeman Doppler Imaging techniques (Morin *et al.* 2008) found evidence for a large scale, relatively simple (dipole) magnetic field configuration in active M dwarfs, which however accounted for only ∼ 10% of the total magnetic energy of the stars. Several talks at FM13 (e.g. by Brown, Garraffo, Vidotto) described recent observations and models showing that both small scale mixed polarity and large scale dipole magnetic field components are required

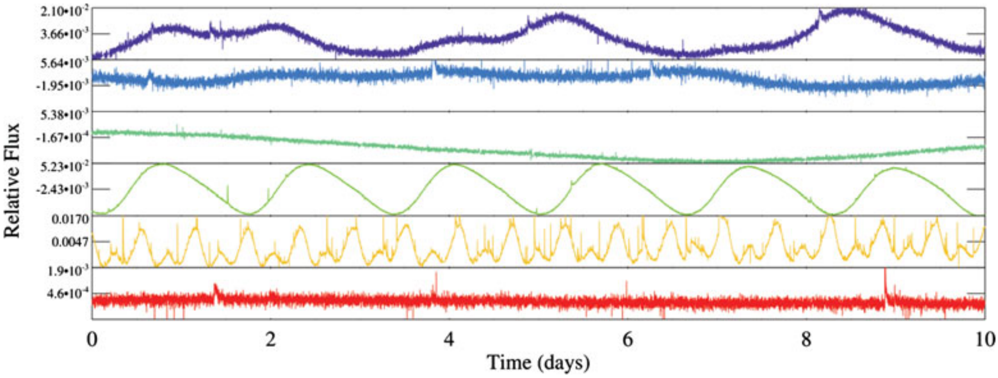

Figure 1. 10-day light curve segments from Kepler short cadence data for 2 G dwarfs (top), 2 K dwarfs (middle) and 2 M dwarfs (bottom). A variety of spot periods and amplitudes are evident. The figure shows that stars with large spots do not necessarily flare (K dwarf, 3rd panel) while stars with no spots do show flares (M dwarf, bottom panel).

in order to explain the rotational evolution observed in low mass stars (see also Garraffo *et al.* 2015).

Thus, we believe that our flare observations support the idea that the magnetic fields on these active stars exist in two states: a large scale dipole field component which may produce a large dark region (starspot) that is responsible for the observed rotational modulation; and a complex field component that results in many small active regions with complicated magnetic topology. These active regions produce flares, but are small enough, and uniformly enough distributed across the stellar surface that they do not cause measureable rotational modulation. In fact, sunspots on the solar surface would fall into the latter category, being short-lived, producing flares, and only rarely causing noticeable change in the solar brightness (and then only observable because of our nearby location to the Sun).

3.2. *Connecting flare light curves and spectra*

Using the GJ 1243 Kepler data, Davenport *et al.* (2014) (hereafter D14) constructed a flare light curve template by combining nearly 1000 "classical" (only one peak) flares. The template shows a characteristic shape with a fast rise and two decay phases, the first rapid, the second slower. Davenport described the template and its use in understanding complex (multiple peak) flares in an earlier talk this week, and his paper is contained in these proceedings.

Solar flares show similar light curve morphology. In solar flare terminology, the fast rise and rapid decay comprise the flare impulsive phase, while the slow decay is the flare gradual phase. The timing between different diagnostics is also similar between solar and stellar flares. For example chromospheric evaporation, as manifested by the Neupert effect which connects the integral of the hard X-ray flux to the instantaneous soft X-ray flux during solar flares, has also been shown to apply to stellar flares using the impulsive U-band (near-UV/blue continuum) and radio observations as proxies for the hard X-rays, and chromospheric lines such as Ca II K as a proxy for the soft X-rays (Hawley *et al.* 1995; Guedel *et al.* 1996). Thus, we have some confidence that stellar and solar flares are a result of the same underlying heating mechanisms, e.g. nonthermal particles accelerated during magnetic reconnection precipitate into and directly heat the lower atmosphere, chromospheric material is evaporated into the corona and produces soft X-rays which also heat the lower atmosphere via backwarming, etc.

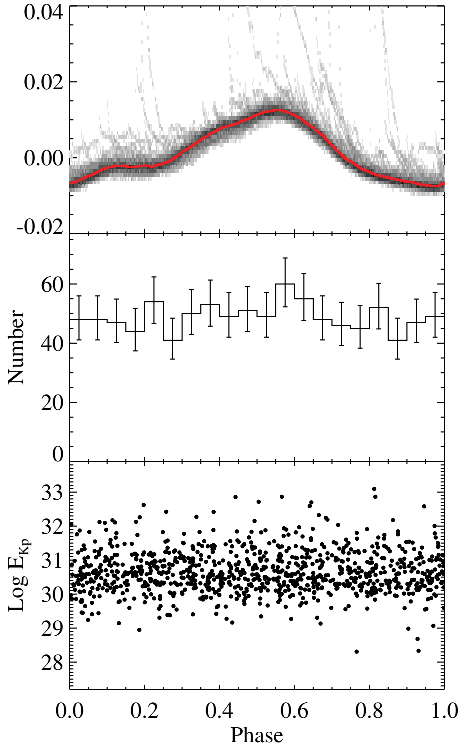

Figure 2. Two months of short cadence Kepler data from the M dwarf GJ 1243 has been folded on the 0.6 day starspot period (top panel). The red line is the median while the gray excursions show flares at all phases. The middle and bottom panels illustrate that the number and energy of the flares do not correlate with the starspot phase.

In a Herculean effort over several years, Kowalski obtained a large body of data on M dwarf flares with simultaneous photometry and spectroscopy using telescopes at Apache Point Observatory, resulting in a large stellar flare atlas (Kowalski *et al.* 2013, hereafter K13). In K13 and references therein, we discussed the evolution of the largest observed flare (the so-called Megaflare) on the dM4e star YZ CMi, which lasted more than 8 hours and had a peak amplitude of $\sim$ 6 magnitudes (a factor $>$ 200x the quiet star!) in the U-band. We proposed a phenomenological model that explains flare spectral evolution using a solar two ribbon flare analogy, as illustrated by the BBSO Hα image in the lower left corner of Figure 4. The colored inset in the top left corner of the figure shows a cartoon of the background red-dwarf photosphere (red), the decaying two ribbon flare area that is emitting in the gradual phase (yellow, BaC), previously heated hotspots of white light flare emission now emitting in the rapid decay phase (purple, HS1) and a newly heated hotspot with ongoing electron precipitation (white, HS2). The observed spectrum (black) may be fit by adding together these components with varying area coverage as indicated in the top right corner, where the BaC emission comes from an area 20x greater than the new hotspot and 10x greater than the decaying hotspots. We identify the hotspots as the sites of the white light continuum emission; in the solar analogy these might be, for example, white light kernels seen at the footpoints of actively heated loops.

Recently the Extreme Ultraviolet Variability Experiment (EVE) on the SDO satellite has produced actual spectra (1000Å wavelength coverage!) during flares (Milligan *et al.* 2012, 2014). They find that the white light footpoint area increases up to the time

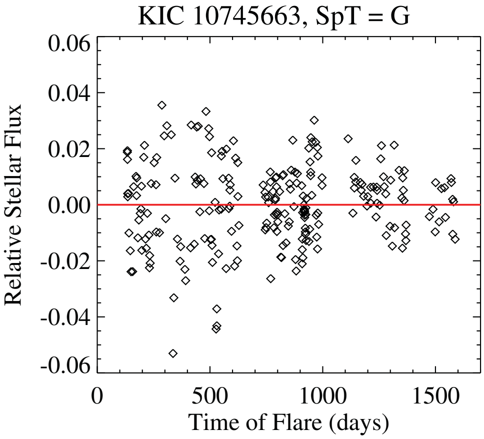

Figure 3. The relative brightness of this G star observed with Kepler does not correlate with the times of detected flares, indicating that the flares are apparently not associated with the dominant starspot(s).

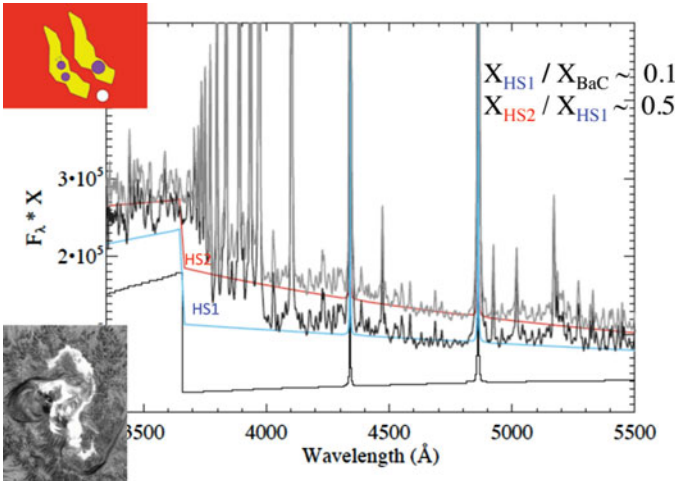

Figure 4. An M dwarf flare spectrum (black line) fit with three continuum components (BaC, HS1, HS2) corresponding to the phenomenological model shown in the upper left corner: decaying ribbons from previously heated flare footpoints (yellow-BaC), decaying hotspots (purple-HS1) and a newly heated hotspot (white-HS2). The continuum components reproduce the observed spectrum when added together with varying area coverage, shown in upper right corner. A typical two-ribbon flare (Hα image from BBSO) providing the solar analogy for this phenomenological M dwarf flare model is shown in the lower left corner.

of the white light peak, while the line and continuum (especially H Lyman and He I) evolution appear similar to observations of M dwarf flares (see K13). Milligan and Fletcher described various aspects of these exciting results at this meeting, see their papers in this proceedings for more details.

Kowalski *et al.* (2015b) have recently published a new set of RHD models that can produce white light emission with a very large electron beam flux ($> 10^{13}$, F13) which he presented at this meeting. The models show promise, finally, of explaining how the color temperature of the continuum radiation can be $\sim$ 10,000K during flares, and how the continuum radiation is connected to the evolution of the beam heating.

Taken as a whole, this evidence points to a unified scenario that can explain many aspects of the flare light curve morphology (D14) and spectral evolution (K13) for M dwarfs. Some elements of this scenario may also apply to white light flare emission and chromospheric spectral evolution on the Sun.

1. rise phase: initial heating from nonthermal electrons, both beam flux and area increase during rise phase producing 10^4K blackbody-like optical/near-UV continuum spectrum and impulsive line radiation with Balmer lines much stronger than Ca II K.

2. rapid decay phase: decreasing beam flux and area, lower color temperature of blackbody-like continuum, increasing Balmer and Ca II K line and Balmer continuum radiation as chromosphere cools and recombines.

3. slow decay phase: characterized by soft X-ray cooling from corona, and Balmer and strong Ca II line emission from chromosphere. The soft X-rays may provide continued heating of the chromosphere through backwarming. There may also be continued low-level particle heating from overlying loops, since the flares occur in complicated magnetic field structures (see Woods paper in this proceedings).

4. Issues and future work

Of course our work is not yet done. The qualitative/phenomenological model described above needs to be much more thoroughly worked out in detail and tested. And there are many observations yet to be obtained. Some key points (with reference to talks at this meeting):

1. A new RHD modeling effort has found that an F13 beam can produce white light emission in a stellar (M dwarf) flare during the first few seconds of the rise phase (Kowalski talk). We now need models including beam evolution and shutoff to try to model the observed spectra during flare decay phases. In particular there is much work to be done on the gradual phase, including the identification and evolution of extended heating sources. Is there still more electron beam heating required an hour after the initial flare impulsive phase? Where does it come from? Can backwarming from the corona really last that long and/or provide enough energy to power the chromospheric emission we see at late times?

2. A very high beam flux (F13) over large areas is not observed in solar flares. Could this be why the Sun doesn't have bright, long-lived white light flares, but more active G dwarfs do (e.g. superflares! Shibata, Nogami, Maehara talks). Need new RHD solar models to test (Heinzel talk).

3. SDO/EVE and IRIS instruments produce great data, but we really need TIME RESOLVED OPTICAL SPECTRA OF SOLAR FLARES (not just a few Å!) to understand the nature of the white light continuum. A large fraction of emitted energy during solar flares is not being observed (Kleint, Berlicki, Fletcher talks).

4. And the stellar astronomers need to get busy and obtain time-resolved optical spectra during a G dwarf superflare!

5. A brief digression into the habitability of planets around M dwarfs. Segura *et al.* (2010) examined the impact of one large flare (including particle impact from a Carrington-type event), but we need to extend modeling to include multiple flares, e.g. the time sequence of flares we have observed on GJ 1243. What happens to the planetary atmosphere when it is constantly bombarded by flares? We are presently working on this with the astrobiology group at the University of Washington (Tilley *et al.* in prep).

Acknowledgements

Kepler was competitively selected as the tenth Discovery mission. Funding for this mission is provided by NASA's Science Mission Directorate. SLH acknowledges support from NSF grant AST13-11678.

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