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Kyoto University visit and participation in Superflare Workshop

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Abstract. This is a report of my visit to Kyoto University in March 2016 to participate in the Superflare Workshop, supported by the International Research Unit of Advanced Future Studies, Kyoto University**.** The Superflare Workshop was very well attended by all Japanese superflare researchers on stars and on the Sun, and also by many international experts. There was valuable scientific discussion of superflares on solar-type stars, possible effects on extrasolar planets and also the possibility of superflares on the Sun and the effect on the Earth. My presentation described empirical evidence and diagnostics of white light flare continuum radiation on low mass stars. Also there was discussion of the new 3.8m Japanese telescope at Okayama Observatory, and the possibility for internaitonal collaboration with the ARC 3.5m Telescope at Apache Point Observatory to obtain new time-dependent observations of superflares.

Keywords: solar-type stars, superflares, Sun, optical telescopes

1. Visit Details

I visited Kyoto from March 1-5, 2016, to participate in the Workshop entitled: “Superflares on Solar-type Stars and Solar Flares, and Their Impacts on Exoplanets and the Earth” which was held at Kyoto University, and organized by Professor Shibata and Professor Nogami, of the Kwasan Observatory and Department of Astronomy. It was a very well-attended and successful meeting with many scientific lectures, discussions and opportunity for new collaborations. I would like to thank Professor Shibata and Professor Nogami for their invitation to participate and for their kind hospitality, and the International Research Unit of Advanced Futures Studies for supporting my visit.

2. Workshop Presentation

I gave a one hour presentation (including time for discussion) at the Superflare Workshop. The title of the presentation was “Observations of Stellar Flares” and it concentrated in particular on the photometric and spectroscopic observations of white-light continuum radiation from flares on low-mass stars, using telescopes both on the ground and in space. In the following sections, I summarize the main results that were presented.

2.1. Spectroscopic observations of flare continuum radiation in M dwarfs

Starting with ground-based photometry dating back to the 1950s, it was clear that the dominant energetic component of flares on low-mass stars (M dwarfs, with mass less than half the mass of the Sun) was the so-called white-light continuum. Flares were observed in broad-band photometric filters to be very bright and very blue, such that a large flare could make the star more than 5 magnitudes (>100 times) brighter in the Johnson U-band and up to 3 magnitudes (>10 times) brighter even in the Johnson V-band. Flares also had a typical light curve shape, with a rapid rise and fast decay followed by a more gradual decay. Following solar terminology, where similar morphology is observed in chromospheric (Ca II K, H-alpha) and X-ray observations of solar flares, these phases were called the impulsive phase (attributed to non-thermal electron beam heating) and the gradual phase (attributed to thermal radiation from the heated flare atmosphere). It is extremely difficult to observe the white-light continuum radiation using optical observations of the Sun (and solar-type stars) since the stars themselves are so bright at optical wavelengths. Thus M dwarfs provide a better platform for investigating the properties and underlying physical processes of the white-light flare continuum. Fortuitously, active M dwarfs also flare much more frequently than active solar-type stars, enabling multi-wavelength campaigns of a few days duration with a good possibility of seeing a large flare.

The next decades saw increasing effort to obtain spectroscopy of M dwarf flares. One such successful campaign resulted in the observation of the “Great Flare” on the dM3e star AD Leo in April 1985 (Hawley & Pettersen 1991). Ground-based data from McDonald Observatory comprised multi-color UBVR photometry, spectroscopy covering the Balmer jump and high order Balmer lines (3500-4400A), while the International Ultraviolet Explorer (IUE) satellite obtained simultaneous ultraviolet spectroscopy. These data showed unequivocally that the flare continuum radiation was very blue, with a blackbody shape that peaked in the near ultraviolet, indicating a color temperature of about 10,000K during the impulsive phase (Hawley & Fisher 1992). The continuum reddened during the gradual phase, but was present for several hours after the flare peak. The mystery of how to produce such a hot blackbody continuum source in the atmosphere of a low temperature M dwarf was not resolved despite initial attempts to apply a solar-like electron beam heating model.

An empirical investigation of a large sample of M dwarf flares with simultaneous photometry and spectroscopy obtained at Apache Point Observatory was recently published in the flare atlas of Kowalski et al. (2013). The sample of 20 flares shows that the flare morphology is more complicated when examined in detail, and in particular flares may be split into impulsive, hybrid and gradual categories with the impulsive flares being the canonical type described above, while hybrid and gradual flares have slower rise and longer decay times. Importantly, the spectroscopy of these events showed that the flare continuum radiation actually has three components, with the hot blackbody dominating during the impulsive phase, but a significant Balmer continuum component can be important even during the impulsive phase of hybrid and gradual flares, and dominates during the gradual phase of all flares. In the later gradual phase of strong flares, a third, cooler blackbody continuum component with T~5000-6000K may be present and energetically important.

The Balmer continuum component was identified in the so-called “Mega Flare” on the dM4e star YZ CMi (Kowalski et al 2010) and shown to anti-correlate with the U-band photometry such that when the hot blackbody continuum (which dominates the U-band) is strong the Balmer continuum is relatively less important. This led to a phenomenological model based on analogy to solar two-ribbon flares, where the hot blackbody continuum is produced in newly heated hotspots radiating impulsive phase emission while the Balmer continuum is primarily coming from the thermal cooling of previously heated flare areas, e.g. from the initial loops in an arcade that are now spreading and cooling in the decay phase. Using this model, Kowalski et al (2012) were able to fit the spectra of the Mega Flare using reasonable area coverage of newly heated and decaying loops. The hybrid and gradual flares would thus represent flares with less or shorter impulsive heating and more extended gradual heating, leading to increased Balmer emission. An important unanswered question is whether solar flares, and flares on other solar-type stars, have similar white light continuum properties, including varying amounts of Balmer, hot blackbody and cooler blackbody emission during different phases of the same flare, and in different flares depending on the heating profile.

2.2 Flare photometry with Ultracam

Although flare spectroscopy has been very important to diagnose the properties of flare continuum radiation in M dwarfs, it is difficult to obtain, requiring (at least) 4m-class telescopes and ideally simultaneous photometry and UV/X-ray spectroscopy, in a campaign where monitoring can cover hours or days. Therefore, flare photometry in specialized filters that provide diagnostics of the flare continuum components described above allows a larger sample of M dwarf flares to be obtained. Also, similar filters can be used to observe solar flares enabling direct comparison of the continuum properties between M dwarfs and the Sun. Such solar work is being carried out by M. Mathioudakis and collaborators using the ROSA instrument on the Dunn Solar Telescope (e.g. Jess et al. 2010). Here I will describe recent results from a large Ultracam survey of M dwarf flares on the NTT and WHT telescopes (Kowalski et al 2016).

Ultracam is a photometric imaging camera with two dichroics in the light path such that three filters may be observed simultaneously. Our flare observations use narrowband custom filters centered on 3500A (in the Balmer continuum), 4170A (in the hot blackbody continuum) and 6000A (in the red continuum). With the 3 filter photometry, we form two colors, FColorB (F(3500)/F(4170)) and FColorR (F(4170)/F(6000)). These are similar to the familiar Johnson colors U-B and B-V except since we are taking flux ratios (not subtracting magnitudes), larger positive values indicate bluer colors. We can connect the flare colors (between different flares, and during the evolution of a single flare) to the spectroscopic results above, by computing synthetic colors from the flare spectroscopy.

The Ultracam results for 20 flares ranging from low to high energy, show that the same Balmer continuum and hot blackbody continuum behavior observed spectroscopically can be diagnosed from the flare colors alone. In a color-color diagram of FColorB vs. FColorR, the relative importance of the Balmer continuum at a given blackbody temperature is shown by the value of FColorB at similar FColorR with hybrid/gradual flares having larger relative FColorB. Also flare evolution typically proceeds from large values for FColorR (hotter blackbody) to smaller values (redder blackbody) and from smaller values for FColorB (less Balmer continuum) to larger values (more Balmer continuum), making a distinctive evolutionary track in the diagram. Finally the 4170 (hot blackbody) light curve is anti-correlated with FColorB (importance of Balmer continuum) as was seen in the spectroscopy.

Taken together, the photometry and spectroscopy of M dwarfs have provided a well-determined empirical picture of the properties of the white-light continuum behavior during flares. The physical processes that lead to this behavior must be investigated with sophisticated radiation hydrodynamics models that will be described in the presentation by A. Kowalski at this meeting. However there are several outstanding observational questions that remain:

1. Is all the continuum radiation coming from the same spatial region?
2. How does the area coverage of the different flare continuum components evolve?
3. Does the Sun show these same continuum properties and evolution during flares?
4. Do superflares on solar-type stars show these same continuum properties?

2.3 Kepler flare photometry

As mentioned above, the observation of white light flares on solar-type stars is very difficult because the star itself is so bright that the flux contrast is often much less than 1%, and also these flares do not occur very frequently even on very active stars. The Kepler satellite which obtained continuous time-series photometry in a broad white-light filter of more than 100,000 solar-type stars for almost four years, has opened a new window into flares on these stars due to its exquisite precision and long monitoring timescale. Maehara et al. (2012) reported on initial Kepler observations of superflares on solar-type stars, so-called because they have energy of $>10^{34}$ ergs (more than 100 times the largest solar flares). Note that the Great Flare and Mega Flare on the M dwarfs described in Section 2.1 also exceed this energy threshold and thus M dwarfs also can produce superflares.

We obtained short (1-min) cadence observations of several G, K and M dwarfs in the Kepler field through Guest Observer proposals in cycles 2 and 3. The M dwarfs comprised both active and inactive stars, since we are interested in whether flares can still occur on stars which do not appear to have active chromospheres or coronae (no H-alpha or X-ray emission). The best observed star was the active dM4e star GJ 1243 with 11 months of Kepler short cadence monitoring data. Davenport et al. (2014) compiled several hundred flares with good signal-to-noise and only one peak and showed that when scaled by the FWHM of the light curve and by the amplitude, all flares followed a remarkably similar evolution that could be described analytically with three functions corresponding to the rapid rise phase, the fast decay phase and the gradual decay phase. However, there were several thousand flares observed, and many of these showed more than one peak ("complex flares"). These could often, but not always, be well-fit using a combination of flares with the analytic morphology. Additional results on GJ 1243 reported in Hawley et al. (2014) indicate that complex flares typically last longer and have higher energy than single flares with the same (highest) peak amplitude, and higher energy flares in general are more likely to be complex. These results may identify complex flares as a superposition of simple flares which could fit into the phenomenological model of new flare heating being triggered in the same arcade or active region.

The inactive M dwarfs did indeed show flares with a rate about 50 times less than the active stars, roughly one flare/week rather than several flares/day. However, this is still a rate that may be important for planets orbiting such stars, which are popular targets for exoplanet searches.

Another investigation enabled by the Kepler data is the correlation between starspots and flares. The inactive stars showed almost no indication of starspots (at less than 0.01% level) but still produced flares. The active star GJ 1243 has a long-lived stable starspot pattern with about 1.5% amplitude and a period of 0.6 days. We compared the flare occurrence throughout the starspot phase and found no correlation with phase for either number of flares or energy of flares (Hawley et al 2014). Our speculation is that this lack of correlation is a manifestation of two different magnetic topologies on low mass stars, as discussed by Morin et al. (2008), Garroffo et al. (2015) and others. A large scale dipole field may be responsible for long-lived polar spots leading to the rotational modulation, while complicated small scale fields may give rise to a large number of solar-like active regions with complicated magnetic structure. The latter do not contribute much (if at all) to the rotational modulation but are the sites of the flares. Thus no correlation would be expected between the observed starspot modulation and the flares.

Our preliminary work on the G and K stars in our sample indicates that similar patterns hold. These stars show much larger but shorter-lived starspot patterns, indicating faster evolution of the large scale field. However, there is still no correlation between the spots and flares (for example, there are not more flares when the star is relatively dimmer indicating a larger coverage of spots). It seems that smaller, more complicated active regions are likely still responsible for the flares but don't contribute much to the rotational modulation.

3. Future Collaboration

Finally, we need to connect the superflares on solar-type stars to those observed on M dwarfs by obtaining spectra of a superflare on a G or K star. This would allow us to investigate whether the continuum radiation during flares on solar-type stars follows the same evolution and exhibits similar physical properties as in the well-studied low mass stars. For this we need dedicated telescopes and instrumentation, such as the new 3.8m telescope at Okayama Observatory and our 3.5m Telescope at Apache Point Observatory. We look forward to discussion of new collaboration between our groups in order to observe superflares on solar-type stars! And I want to express my thanks again to the International Research Unit of Advanced Future Studies, Kyoto University, for supporting my attendance at this very productive workshop and to Professor Shibata, Professor Nogami and the many workshop participants for the interesting and exciting scientific discussions of superflares.

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