May 2018
No. 2018-006-e

Journal of Integrated Creative Studies

Flares on the Sun and Other Stars

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Abstract. Solar and stellar flares represent a transdisciplinary topic, covering the branches of solar physics, stellar astrophysics, space weather and planetary and exo-planetary research. Moreover, a recent discovery of the so-called superflares by the Kyoto University team had opened new frontiers in this discipline, both from the astrophysical as well as practical points of view. The principal aim of my visit to Kyoto University (Graduate School of Science) was to bring my expertise in the non-LTE (i.e. departures from Local Thermodynamic Equilibrium) radiative-transfer modeling of solar and stellar flares to group of Prof. K. Shibata and conduct, in a close collaboration with his team, a new research on modeling spectra of solar and stellar flares. We focused on three topics: white-light emission of stellar superflares, MgII line asymmetries observed in solar flares by *IRIS* satellite, and coupled hydrodynamical and radiative-transfer modeling of evolving flare atmospheres. The latter theoretical topic has a close relation to the second one which is more observational. Concerning superflares, we have proposed a new idea how to interpret the white-light emission from superflares observed by *Kepler* satellite. Our new scenario takes into account the presence of extended flare loops presumably overlying large areas over the stellar disk and substantially contributing to the white-light emission during superflares. The respective paper is now accepted in The Astrophysical Journal (USA). The idea of big loops may change the current paradigm of understanding the stellar flare, and namely superflare white-light emission and will be extended also to spectral lines.

Keywords: Solar and Stellar Flares, Superflares, Spectroscopy and Radiative-Transfer Modeling, Analysis of Space Data

1. Subject of the Report

Research and teaching project report for the invited "Distinguished Visiting Professor" six weeks visit of Professor Petr Heinzel, DSc. from the Astronomical Institute of the Czech Academy of Sciences, Czech Republic. Invitation by the Kyoto University International Research Unit of Advanced Future Studies to carry research and education in the field of solar and stellar astrophysics, in collaboration with Professor Kazunari Shibata and his team at the Graduate School of Science of the Kyoto University, from October 1 – November 12, 2017.

2. Introduction

Motivated by transdisciplinary research of Prof. K. Shibata on solar and stellar flares and their influence on planets-exoplanets (Shibata 2016), I have focused during my stay at Kyoto University on modelling of stellar superflares and on understanding the new space observations of solar flares. This was done in a close collaboration with flare group of Prof. K. Shibata. Moreover, I was also involved in other research projects, and namely those related to solar prominences. Below is the report on three research topics and on my lecturing for undergraduate and graduate students.

3. Research Collaboration

3.1 Superflares on *Kepler* stars

During my stay I have presented a novel idea how to model the white-light emission of superflare stars as detected by *Kepler* satellite (Maehara et al. 2012). All these superflares are WLFs because they exhibit a strong enhancement of stellar flux in the visible continuum. The peak sensitivity of the *Kepler* detector is around 600 nm. Standard assumption is that this emission comes from flare ribbons which produce a black-body radiation at temperature 10 000 K (Shibayama et al. 2013). My suggestion was that also extended flare loops, overlying the whole active region (starspot area) might contribute to the continuum emission. To prove this, I developed a model of continuum radiation of such loops, considering the hydrogen recombination continua (Paschen and Brackett), free-free emission (i.e. due to proton-electron interactions), and Thomson scattering on loop electrons. While the latter is important at low electron densities not considered in superflare loops, both recombination and free-free continua play an important role and their relative importance depends on temperature. I have computed the stellar flux enhancement for various loop densities, temperatures and line-of-sight dimensions, and for two stellar cases: solar-like and M-dwarf cool stars. The conclusion is that the loop arcade can substantially contribute to the flux enhancement during superflares, and namely in case of dMe stars where the contrast is larger due to their low effective temperature. A key parameter is the electron density of flaring loops, which must be at least between 10^{12} and 10^{13} cm^{-3}, in order to get the theoretical amplitude comparable with that typically detected by *Kepler*. With Prof. Shibata we have discussed the conditions necessary to reach such relatively high electron densities (usually not met in the case of solar flares) and he has suggested the reconnection scenario which naturally leads to higher densities required by models. I highly appreciate fruitful discussions with Prof. Shibata and his superflare group (namely H. Maehara, Y. Notsu, S. Honda and K. Namekata). Together with K. Shibata we wrote a paper on this novel approach which was submitted to *The Astrophysical Journal* (Heinzel and Shibata 2018). The referee was very competent person, however, we had to convince him/her how our novel ideas change the standard paradigm of interpreting the stellar flare spectra. Currently the paper is accepted and will be soon published (see also the arXiv preprint). With the group of stellar flares we plan to continue this kind of research and apply my radiation modelling codes to future spectral observations obtained e.g. by new Okayama 3.8 m telescope. The results of this joint research were presented during the recent EWASS (EAS) Conference in Liverpool as a poster (Heinzel et al. 2018).

3.2 Blue wing enhancement of the chromospheric MgII h and k lines in a solar flare
During my stay I was involved in the analysis of *IRIS* satellite spectra of a solar flare. A. Tei and collaborators discovered a blue asymmetry in the MgII h and k lines. Based on my suggestions, A. Tei used the standard cloud model to synthesize the theoretical spectrum, using the input parameters line-of-sight velocity, Doppler width, line-center optical thickness and the line source function. The fitting procedure was very successful, the cloud model was able to explain a small intensity hump in the blue wing and a depression of the blue peak of both lines. This corresponds to scenario of a cool upflowing cloud of plasma, as originally suggested by Canfield et al. (1990). We also explored the range of these parameters, in order to see how sensitive is the observed blue asymmetry to their variations. A complex paper presenting the *IRIS* observations and the cloud modelling was accepted in *PASJ* (Tei et al. 2018). The results were also the subject of a *RHESSI* Nugget, proposed by the Editor H. Hudson. This observational study is closely related to the following topic in which I was also involved.

3.3 Non-LTE modelling of MgII lines in time-dependent flare atmospheres
Undergraduate student T. Nakamura, working under supervision of Prof. K. Shibata, has developed a 1D hydrodynamical model of an electron-beam heated flare. Within the grid of models computed for a range of beam parameters (energy flux, spectral index, cut-off energy), he has found that some models exhibit an upflow of cool plasma, similar to that discovered in the work of A. Tei. Based on that, I was asked to use my radiative-transfer non-LTE codes (so-called MALI codes) to compute the synthetic spectrum of MgII lines using selected snapshots from these hydrodynamical simulations. After a slight modification of my Magnesium code I was finally able to obtain the MgII line profiles which exhibit quite similar characteristics as observed by *IRIS*, i.e. a small hump in the blue wing and lowering of the blue peak due to absorption by an upward moving plasma. This was done at the end of my stay. However, it would be very valuable to see under which plasma conditions such asymmetries arise from time-dependent simulations. One could also compare these simulations with similar ones which could be performed using the *Flarix* code developed at the Astronomical Institute of the Czech Academy of Sciences. Therefore, a future collaboration on this topic is highly desirable, I suggest to involve also Dr. J. Kašparová who works with me on *Flarix* simulations. Below is one example of my MALI simulations done in Kyoto.

4. Lectures, Seminars and Conference Participation

4.1 Lectures and Seminars
During my stay at Kyoto University I have given several lectures for undergraduate and graduate students. Two lectures were given on solar prominences where I explained the basics of the non-LTE (i.e. departures from LTE – local thermodynamic equilibrium) physics of prominences and principles of spectral line formation in these objects (see Heinzel 2015). This was useful namely for students who are analysing the prominence spectra, including those obtained by Domeless Solar Telescope (DST) at Hida Observatory. I was also giving an expert advice to undergraduate student H. Yuwei whose work is oriented to development of his own non-LTE prominence code, using the ALI (Accelerated Lambda Iteration) techniques and partial redistribution.
At the beginning of my stay I also gave a lecture on White-Light Flares (WLF) for the solar group. This was a basis for further discussion on WLF spectroscopy and modelling.
I participated in several topical seminars (MHD seminars, prominence seminars, superflare seminars, observational seminars), where I took an active part in discussions.
I gave also a seminar at Hida observatory – see below.

4.2 APSPM Conference
From November 6 – 10, 2017, I have participated in the APSPM Conference which was held at Kyoto University (Asia-Pacific Solar Physics Meeting). This gave me an opportunity to meet other solar

scientists from Japan, but also from other countries. During the meeting I gave an overview talk "Continuum emission of solar flares". I had many discussions with other participants.

4.3 Public Talk

On October 19, 2017 I gave a public talk at Yukawa Institute of Theoretical Physics, in the frame of interdisciplinary meeting organized by Prof. Murase. I talked about the synergy between solar and stellar flare studies. A particular focus was on superflares discovered from *Kepler* data by the Kyoto group. Superflares represent one major topic I have been dealing with during my stay at the Kyoto University.

5. Visit to Hida Observatory

Between October 29 and November 1, 2017 I visited the Hida Observatory, on invitation of Prof. Ichimoto. I was mainly interested in the DST and its spectrographs and I have discussed various possibilities of cooperation in solar observations. I have given there a seminar on observational facilities of the Ondřejov Observatory which include also a wide-band, low-dispersion spectrograph *Ocean Optics* (Kotrč et al. 2016), same as installed on Hida H-alpha telescope. A collaboration in using the spectral data from such instruments is envisaged.

6. Acknowledgements

I am deeply indebted to Prof. K. Shibata for his kind invitation which enabled me to visit the Kyoto University and work in his excellent group. I appreciate all the collaborations and discussions. I thank also Prof. K. Ichimoto for inviting me to Hida Observatory where I spent wonderful days. Prof. A. Asai kindly helped me with the logistics of my visit and I also thank the whole staff of the Kwasan-Hida Observatory for all their help. Last, but not least, my collaborations and discussions with many students of the group are also highly appreciated.
I acknowledge the support by the International Research Unit of Advanced Future Studies at Kyoto University during my stay in Japan.

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