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Scientific requirements for future spatially resolved white-light and broad-band high-cadence observations of the Sun

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Abstract

Several important issues are open in the field of solar variability and they wait their solution which up to now was attempted using critical ground-based instrumentations. However, accurate photometric data are attainable only from space. New observational material should be collected with high enough spatial and spectral resolution, covering the whole visible range of the electromagnetic spectrum as well infrared and ultraviolet to reconstruct the total solar irradiance: (1) the absolute contributions of different small-scale structural entities of the solar atmosphere from the white light flares and from micro-flares are still poorly known; (2) we do not know the absolute contributions of different structural elements of the solar atmosphere to the long-term and to the cyclic variations of the solar irradiance, including features of the polar regions of the Sun; (3) the variations of the chromospheric magnetic network are still poorly evaluated; (4) only scarce information is available about the spectral variations of different small-scale features in the high photosphere. Variability of the Sun in white light can be studied with higher spectral, spatial and time resolution using space-born telescopes, which are more appropriate for this purpose than ground based observatories because of better seeing conditions, no interference of the terrestrial atmosphere and a more precise calibration procedure. Scientific requirements for such observations and the possible experimental tools proposed for their solution. Suggested solar studies have broader astrophysical importance.

Keywords: Sun; Solar activity; Flares; Coronal mass ejections; Solar irradiance variations; White light; High resolution; Photosphere; Chromosphere

1. Introduction

Nobody doubts about the relevance of the chromosphere for flares. The old term 'chromospheric flare' nicely expresses this attitude. The relevance of the chromosphere dynamics for coronal mass ejections (CMEs) is not so evident (prominences, dimming; waves, electromagnetic couplings) and still under debates. We believe that this role is very important and still underestimated. The same can be said about the role of the chromosphere for the solar wind formation. Initially it was neglected in theory and in observations, but now it is appreciated, including the case of the fast wind. Why photosphere, white light (WL) and broad band (BB) observations are needed to solve problems of solar flares, CMEs and solar activity cycles?

The photosphere is the closest observable domain to opaque interiors. Processes in the chromosphere and in the corona could be better understood only with better knowledge of the photospheric dynamics, which is transmitting energy, momentum and mass to these atmospheric layers from interiors. The ultimate free energy, momentum and mass sources of the solar activity are inside interiors of the Sun. The main observed energy and power variations in absolute values associated with the solar activity cycle belong to WL, not to other secondary domains of the electromagnetic spectrum with shorter or longer wavelengths

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or to the solar wind outflow. The sufficiently detailed knowledge of the solar WL and BB variability near its spectral maximum is of paramount importance, but still not available. It includes the ubiquitous chromospheric magnetic network and its photospheric counterparts: the supergranulation flows. But, these variations relatively subtle, they are difficult to measure in a reliable manner. They are often neglected in models. Insufficient combined spectral/space/time resolution is a big unsolved problem (Veselovsky and Koutchmy, 2006).

White-light continuum occurs in essentially all flares (Hudson et al., 2006), but sensitivity levels and contrast could be insufficient for the registration of the WL signal (Neidig, 1989). We believe that WLs are direct indicators of subphotospheric drivers of solar flares. Local 25% increase in effective photosphere temperature here is sufficient to produce double brightening in the flare foot points. Non-thermal processes are also possible here. The Sun is the yellow-green star, which dissipates its energy mainly in WL. Here is the main dissipation channel of the solar energy. We strongly believe based on presented arguments about the important role of the missing or insufficient information namely about this main, but not sufficiently explored channel of the dissipation. We think that it is a rational of suggested studies.

2. The foot point problem

What is the difference in plasma parameters, electric and magnetic fields between hot and cool foot points at the photospheric level? This important question (Katsukawa and Tsuneta, 2005) is still open and cannot be resolved without photospheric WL and chromospheric BB high-cadence measurements. Note that not only faculae are seen near the disk center, but the network bright elements are evidenced, as well as polar faculae (Fig. 1). The problems of coronal heating also cannot be resolved using theoretical modeling alone. New observations of high photometric precision are needed in this case too. No single index (the sunspot number, the f10.7, Ca K, and Mg II indices, and the He I equivalent width) can satisfactorily describe both the level of variability on time scales beyond 27 days, and relative changes of irradiance on shorter time scales (Dudok de Wit et al., 2008). Any significant variation was not found in umbral core of sunspots, mean umbral and mean penumbral intensities with solar cycle (Mathew et al., 2007), which is in contrast to earlier findings for the umbral core intensity. A strong and clear dependence of the umbral brightness on sunspot size exist. Solar irradiance variations show strong wavelength dependence. Data is not sufficient for their direct evaluation. Observed SUSIM UV spectra were used to extrapolate available models to shorter wavelengths with the conclusion: up to 60% of the total irradiance variations over the solar cycle might be produced at wavelengths below 400 nm (Krivova et al., 2006). This conclusion needs direct observational check.

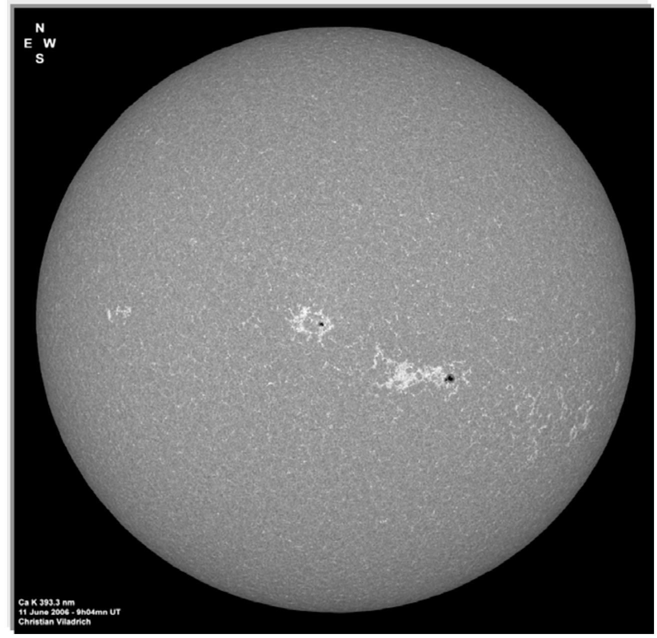

Fig. 1. Sample of a broad band CaII K filtergram (393.3 nm, 0.4 nm FWHM). Courtesy of Christian Viladrich (France).

3. Weaknesses of current and planned missions

What do we have for observations of solar activity during the next cycle? Let us briefly discuss some current as well as planned missions and projects (at the ground and in space).

Solar Radiation and Climate Experiment (**SORCE**) satellite (http://lasp.colorado.edu/sorce/) measures the Sun's output with the use of state-of-the-art radiometers, spectrometers, photodiodes, detectors, and bolometers. The measurements provided by SORCE specifically address long-term climate change, natural variability and enhanced climate prediction, and atmospheric ozone and UV-B radiation. No telescopically resolved images. Nevertheless, the very important finding for the first time is that the total solar irradiance increase during October 28, 2003 flare was about 4.6×10^{32} ergs, i.e. 0.27% (Woods et al., 2004). This is in concord with our expectation that WL energy contribution plays the important role as a primary factor in the solar flare phenomenon (Veselovsky et al., 2004). Another interesting result for the UV flare variations is that the broad wings of the H I Lyman-alpha (121.6 nm) emission increased by more than a factor of 2 during the X17 flare while the core of the Lyman-alpha emission only increased by 20%. Systematic measurements of this kind are needed in future complemented by telescopically resolved images. By the way, the albedo of the Earth and the lack of strict instantaneous balance between incoming and out-coming energy is still poorly know (http://lasp.colorado.edu/sorce/2006ScienceMeeting/presentations/Day01_Wed/S1_01_Woods.pdf). Contribution of clouds and characteristic time scales in this approximate balance variations remain one of challenges in our knowledge of climate.

SOHO is a very successful mission, but it has no WL diagnostics with demanded sensitivity and resolution to observe eruptive processes and long-term variations on the disk. **TRACE** (**T**ransition **R**egion **A**nd **C**oronal **E**xplorer) is also a highly successful satellite mission with following three science objectives (http://sunland.gsfc.nasa.gov/smex/trace/): (1) to follow the evolution of magnetic field structures from the solar surface to the corona; (2) to investigate the mechanisms of the heating of the outer solar atmosphere (3) to investigate the triggers and onset of solar flares and mass ejections. We can suggest that a similar mission should be complemented by WL observations of the photospheric dynamics with a comparable space–time resolution and a photometric quality over the whole disk.

Solar Dynamics Observatory **(SDO)** is intended to help understanding of the Sun's influence on Earth and Near-Earth space by studying the solar atmosphere on small scales of space and time and in many wavelengths simultaneously. (http://sdo.gsfc.nasa.gov/sdo_mission_science. htm). SDO goals are formulated as follows: (1) understand the solar cycle; (2) identify the role of the magnetic field in delivering energy to the solar atmosphere and its many layers; (3) study how the outer regions of the Sun's atmosphere evolve over time – ranging from seconds to centuries – and space; (4) monitor the radiation (ex: UV, EUV, etc.) levels of solar output. The goals 1, 2 need additional full disk observations about BB variations, which are beyond the scope of this potentially prolific mission.

Science goals of **Solar-B** mission – to determine the mechanisms responsible for heating the corona in active regions and the quiet Sun; to determine the mechanisms responsible for transient phenomena, such as flares and coronal mass ejections; to investigate the processes responsible for energy transfer from the photosphere to the corona (http://www.mssl.ucl.ac.uk/www_solar/solarB/science.html). It is evident, that these goals are not achievable in a full measure because the lack of needed high cadence WL and BB measurements, including full-disk images.

The **Sunrise** project aims at high-resolution spectropolarimetric observations of the solar atmosphere 'on the intrinsic spatial scale of its magnetic structure' (http://www.mps.mpg.de/de/projekte/sunrise/). Balloon born telescope with 1 m aperture has very limited temporal coverage. Spectra and images will resolve spatial scales down to 35 km on the Sun. The main scientific goal of the mission is to understand the formation of magnetic structures in the solar atmosphere and to study their interaction with the convective plasma flows. It is assumed that "the magnetic field is the source of solar activity". This pre-assumption is still an open issue: not only the magnetic field, but also other independent electrodynamic parameters (first of all – electric fields) and plasma characteristics, radiation and bulk plasma energy transports, play important role in the solar activity phenomena (Veselovsky and Panasenco, 2006).

The Space Weather Explorer – **KuaFu** mission is being proposed as a "L1 + Polar" triple star project, which aims at space weather science and provide simultaneous, long-term, and synoptic observations of the complete chain of disturbances from the solar atmosphere to the geospace. The KuaFu mission is composed of three spacecraft: KuaFu-A, KuaFu-B1 and KuaFu-B2. KuaFu-A will be located at the L1 liberation point and have instruments to observe solar extreme ultraviolet (EUV) emissions and white light Coronal Mass Ejections (CMEs), and to measure radio waves, the local plasma and magnetic field, and high-energy particles. KuaFu-B1 and KuaFu-B2 will fly in polar orbits chosen to facilitate continuous (24 hours a day) observation of the north polar aurora oval. The mission is suggested to be launched at the next solar maximum about in 2012, and with an initial mission lifetime of two to three years. KuaFu data will be used for the scientific study of space weather phenomena, and will be used for space weather monitoring and forecast purposes. It will also support fundamental research on the following subjects: to identify on the Sun the unique signatures indicating eruptive events, to study various coupling relations between different phenomena in the course of the disturbance propagation from the Sun to geospace, the physical processes of energy transfer from input to the sink of the Sun-geospace system. The KuaFu mission will be an essential element of the ILWS mission lineup. Moreover, KuaFu and Solar Obiter together will offer unique perspectives and new vantage points for three-dimensional global solar and heliospheric research. http://www.cosis.net/abstracts/IAGA2005/01035/IAGA2005-A-01035.pdf. No WL telescopic observations of the solar photosphere are envisioned in this project.

SMESE/LYOT project is a small satellite mission for the investigation of the structure and variability of the low solar corona observed in UV Lyman alpha emission of the disk and out of the limb using telescope and coronagraph images obtained with a high space and time resolution. The focus of the mission is on the space weather applications and high signal to noise ratio when monitoring the chromospheric as well coronal structures to infer the magnetic fields in the corona (http://www.ias.u-psud.fr/www/tpl2page.php?pageID=717). No telescopically resolved photospheric WL images are envisioned in this interesting project.

Advanced Technology Solar Telescope **(ATST)** is a 4-m ground based facility to study fundamental astrophysical processes in the solar atmosphere (http://atst.nso.edu/). The ATST project intends to attack critical details of the non-linear dynamical processes that govern the highly conducting, turbulent solar plasma. Angular resolution is ~0.1 arcsec or better, good cadence. A broad set of diagnostics from 0.3 to 35 μm. Precise magnetic and velocity field measurements are envisioned to resolve the pressure scale height and the photon mean free path. No precise and absolute IR and WL intensity calibration is possible, because of the atmospheric perturbations and no full disk observations. No 24 h coverage. The broad scientific questions are: (1) How are cosmic magnetic fields generated and how are they destroyed? (2) What role do cosmic magnetic fields play in the organization of plasma structures and the impulsive releases of energy seen ubiquitously in the universe? (3) What are the mechanisms responsible for solar variability (that ultimately affects the Earth)? Note that similar questions are addressed by less ambitious projects.

The prime scientific goal of the ground-based on-axis 1.5 m **GREGOR** telescope with adaptive optics (Tenerife, under construction) is high precision measurements of the solar magnetic field. Magnetic activity of the Sun considered "to be responsible for the energy balance of the outer atmosphere, it causes the activity cycle and the concomitant variability of the solar luminosity and it produces most of the sometimes spectacular visible phenomena, like sunspots, prominences, flares and coronal mass ejections" (http://gregor.kis.uni-freiburg.de/). One should comment again, that not only magnetic fields per se, but also other physically independent parameters mentioned earlier are involved and need to be accurately measured for an understanding of the solar variability at all space–time scales. It is clear, that energy budget issues of sunspots and chromosphere cannot be resolved if based only on these observations. Measurements submitted to atmospheric perturbations and no 24 h coverage.

Big Bear Solar Observatory New Solar Telescope **(NST)** is the new off-axis 1.6 m solar telescope at the BBSO & NJIT with adaptive optics (http://www.bbso.njit.edu/newtelescope/index.html). It is smaller and developed before the ATST (like the GREGOR project). The same comments follow as above.

The **Chinese Space Solar Telescope** with its 1 m aperture (Ai et al., 2002) could be used for the suggested WL measurements if provided by additional registration devices to measure the WL variations with a high and stable accuracy.

SOLIS (Synoptic Optical Long-term Investigations of the Sun) is undertaken by National Solar Observatory at Kitt-Peak. It is aimed at providing unique observations of the Sun on a continuing basis for several decades using state-of-the-art techniques. These long-term studies of the astronomical object most important to humanity should provide fundamental data to understand the solar activity cycle, sudden energy releases in the solar atmosphere, and solar irradiance changes and their relationship to global change (from the presentation of the project at: http://solis.nso.edu/). Unfortunately, it is a ground-based project submitted to all perturbations due to the Earth atmosphere and without a 24 h coverage. Difference imaging should be done at very high speed to beat the seeing, which obviously is not compatible with the high accuracy needed to perform precise photometric measurements. ***What is needed, is SOLIS in Space!***

The use of optical interferometers in space is promising for obtaining a higher spatial resolution with small telescopes connected in one optical system (Damé and Koutchmy, 2006).

4. Requirements for future observations

What do we need ideally?

(1) Spectral variability of flares and eruptions exists. It is unclear how large it can be from case to case. Precise photometric measurements of the solar disk from space, in BB including the continuum spectrum and at least 1 chromospheric channel are needed to touch this problem with temporal resolution up to $\sim$ 1 s, angular resolution $\sim$ 1 arcsec and better. Stability of the absolute intensity calibration of pixels 0.05% and 24 h coverage are demanded for investigation of long-term variations. The Earth's atmosphere screen precludes the accurate absolutely calibrated measurements of them to look at difference images. Observations from space are unavoidably needed to investigate relevant photospheric and chromospheric processes. There exists an idea, that only several (say, up to five) strongest lines should be controlled and it is practically enough for the sufficiently accurate monitoring of the solar UV radiation. We should remark in this regard, that continuum can also vary and needs measurements of spectral changes. The problem can be not oversimplified a priori.

(2) Various eruptions on the Sun have different distributions over the energy channels: plasma kinetic energy, heat, accelerated particles, total and spectral electromagnetic radiation. Geometry of events is also highly variable (Veselovsky, 1999; Veselovsky and Panasenco, 2006). Various solar flares have different spectra of electromagnetic radiation. This point needs spectroscopic investigations, which were not performed in a regular manner. The consequence of this spectral variability can be important in practice: not all eruptions produce ionospheric effects on the Earth. The physics behind this spectral diversification could be similar to the situation met with electric discharges: the density, composition, temperature, magnetic field, geometry. Nonthermal and accelerated particles and many other factors are important and determine the emitted spectrum of the electric discharge in the laboratory. The same can be said about flares understood as a kind of electric discharges on the Sun: their characteristics depend on the same physical parameters, which are different for different situations on the Sun (height, location, etc.). Different flares could be accompanied (or not) by powerful (weak) motions. The demarcation between CME-like and flare-like eruptive processes can be quantified by the dimensionless number Ve, which is known as 'the velocity/emission dimensionless number' and represents the ratio of the emitted plasma kinetic energy to the emitted electromagnetic radiation during the event. For the measurements of this quantity, one needs many spectral and plasma characteristics. The proportion between 'proton flares' and their optical

or X-ray class is also not one-to one. Response of the top-side ionosphere depends on these details and needs more investigation in this respect (Dmitriev et al., 2006).

(3) Physical openness degree is not always clear for the structures and processes on the Sun. Premature concepts of 'primary energy release sites' in the past leaded to erroneous flare paradigms related to reconnection cartoons in closed boxes with a purely internal instability. It is not easy to follow even partially the whole chain of the free energy transformations between different space and time scales during the preparation and development phase of eruptive events on the Sun. Direct and inverse energy cascades from larger to smaller sizes and opposite way coexist. We need more observational information about all sides of these concurrent processes in the open system: photosphere-chromosphere-corona under controlled boundary conditions for the better model representations, which are still lacking. We do not know in a sufficient measure all transports inside and through their imaginary boundaries to evaluate Trieste numbers, which are dimensionless ratios of circulating and crossing parts of mass, momentum and energy fluxes.

(4) Stark effect measurements are needed for quantitative evaluation of electric fields on the Sun. Those measurements are difficult because of the low values of electric fields in comparison with magnetic field intensity. Indeed, the factor v/c appears to be small, of the order of 10^{-3} and even less, in frozen approximation. Selection of the most sensitive and clean lines should be done based on estimates of electric dipole moments of transitions. Lines of highly excited ions and atoms are best candidates in this respect. Measured values of 5–10 V/cm were reported for erupting protuberances in accordance with the estimates of the pressure broadening (Foukal et al., 1987). Reliable and regular measurements of electric fields on the Sun are still absent, though their principal role in the solar physics was realized as early as a century ago (Hale and Babcock, 1915).

(5) With a temporal resolution of 1 s and a pixel size of 0.5 arcsec, the amount of data will be very big for a space telescope. In order to achieve a spatial resolution of 1 arcsec (pixel of 0.5 arcsec) on the full disk, a 4000×4000 CCD is necessary, with 2 bytes per pixel for a precise photometry. With a temporal resolution of 1 s, the output will be 32 MB/s (it could be reduced by compression). Such a rate is probably not reasonable, so that one has to find some compromise between the field of view (full disk, regions) and the temporal resolution: great difficulties exist. Temporal resolution should be as high as possible because it is not clear up to now, what time scales appear to be main contributors to the energy and power. Programmatic computer solutions should be used on board for the final information extraction and transmission of this scientific product. Only some key images should be also transmitted on the Earth for the control of the quality of operations. More elaborated assessment is needed in this part in future development of suggested ideas of the project. Otherwise, we never will know real answers to the posed questions.

(6) We are aimed to tackle two main unsolved problems using a full disk instrument. First, more local and shorter term open question will be addressed: "What are quantitative contributions of different features to a white light flare?" White light energy and power of solar flares will be measured pixel by pixel with better spectral/temporal/space resolution than up to now. Second, more global and longer term measurements are envisioned for the better understanding of another open question: "What are quantitative contributions of different pixel elements on the Sun to the total solar irradiance and its variations during the cycle?"

5. Discussion

It is often assumed (not explicitly or even explicitly but without sufficient justifications), that the subphotospheric dynamics is not essential for the flare and CME initiation and development (spontaneous reconnection models in the corona, energy storage and instabilities in the corona etc.). We find this approach too restrictive and physically not sufficient because of the neglect of the transmission through the photosphere and interiors of the Sun of the energy, momentum and mass towards the solar atmosphere during these processes. Strongest solar flares and coronal mass ejections never happen without preceding and ongoing 'new magnetic flux emergence' in the photosphere, which is governed by 'MHD and heat machine' in interiors of the Sun. They are only 'crests on the top of the breaking ocean wave' with brightest and most spectacular manifestations, big instant power, but lower total energy. These fast and short crests are directly driven by slow and large ambient energy sources situated beneath and above the photosphere. The approach of 'closed physical reservoirs' should be replaced by open systems. Initial and boundary conditions decide the evolution and internal life of selected reservoirs under consideration. The focus in theories and observations should be shifted in this direction if we really want physical understanding and forecasts.

It is also often assumed that WL flares on the Sun initiated by beams of accelerated particles from the corona. This explanation meets with difficulties: under the thick-target model assumptions, the electron beam must extend down to 15–20 keV, and the energy input to the chromosphere should occur within the collisional stopping depth of these electrons – approximately $2 \times 10^{-4}\,\mathrm{g\,cm^{-2}}$ (Fletcher et al., 2007). We suggest that even lower energy suprathermal electrons are involved. Strong flares and CMEs are initiated and driven by processes coming from solar interiors, i.e. the photospheric dynamics plays not a secondary and passive, but a primary and active role, which is observationally documented as 'new magnetic flux emergence', WL brightening, sub-millimeter radio wave bursts, electron-positron annihilation line emission and deserves more detailed telescopic investigation then was done up to now by ground based observations. Acceleration of suprathermal and more energetic particle can be observed here. Difference imaging is a potential method to be used, similar to the highly successful method used to visualize CMEs on WL LASCO images. We stress again, that not only magnetic energy (low beta regimes) is important, but other types of the free energy involved in the solar activity processes. Magnetic activity is only a part of whole story in attempts of explanation.

Available estimates of different kinds of energy and power in flares are highly uncertain in spite of many efforts. They are not convincing because of overestimated accuracy in the situation when many important input parameters are not measured with needed precision (plasma density, velocity, temperature magnetic field distributions, integration volumes etc.). As an example, we mention only the recent paper (Emslie et al., 2005). There is no firm observational ground for general belief in the dominant role of magnetic field energy accumulation in current sheets, which are 'primary components of energy'. Moreover, thin loops and filaments are clearly documented before, during and after flares. Transient current sheets arise as aftermath of CME eruption in a manner similar to comet tail. They are seen sometimes as new coronal rays under appropriate viewing conditions.

Past, existent as well as most of planned missions and ground based projects are not sufficient to resolve several important questions of the ultimate solar activity origins. It concerns flares and CMEs as well as the solar magnetic cycles. For better observational and theoretical grounds of our knowledge we need photometric quality photospheric/chromospheric high cadence images for adequate models of flares and CMEs.

6. Conclusions

The light flux contributions of different small-scale structural entities of the solar atmosphere forming the white light flares and micro-flares are still poorly known and their short-time variations are unknown. We do not know the absolute contributions of different structural elements of the solar atmosphere to the long-term and to the cyclic variations of the solar irradiance, including features of the polar regions of the Sun. The variations of the chromospheric magnetic network and intra-network elements are still poorly evaluated especially at high heliolatitudes. Only scarce information is available about the spectral variations of different small-scale features in the high photosphere. Precise photometric measurements with a 24 h coverage are achievable only from space. It is a difficult, but solvable task. Without this information our knowledge will remain essentially incomplete.

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