Current state-of-art in the field and outcomes of the project

It is well-known for more than 60 years that the corona of the Sun is heated to several million degrees while the solar surface is almost 1000 times cooler (Grotrian 1939; Edlen 1942). It has been also recognized that magnetic fields play a key role in heating of the solar corona and that the primary energy source for this heating must lie in the turbulent convection zone below the solar photosphere (e.g. Bray et al. 1991; Golub & Pasachoff 1998; Aschwanden 2004).

Up to this point there exists a common consensus among the solar physicists in the last decades. This consensus is also supported from the view of energy budget. Muller et al. (1994) showed that the energy available in the photosphere in the form appropriate for heating of the solar quiet corona is about 2 orders of magnitude larger than required ~300 $W.m^{-2}$ (Withbroe & Noyes 1977, Aschwanden 2001). Nevertheless further details are still very unclear. In fact no particular type of the physical heating mechanisms responsible for the hot solar coronal plasma in different coronal structures have not been observationally verified unambiguously so far.

It was found theoretically that the interaction of the magnetic field with convective flows in/below the solar photosphere can produce two types of magnetic disturbances in the solar coronal structures (e.g. Priest 1982, Walsh & Ireland 2003). Firstly, the buffeting of concentrations of the magnetic flux in the photosphere by the granulation flow generates magneto-hydrodynamic (MHD) waves which can propagate upward along magnetic flux tubes and dissipate their energy in the chromosphere or corona (e.g. Ofman et al. 1998). Secondly, in coronal loops the random motions of the foot points can produce twisting and braiding of coronal field lines, which generates field-aligned electric currents that can be dissipated resistively (e.g. Parker 1972, 1983; Heyvaerts & Priest 1983; van Ballegooijen 1990). The main difference between these processes is that plasma inertia plays a key role in wave propagation, but it is not important for the dynamics of field-aligned currents appearing along the coronal loops. Thus the described types of the magnetic heating mechanisms can be crudely classified as either wave-heating or current-heating mechanisms.

Such a simple general scheme has been broadened by results of several theoretical efforts to identify possible individual candidates for the heating mechanism (for reviews on coronal heating theory, see Narain & Ulmschneider 1990, 1996; Zirker 1993; Roberts 2000; Walsh & Ireland 2003; Aschwanden 2004). So far several dozens of the individual heating mechanisms have been proposed theoretically.

As one of the most preferred mechanisms we can mention the essential Parker's idea (Parker 1983, 1988, 1994) of nanoflares occurring in the tangled coronal magnetic fields which was elaborated recently by Priest et al. (2002) into a more complicated (and realistic) “tectonic” heating mechanism. On the other hand the wave-heating mechanism seems to be favourite in case of the solar coronal “open” magnetic structures like e.g. coronal plumes or coronal holes (Ofman 2005). Some other promising candidates are clearly explained by Walsh & Ireland (2003) and listed by Klimchuk (2006). In order to clarify which of them is reasonable working in different coronal structures (active region, quiet atmosphere, open/closed field configurations, network/internetwork) further comparisons of the predictions of theoretical models and state-of-art observations are highly needed. This was pointed out also during the last world-class conference gathered to discuss coronal heating problem (SOHO15 workshop "Coronal Heating", St. Andrews, Scotland, September 2004, see Cargill 2004).

Due to reasons already understood (Judge 1999) we know that only safe way to proceed further in this branch of research is the so-called 'forward' modeling of the problem. This forward approach contains prescription of a source of energy and mechanism for converting that energy into heat, together with the derived description of the coronal plasma response and final prediction of the emitted spectrum and its manifestation as observable quantities (Klimchuk 2006).

During the last decade a lot of new results have been presented in the form of detail description of behaviour of the observable quantities like line emissivity, Doppler shifts, and broadening of the coronal and transition region spectral lines (e.g. Hansteen 1993, Wikstol et al. 1997, 2000, Muller et al. 2003, Bogdan et al. 2003, Taroyan et al., 2006). These groups used different 1D or 2D numerical (magneto) - hydrodynamical codes under different boundary conditions. Their results showed that indeed there can be distinguished between different heating mechanisms as predictions of the observable quantities (their relations) behave in different ways or even in opposite way. Recently Gudiksen & Nordlund (2005) modeled a small part of the quiet corona in full 3D using potential extrapolation of the magnetic flux measured in the photosphere. Peter et al. (2004) extended this study to synthesis of the emission line spectra from the computational domain data. The overall statistical results of such numerical experiment copy adequately spatially averaged observables of the solar corona and the transition region between the chromosphere and the corona, e.g. net redshift of the transition region and low corona emission lines. Nevertheless no high resolution comparison has been made so far. However, it is possible to compare predictions of some of these models with the observables quantities. This is the right, highly needed task to be done (Cargill 2004, Klimchuk 2006).

The space missions SoHO[1] (Domingo et al. 1995) and TRACE[2] (Handy et al. 1999) started a new era in the exploration of the solar corona unveiling new impulsive and highly dynamic phenomena. The previously accepted view, created in the Skylab era (Orall 1981), with corona consisting of coronal loops instead of the classical spherically symmetric atmosphere interspersed with coronal streamers, has been changed again. Loops as the building parts of the corona remained but dynamics and impulsive events taking place on different temporal and spatial scales seem to dominate in our current concept of the solar corona (Aschwanden 2004, Cargill 2004).

This change of the concept was mostly due to improved spatial and temporal resolution of the imaging and spectroscopic instrumentation on board the SoHO mission and the TRACE satellite. Nowadays we are able to observe topology and variations of the solar coronal structures with the spatial resolution down to 0.5 arc sec and the temporal resolution ~10s. Additionally, spectral profiles of several emission lines in the UV spectral range originating from the chromosphere, transition

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[1]SoHO – Solar and Heliospheric Observatory
[2]TRACE – Transition Region and Coronal Explorer

region, and the corona can be acquired with sufficient signal to noise ratio and spectral resolution. These possibilities were exploited for addressing the coronal heating problem in papers dealing with blinkers, coronal X-ray bright points, explosive events, coronal loop dynamics (e.g. Harrison 1997; Brkovic & Peter 2004; Doyle et al. 2004; Teriaca et al. 2004; Marsh & Walsh 2006; and many others). Unfortunately, most of these papers deal with the upper atmosphere alone without a connection to the photospheric dynamics.

Important change was also made on the prime ground-based solar observatories. In the recent years, several high-tech solar telescopes were equipped with adaptive optics or post-facto restoration of observations. The facilities are available also to external observers granting observing time through the OPTICON[3] program or international time at the ENO[4].

These facilities has been used also for observations related to the topic of the coronal heating. So far most colleagues have been interested mostly in the dynamics of the photospheric G-band bright points as tracers of the magnetic flux concentrations in the photosphere (Berger et al. 1998, Nisenson et al. 2003, de Wijn et al. 2005) following the pioneering work of Muller at al. (1994).

Nevertheless no results have been presented (to our knowledge) up to now using direct comparison of the high resolution ground-based measurements of the photospheric magnetic flux concentrations dynamics and the variability and dynamics of the transition region and coronal plasma. Similarly, coronagraphic or total eclipse measurements, of the high-frequency intensity oscillations in the active region loops have been made at different coronal observatories (different expeditions) but so far without a support of other space-born instruments (see e.g. Rudawy el al. 2004, and references therein). Additionally, results of these measurements are quite contradictory till now.

Therefore this project proposal is aimed to fill the gap between usually uncoordinated observations performed mostly isolated, either focused on the corona (and transition region) emission or dealing with the solar photosphere only. Both type of instrumentation - space-born instruments and ground-based telescopes - will be used for coordinated observing campaigns. We plan to utilize our already acquired data sets as well as gather new complex co-spatially and co-temporally taken observational material to address the coronal heating problem. In particular, we want to address the question on an interplay between coronal emission and dynamics of the photospheric magnetic flux concentrations, and to proof observational evidences for existence of high-frequency MHD waves in the coronal loops.

Project objectives

General objective of the project is to validate or discard proposed theoretical heating mechanisms of the solar corona comparing predictions of these mechanisms

[3]OPTICON Trans-national access programme: *www.otri.iac.es/opticon/*
[4]ENO – European Northern Observatory: *www.iac.es/eno*

elaborated through numerical modeling with the state-of-art ground-based and space-born observations performed in cooperation. Observations will be performed using the already tested joint observation programs for the instruments on board SoHO, TRACE, RHESSI[5] satellites together with the ground-based telescopes at the ENO (Canary Islands, Spain) and at coronal station at the Lomnicky Peak (Slovakia). Measurements will be coordinated in a way to obtain the best possible profit from the multi-wavelength observations. Some interesting data sets already acquired using some other facilities (e.g. VLA[6]) will be used as well. Our work will be focused on different structures in the solar corona as different mechanisms might be working dominantly in these structures.

Project will consist of four different parts related to different targets of interest. In particular, we plan to observe and analyse data gathered for: network in the quiet solar atmosphere, microflares in the solar active regions, brightenings in the quiet solar corona, and long coronal loops in the solar active regions. All four parts are aimed to the general objective and some synergy effect is expected as well, namely:

Solar network: results of different works show contradictory results on variability, waves and energy transport in/above network in the quiet solar atmosphere (e.g. Curdt et al. 1998, 1999; Berghmans & Clette 1999; Banerjee et al. 2001; De Moortel et al. 2002; Gomory et al. 2006). Whether direction of the observed waves is upward or downward will be aimed to be addressed here using CDS[7] /SoHO measurements of several emission lines originating in the chromosphere (e.g. He I 58.4 nm), transition region (e.g. O V 62.9 nm), and corona (e.g. Si XII 52.0 nm)[8]. Additionally, we will investigate which features determine the direction of the wave propagation (e.g. magnetic flux evolution, magnetic field topology, photospheric bright points dynamics) using the G-band ground-based measurements. This questions is closely related to the preferred heating mechanism in such structures as it was shown by Wikstol et al. (1997, 2001). The SoHO joint observation program JOP171[9] will be run several times enlarging the already acquired volume of such data to proof the previously contradictory results. Approach used in work of Gomory et al. (2006) will be extended for long time series. The propagation direction of the waves will be searched using several data sets[10].

Solar microflares: we will analyse the RHESSI observations of the dynamics and plasma evolution during microflares in solar active regions by studying the chromospheric response to electron beam and/or conductive heating. This response will be observed using the ground-based (Ca II H line, H alpha line) and space-born imaging observations (Lyman alpha line, UV 160nm continuum). The comparison of the observational data with theoretical predictions in the frame of electron-beam-driven and conductively driven chromospheric evaporation for individual microflares can help us to better understand: whether non-thermal electrons are present in microflares which hints at magnetic reconnection as the

[5] RHESSI - Reuven Ramaty High Energy Solar Spectroscopic Imager

[6] VLA - Very Large Array

[7] CDS – Coronal Diagnostic Spectrometer

[8] Full list of the UV emision lines: *http://www.astro.sk/~choc/open/apvv_vv2006/apvv_vv2006.html*

[9] SoHO JOP 171: *http://sohowww.nascom.nasa.gov/soc/JOPs/jop171/*

[10] An example of the data set: *http://www.astro.sk/~choc/open/apvv_vv2006/apvv_vv2006.html*

underlying physical process; how much plasma is brought into the corona by microflares; which process (electron beams or heat conduction from the hot coronal microflare plasma) dominates the mass transport, and how much energy is deposited during microflares which is available for the heating of the corona. We plan to address similar issues like it was done for regular flares (Veronig & Brown 2004, Veronig et al. 2005). This goal will be reached using coordinated observations of the DOT telescope, EIT, CDS and MDI instruments on board SoHO, TRACE and telescopes at the Kanzelhoehe Observatory (Austria) and Hvar Observatory (Croatia). First campaign was already performed on June/July 2006[11].

Coronal brightenings: impulsive enhancements of the coronal emission in soft X-rays and high-temperature EUV lines are observed for a long time as so-called coronal bright points (see Aschwanden 2004) or blinkers (Harrison 1997). Are these events just miniature flares, do they originate in chromosphere, transition region, or corona ? In the quest for the energy transport direction, the unique archive data set will be used. This data set, acquired using the VLA, and CDS, EIT, and SUMER instruments on-board SoHO, will be used for a very extended time coverage of almost 10 hours (data from July 12, 1996). In particular, as completely new addition the SUMER data will be used in determination of the direction of the energy flow enhancing the coronal emission in radio ranges. This will allow to extend significantly results obtained earlier (Krucker a Benz, 2000).

High-frequency loop oscillations: theoretical studies showed that only high-frequency MHD waves (> 1 Hz) are capable of significant heating (e.g. Porter et al. 1994, Aschwanden 2004). Although several attempts have been made to detect these oscillation using the coronal forbidden lines in the visual solar spectral range the results are still contradictory (e.g. Pasachoff & Landman 1984; Koutchmy et al. 1994; Cowsik et al. 1999; Williams et al. 2001, 2002; Rudawy et al. 2004). Because no space mission capable of such measurements will be launched at least until the year 2015 new measurements using ground-based coronagraphs are highly required (Cargill 2004). We plan to install and operate at the Lomnicky Peak Observatory SECIS - highly dedicated instrument for this task (Phillips et al. 2000). The loan of the the instrument and cooperation in data analysis were contractually agreed. New version of the instrument is planned to be installed and used as well (Dual Rapid Imager). Coordinated observations with the space-born instruments are anticipated already since the year 2007.

Each part of the project will contain the following four common stages: (1) observations - planning, coordination, performance, (data archive mining); (2) data handling - reduction, coalignment, and merging of the data; (3) analysis and comparison of the observational results to the theoretical predictions; and finally (4) formulation and dissemination of the results. Some additional material to the project proposal has been prepared (images and web links) for illustration of the proposal[12].

Originality of the project is mainly twofold. Firstly, coordinated combination of the currently available space-born and ground-based observations for testing the coronal heating mechanisms is very rare and so data we plan to acquire and analyse are very

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[11]Summer 2006 campaign web page: *http://www.astro.sk/~choc/open/06_dot/06_dot.html*
[12]Proposal additional material: *http://www.astro.sk/~choc/open/apvv_vv2006/apvv_vv2006.html*

novel. Secondly, our unique procedure of data coalignment and merging allows very precise data analysis which has not yet been applied. These new data and the innovative approach to their analysis promise to step further in comparison of observations and theory of the coronal heating mechanisms.

Methodology

Methods for gaining project objectives are described briefly following four mentioned project stages. These stages are common for all four parts of the proposed project:

observations: planned data acquisition can be divided to three tasks related to the instruments involved:

1/ space-born observations on board SoHO, TRACE, RHESSI (Solar-B) satellites;
2/ ground-based observations at different telescopes at the ENO (DOT, SST, VTT, La Palma/Tenerife, Canary Islands, Spain) but preferably at the DOT telescope
3/ ground-based coronal observations at own facility using coronagraphs with the dedicated auxiliary instrumentation - Lomnicky Peak Observatory (Slovakia).

Crucial point of the proposal is coordination of the ground-based observations with the joint observation programs for the space-born instruments.

data handling: the best data will be reduced using the IDL software and the dedicated SolarSoft package using facilities available at our institute. Precise coalignment of imaging and spectral data will be done using our own routines developed, and using specially acquired data acquired by all instruments in use.

analysis and comparison of observations & predictions: The following approaches will be applied: tomography of the solar atmosphere, spectral characteristics determination, correlations, wavelet analysis, and extrapolation of the photospheric magnetograms, etc.. Some of them were already used by our group (e.g. Gomory et al., 2006; Tomasz et al. 2004; Rybak et al. 2004a, 2004b, 2004c). This work will be performed in cooperation with colleagues from:

- Sterrenkundig Instituut, Universiteit Utrecht, Utrecht, The Netherlands (SIU);
- IGAM/Institute for Physics, University of Graz, Graz, Austria;
- Max-Planck-Institute for Solar System Research, Katlenburg-Lindau, Germany;
- School of Mathematics, University of St Andrews, St Andrews, UK;
- Institute of Astronomy, ETH Zentrum, Zurich, Switzerland;
- Hvar Observatory, Faculty of Geodesy, University of Zagreb, Zagreb, Croatia;
- Astronomical Institute, University of Wroclaw, Wroclaw, Poland.

formulation and dissemination of the results: the results of the observations and comparisons with the predictions will be presented in the world-rank conferences and in the refereed astrophysical journals in cooperation with the colleagues from the institutes mentioned above. General public will be addressed as well via popular amateur astronomical journal in Slovak language, public lectures and a dedicated web page.

Professional quality of research team, management of the team, infrastructure

Research team of the project combines two senior researchers working in the field of solar physics for more than 20 years, three younger colleagues just after/before PhD defence, an engineer of electrons, and assistants. We expect a enlargement of the team for diploma and PhD students during the project period.

Senior team members are of a high international level of professional competence in:

- high-resolution ground-based observations (more than 15 observing campaign at VTT, DOT, SST telescopes at the ENO, La Palma/Tenerife, Canary Islands, Spain),
- planning and performing the space-born observing campaigns (several runs of the SoHO joint operation programs JOP078 and JOP171);
- management of a cooperative observational campaigns using ground-based and space-born instruments (e.g. JOP185 SoHO+TRACE joint operation campaign);
- experience with data reduction and handling;
- interpretation and presentation of the results (114 and 75 NASA ADS records)[13].

Younger colleagues were trained in the recent years benefiting greatly from EU support attending:

- 3 international solar physics schools
- 4 observing campaigns through Research Training Network (ESMN-2 project)
- stays in renown solar physics institutions through EC supported Marie Curie Actions (JK - 3 months at IAC, La Laguna, Spain, 24 months at SIU, Utrecht, Netherlands, PG – 10 months at SIU, Utrecht, Netherlands, and 6 months at AIP, Potsdam, Germany).

Team already published together the papers on topics of the photospheric dynamics, solar network waves, and ground-based and space-born instrumentation, which are quite nearly related to topic of this proposal.

The engineer and the assistants will be in charge for technical support for observations at the Lomnicky Peak Observatory and for performing these observations respectively. They have more than 10-years experiences in this work.

Coordination of the research will be roughly organized according to the skills/interests of the team members. Namely:

- J. Rybák - management of the project, planning and coordination of the ground-based and space-born campaigns, coalignment of the acquired data; interpretation;
- Kučera – reduction of the data, analysis of the photospheric spectra and images, interpretation;
- P. Gomory – reduction and analysis of the UV/visual spectral line observations,
- J. Koza – solar tomography and inversion of the photospheric spectra;
- O. Štrbák – photospheric bright points dynamics;
- J. Ambroz - technical support for observations at the Lomnicky Peak Observatory.

[13] J. Rybak's NASA ADS bib record: *www.astro.sk/~choc/open/apvv_vv2006/apvv_vv2006.html*

Because the team is oriented more observationally we will continue in our cooperation in interpretation of the observations with the colleagues from the above mentioned institutions.

The Astronomical Institute, Slovak Academy of Sciences (AISAS) owns infrastructure necessary for reaching the project goals including computers, IDL multiuser license, SolarSoft package installation, library, Internet. AISAS has proprietor access to the Lomnicky Peak Observatory - high-altitude observatory equipped with the coronagraphs and auxiliary instrumentation. We will apply for the publicly available observing time at the SoHO instruments and the TRACE satellite repeating our joint observing campaigns JOP171 and JOP185. Observations at the ENO will be performed in cooperations with the partners abroad. Basically we plan to apply for the free observing time (OPTICON project). Additionally, we plan to purchase 28 observing day at the DOT telescope (SIU, Utrecht, Netherlands) for a very interesting price based on the the previous close cooperation between SIU ans AISAS.

Outcomes and impacts of the project

Results and expected outcomes of the project can be quantified in two ways. At first, we can expect data gathered from observing campaigns with the close cooperation of the ground-based and space-born instruments. Telescopes at the ENO are located at one of the best places over the world for such task so there is the highest change for successful common data acquisition with the space-born instruments. The space instruments on board SoHO, TRACE, and RHESSI are regularly working in nominal conditions all over the year without serious problems. Their operation is scheduled beyond the proposed project length. Successful observations at the Lomnicky Peak Observatory can be expected as well, mostly in autumn. This facility is available full time for purpose of our project. Secondly, due to quite complex data gathered we expect that these data sets will be possible to use for several scientific refereed papers related to the topic of the coronal heating which will be submitted to the particular astrophysical journals (e.g. Astronomy & Astrophysics, Solar Physics). Results will be also presented at prestigious scientific conferences and workshops (e.g. SoHO workshop series).

Interaction between research and education

Senior researchers involved in the project give regularly lectures/practica on solar physics and on astronomical instruments at the Faculty of the Natural Sciences of the Pavol Jozef Safarik University in Kosice and supervise the diploma works . Experience and data acquired during the project will be used in these lectures/practica and for the diploma works. Involvement of diploma students to the project is planned. The material will be also used for the PhD study program in solar physics running at AISAS in cooperation with the Faculty of math, physics, and informatics of the Comenius University in Bratislava. Observational material and results will be presented at lectures given to the public visitors to the Astronomical Institute at Tatranska Lomnica (dozens per year). Dedicated web page to the project will be created as well. General popular articles will be submitted to the Slovak popular science journals Kozmos and Quark.

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