Mem. S.A.It. Vol. 80, 233
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What are the prospects for the study of the Sun and solar–terrestrial relations?

D. Spadaro

INAF, Osservatorio Astrofisico di Catania, Via S. Sofia 78, I–95123 Catania, Italy
e-mail: `dspadaro@oact.inaf.it`

Abstract. The aim of this paper is to introduce shortly the main open questions in the knowledge of physical processes occurring in the Sun and heliosphere and of their effects on the interplanetary and circumterrestrial environment. Starting from the considerable developments in the last decade, particularly owing to the availability of new and more effective, both ground– and space–based, instruments of investigation, that were also characterised by a significant contribution of the Italian scientific community, the paper will describe some researches which attempt to address these questions. A special attention will be devoted to the prospects opening up with the currently available instruments and their possible sinergies, as well as to the opportunities that should be provided by the new instruments planned for the next decade.

Key words. Sun: general – Sun: atmosphere – Sun: solar wind

1. Introduction

The last decade has been characterised by a considerable development in the knowledge of the Sun and heliosphere, thanks to new and more effective ground– and space–based instruments.

For instance, the increase in spatial resolution achieved by some ground–based solar telescope has given more and more detailed information on the physical structure and dynamics of the photosphere and chromosphere, as well as of their basic elements (granulation, sunspots, faculae, network, etc.).

Another milestone is undoubtedly the ESA/NASA SOlar and Heliospheric Observatory (SOHO), whose payload consisting of twelve complementary instruments (Domingo et al. 1995) has carried out comprehensive observations of the photosphere, chromosphere, transition region and corona, as well as in–situ solar wind plasma measurements, thus resulting in a global study of the Sun from its interior up to 1 A.U. and beyond.

In addition, a series of instruments devoted to the study of the properties of the terrestrial ionosphere and magnetosphere and of their variations has made possible to correlate the alterations of the terrestrial environment to the interplanetary perturbations induced by the most energetic phenomena characterising the magnetic solar activity (flares, prominence eruptions, coronal mass ejections), greatly stimulating the physical investigations on the solar–terrestrial relations.

The contribution given by the Italian scientific community in all these fields is significant and widely recognised, also for the development of new hardware. According to these re-

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Send offprint requests to: D. Spadaro

cent results and developments, it is important now to wonder what are the main drivers for solar research in Italy and what are the principal questions we want to address by our activities.

As starting point, we report an extract from the Long Term Plan of INAF (prepared in 2006), asserting that:
”The present focus of the solar, interplanetary and magnetospheric physics is on the variety of phenomena collected under the umbrella definition of *Solar Activity*.
The content of this field, very rich of physical effects, arguably could be condensed as: *Complex interaction of the magnetic field and plasma over a wide dynamic range of conditions.*
The *magnetic field* is generated inside the Sun, threads through the solar atmosphere, the heliosphere and the planets magnetosphere; on the other hand, the entire Sun, the heliosphere, and the outer atmospheres of several planets are in *plasma state*.
The physical conditions in which the interactions between ionised plasmas and electromagnetic fields occur are very common in the Universe.”
This may indicate a possible unitary line for the future, that can concentrate our research efforts.

2. The challenge of solar physics

A major step forward in understanding the processes leading to a hot, variable solar corona and its expansion into the interplanetary space to form the magnetised solar wind and the heliosphere, is crucial since at present issues such as the origin of life and life sustainability in planetary systems are becoming of increasing interest. They need to be addressed not only in terms of the energetic coupling of the star and its planetary system, but also in terms of the highly variable magnetic coupling and associated phenomena.

The whole solar atmosphere is involved in the process leading to the strong and continuous energy deposition at coronal level. The primary energy source lies in the mechanical energy generated by plasma motions at the top boundary of the convection zone, and the magnetic field plays a dominant role in any mechanism apt to transport and dissipate such energy in the corona. The denser lower atmosphere also acts as a mass reservoir. On the other hand, the energy dissipated at coronal levels leads in the end to the expansion of the heated coronal plasma out of the stellar gravitational field, that thus forms the heliosphere, extending to about 100 astronomical units. All this implies a unified picture of the solar atmosphere–heliosphere system that gathers different lines of research into a cooperative effort.

2.1. Mass and energy input

The understanding of the physics and structure of the hot solar corona starts from a detailed study of the magnetic field properties in the lower solar atmosphere, and of its interaction with plasma motions. In fact, the amount of flux emanating from a magnetic concentration on the photosphere is controlled by the topology and dynamics of convective flows (Berrilli et al. 2004, 2005; Del Moro et al. 2004, 2007). Hence an in–depth study of the photospheric and chromospheric dynamics in quiet regions and emerging active regions is highly required: recent results obtained by IBIS/DST (Cavallini et al. 2001) observations of granulation/supergranulation and network (Janssen & Cauzzi 2006; Vecchio et al. 2007; Cauzzi et al. 2008) and by THEMIS/IPM (Cavallini 1998) observations of active filament systems (AFS, Spadaro et al. 2004; Zuccarello et al. 2005, 2007) are interesting for this subject.

In principle, many mechanisms are able to supply the corona with enough mass and energy: MHD waves originating at the top of the convective zone (excited by oscillations?), magnetic reconnection producing plasma jets, micro– and nano–flares, inducing chromospheric evaporation. However, all these processes, which imply a strong link between the photospheric magnetic fields and those in the upper layers, occur with typical spatial scales comparable to the intergranular distances, i.e. ~0.1 arcsec, corresponding to about 75 km on the Sun. Therefore, in order to single out the most effective mechanisms acting in the lower solar atmosphere to provide the mass and energy input to the hot corona, it is necessary to collect measurements (plasma velocities, magnetic fields, phase differences between their fluctuations) with a spatial resolution comparable with the intergranular scales, a high dynamic range for intensity (10^4) and a cadence of 1 minute or less, together with nearly simultaneous high resolution UV and EUV images of the transition region and lower corona. A major achievement is expected through high resolution bidimensional multiwavelength spectro-polarimetric observations of the photosphere and chromosphere performed by IBIS/DST (Cavallini et al. 2001) and SOT/Hinode (Tsuneta et al. 2008), that can provide significant information on the Stokes parameters characterising the radiation which originates in these layers of the solar atmosphere. The future prospect is given by the development of large ground-based telescopes, such as the European Solar Telescope (EST, see Zuccarello et al. 2008).

2.2. Heating of coronal structures

The location of the heating release inside coronal magnetic structures and its temporal properties (constant, impulsive or gradual) are still an open issue, as well as the mechanisms of energy dissipation – resistive or viscous damping of MHD waves, ohmic heating by electric currents induced by magnetic field changes, etc. (see, e.g., Klimchuk 2006). In fact, a direct detection of these processes is difficult at the moment, since it requires EUV and X–ray observations with spatial resolution ∼0.01 arcsec, temporal resolution ≤1 s and spectral resolution sufficient to measure velocities ∼1 km s^{-1}, significantly below the values characterising the present instruments.

Some new interesting results have been obtained by the instruments onboard the Hinode mission, launched on September 2006. For instance, images collected in five different filters by the X-Ray Telescope (XRT) have been used to describe the fine thermal structure of a coronal active region (Reale et al. 2007). This investigation confirmed the multi-strand picture of magnetic loops, the building blocks of the outer solar atmosphere, which cannot be considered as monoliths, but are constituted by many, thermally isolated, closed magnetic flux tubes. Moreover, the Extreme Ultraviolet Imaging Spectrometer (EIS) carried out a systematic investigation of plasma flows in active region loops (Del Zanna 2008), putting into evidence the predominance of downflows inside active regions, with velocities increasing at lower temperatures, and of upflows at the boundaries of active regions, with velocities increasing at higher temperatures. All this information can contribute to shed some light on the coronal heating mechanisms, but a major step ahead is expected from the data of both the Extreme Ultraviolet Spectrometer (EUS) and Extreme Ultraviolet Imager (EUVI), proposed for the science payload of Solar Orbiter (see below).

A possible alternative approach to this problem is the development of accurate models, with convincing heating mechanisms, that describe the hydrodynamics of the coronal plasma confined in closed and open magnetic field structures, the synthesis of the spectral emission expected from these structures and the comparison with EUV and X–ray data obtained with high signal-to-noise ratio and resolution requirements one order of magnitude less stringent. The observations should give profiles of temperature, velocity and density along the considered structures, as a function of time, in order to study their variability and plasma flows. It is also very important to investigate the chromosphere – transition region interface, where the coronal structures are rooted, which requires coordinated multiwavelength (from visible to EUV) observations, carried out from both ground and space.

Some Italian groups have already given significant contributions in this field of investigation, and are expected to improve their capabilities of analysis, adopting more powerful numerical codes as well as new tools for spectroscopic diagnostics (ADAS, CHIANTI), developed in close cooperation with UK and US scientists. These tools are capable to provide very accurate atomic parameters (ionisation balance, level populations), necessary for the analysis of the solar plasma emission.

Another fundamental ingredient in this context is the chemical composition of the solar outer atmosphere. The helium abundance is not yet known with satisfactory precision, while there is no general agreement, at present, on the existence of abundance variations among regions with different magnetic configurations or with respect to the photosphere (e.g., Spadaro et al. 1996).

Notwithstanding the importance of the role played by the magnetic field in the physics of the solar corona, our quantitative knowledge about coronal magnetic fields is still very poor, if not totally absent. The absolute lack of reliable measurements of the intensity of coronal magnetic fields is an extremely serious handicap for our comprehension and modelling not only of coronal heating, but also of the physical mechanisms which are at the base of the equilibrium and evolution of coronal structures. The only technique which is often used, at present, to obtain quantitative data on coronal magnetic fields is based on the extrapolation to the corona, by means of numerical techniques based on the solution of Maxwell's equations, of photospheric magnetic fields obtained through magnetographs operating in the visible region of the electromagnetic spectrum.

Direct measurements of the coronal magnetic fields are possible by means of spectropolarimetric techniques in the ultraviolet. It is known that resonance polarisation in spectral lines is deeply modified by the presence of a magnetic field (Hanle effect). This physical effect has been recently applied in astrophysics for the determination of the vector magnetic field in solar prominences (e.g., López Ariste et al. 2005) and in other astrophysical objects. The Hanle effect can operate in the solar corona in the UV lines of the Lyman series and in the O VI line at 1032 Å, which are radiatively excited by the radiation coming from the solar disc. The resonance polarisation of these lines should be modified by the presence of magnetic fields in a predictable way, then allowing the measurement of coronal magnetic fields by means of an ultraviolet spectro-polarimeter operating on board of a space mission. There is a significant interest of some Italian solar groups in developing this technique. It should be quoted here, for the sake of completeness, that information on coronal magnetic fields can also be obtained through the analysis of radio observations. Hence these methods deserve a greater attention in this context.

2.3. Origin and acceleration of the solar wind

Outward coronal expansion can occur only along open coronal magnetic field lines, with footpoints in the large unipolar regions, named coronal holes. Alternatively, plasma can escape along field lines that are opening via magnetic reconnection. The corona is thus structured by the competition between the general tendency of the hot corona to expand into the solar wind and the opposing tendency of the anchored bipolar magnetic fields to seek a closed configuration in which plasma may be trapped under the condition of high electrical conductivity.

There are some indications that the expansion of the fast wind in coronal holes originates along the boundaries of the chromospheric network, so that the chromospheric magnetic structure plays an important role in the acceleration process (e.g., Hassler et al. 1999). There is a considerable interest in verifying this picture, which requires the direct observations of the solar poles, not yet possible by remote-sensing techniques.

As for the slow wind, continuous low speed flows have been observed by UVCS/SOHO (Kohl et al. 1995) just outside coronal streamers and above the streamer cusp (Abbo & Antonucci 2002; Antonucci et al. 2005; Spadaro et al. 2005). For a firm identification of the source regions of the slow solar wind, it is therefore important to investigate the correlation in the extended corona among magnetic topology, wind speed and elemental abundances (specifically He). This can be accomplished only by simultaneous measurements of such parameters.

The heating and acceleration of the solar wind remains a basic unsolved problem in solar and heliospheric physics. Observations by UVCS/SOHO of both coronal holes (e.g., Kohl et al. 1999; Telloni et al. 2007) and streamer cores and boundaries (e.g., Spadaro et al. 2007; Susino et al. 2008) suggest that these processes can be explained in terms of the damping of the high–frequency part of a spectrum of outward propagating Alfvén waves by ion–cyclotron resonance. The transfer of mechanical energy from the inner atmosphere occurs by low frequency Alfvén waves, is distributed to higher frequencies through turbulent cascade and then dissipated via wave–particle interactions (e.g., Verdini & Velli 2007). Hence the efficiency of the mechanism depends on the charge-to-mass ratio of the absorbing ions.

To verify this scenario, remote–sensing observations of the profiles of lines emitted by ions with different charge-to-mass ratio are required: for instance, He II λ304 (Z/A=0.25), O VI λ1032 (0.31), H I Lyα (1.0) and so on. Note that once again the observation of He lines turns out crucial. Moreover, measurements of the coronal magnetic field fluctuations are necessary, as well as in–situ measurements of the particle distribution functions within 0.3 A.U. Such measurements should be characterised by high angular and energy resolution, and sampled at frequencies comparable to the proton cyclotron frequency. The knowledge of all these data will allow a detailed description of the evolution of turbulence, wave spectrum and particle distribution functions in the region of the extended corona where the plasma is heated and accelerated outward, developing the kinetic approach to the study of the solar wind (Velli, Bruno & Malara 2003; Bruno & Carbone 2005). A significant contribution to this approach is expected from the plasma data provided by the Solar Wind Analyser (SWA), proposed for the scientific payload of Solar Orbiter (Bruno 2008).

3. Future opportunities

What are the prospects of development for solar research according to the scientific drivers outlined in the previous section? It is almost clear that important breakthroughs will be achieved with the combination of space-based instruments and high resolution, innovative instrumentation from ground, as it is asserted in the Long Term Plan of INAF.

A significant contribution to single out the primary mechanisms acting in the lower solar atmosphere to provide the mass and energy input to the hot corona is expected from the solar ground-based instruments recently developed and planned for the future, as already discussed in Sect. 2.1. These observations, mainly carried out in visible and infrared light, should be coordinate with space EUV and X-ray observations, in order to cover the whole solar atmosphere.

Several solar space missions, with significant innovations, have recently been launched or are foreseen in the next decade: the Solar Dynamics Observatory (SDO), designed to observe the Sun's dynamics and understand the nature of solar variations, from the stellar core to the turbulent atmosphere; later on, Solar Orbiter, coupled with the Solar Sentinels within the Heliosphere Exploration (HELEX) programme, and Solar Probe, very ambitious and challenging missions for the space technology presently available, designed to fly very close to the Sun (within 0.25 A.U.) and above its poles. These missions, which are parts of the ILWS (International Living with a Star) programme, an initiative carried out by the cooperation of several space agencies, promise to bring about major breakthroughs in solar and heliospheric physics. For instance, the stringent requirements on the spatial, temporal and spectral resolution discussed in Sect. 2 can be fulfilled by observations at least one order of magnitude more resolved than the present ones. Moreover, the coronagraphic UV observations covering the coronal regions from the solar limb to 2 $R_\odot$ are suitable to determine the coronal magnetic fields and the abundance of Helium in the solar corona. It is very important to investigate the correlation between the Helium abundance and the magnetic field topology.

Multiwavelength remote-sensing observations of the polar regions will be finally available: they will allow to study the origin and initial acceleration of the solar wind in coronal holes, and to obtain data on spectral lines emitted by ions with different Z/A ratios, necessary to verify some scenarios proposed for the solar wind heating and acceleration. To this aim, a quantum leap is expected via in-situ measurements of the fluctuations of magnetic fields and distribution functions of protons, electrons, minor ions, energetic particles and neutral atoms, collected in the inner heliosphere (within 0.3 A.U.) with high angular and energy resolution and with a cadence of order of ten ms. The Italian solar and heliospheric community is involved in all these programmes, in particular Solar Orbiter, and its research activities should significantly benefit from this opportunity. Some members are participating in the development of SWA and of the imager EUVI, while an Italian team has proposed METIS (Multi-Element Telescope for Imaging and Spectroscopy). Combining ultraviolet spectrometry, on disc and off limb (out to 1.4 $R_\odot$), with UV spectro-imaging and visible and UV imaging coronography capabilities, METIS is able to provide new and crucial observations, essential to address the above identified scientific objectives. It is furthermore designed to benefit from the Solar Orbiter mission profile characterised by quasi-corotation intervals, close approach to the Sun and out-of-ecliptic phase.

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