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# From the solar core to the terrestrial magnetosphere: a progress report on the study of the Sun and solar–terrestrial relations

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**Abstract.** The knowledge of physical processes occurring in the Sun and heliosphere has considerably developed in the last decade, particularly owing to the availability of new and more effective, both ground– and space–based, instruments of investigation. The Italian contribution in this field is widely recognized within the international scientific community. The most recent results have evidenced the crucial role played by magnetic fields in structuring the solar atmosphere and causing its dynamic behaviour. Moreover, a considerable interest in studying the alterations of the terrestrial environment due to interplanetary perturbations induced by the most energetic phenomena of the magnetic solar activity (flares, prominence eruptions, coronal mass ejections) has risen in the last years. The aim of this paper is to review shortly the studies on the Sun, the heliosphere and the solar–terrestrial relations being carried out in Italy at the present time, and to outline their future prospects.

**Key words.** Sun: general – Sun: interior – Sun: atmosphere – Sun: particle emission

## 1. Introduction

The last decade has been characterized 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 such as the French–Italian THEMIS, the Dutch Open Telescope (DOT), the Swedish 1–meter Solar Telescope (SST), all operating at Canary Islands, and the Dunn Solar Telescope (DST), operating at Sac Peak (NM, USA), 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), launched on December 2, 1995 and still in orbit (Domingo et al. 1995). SOHO is placed in a halo orbit around the Sun-Earth L1 Lagrangian equilibrium point, where it is continuously pointing the Sun centre, and carries a payload consisting of twelve complementary instruments which have made possible 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.

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The measurements carried out by the out–of–ecliptic Ulysses space mission, launched in 1990 and still operational, whose orbit has an angle of 80 degrees with respect to the solar equator, have revealed the structure of the heliosphere, showing that it is primarily determined by the large–scale configuration of the solar magnetic field. These results have also established a firmer link of the solar wind properties to those of the source regions in the corona (e.g., McComas et al. 1994).

A series of instruments devoted to the study of the properties of the terrestrial ionosphere and magnetosphere and of their variations have made possible to correlate the alterations of the terrestrial environment to the interplanetary perturbations induced by the most energetic phenomena characterizing 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 recognized, also for the development of new hardware. Here it is worth quoting the participation in the UltraViolet Coronagraph Spectrometer (UVCS), built in cooperation with the Harvard–Smithsonian Center for Astrophysics for the SOHO mission (Kohl et al. 1995), the implementation of the Italian Panoramic Monochromator (IPM) for the THEMIS telescope (Cavallini 1998), the Interferometric BIdimensional Spectrometer (IBIS) recently installed on the DST at Sac Peak (Cavallini et al. 2001), the Trieste Solar Radio System (TSRS), devoted to continuously monitoring the radio emission from the solar corona, the network for the measurement of variations in the geomagnetic field (SEGMA), the radar network for the study of the dynamical state of the magnetosphere–ionosphere system (SuperDARN) and the SVIRCO observatory, for measuring and monitoring the flux of cosmic rays incident on Earth.

According to these recent 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. This may help to outline a possible unitary line for the future, that can concentrate our research efforts.

## 2. Inside the Sun

Long-lasting observations by SOHO helioseismological instruments have allowed to deduce much more precise information about the Sun's interior than that obtained in previous investigations of solar oscillations, so putting the theories of how the Sun works to a severe test. The results about the speed of rotation, as a function of both radius and latitude, as well as about the speed of the sound in the deep interior are undoubtedly remarkable, and have been achieved with a significant contribution of the groups of Catania, Pisa and Rome. They confirmed the high accuracy of models developed to describe the solar internal structure and dynamics. However, some discrepancies higher than the estimated measuring errors have recently come out as a consequence of the new determinations of oxygen and other heavy–element abundances (e.g., Bahcall et al. 2005; Antia & Basu 2005). Solar models constructed with the newer and lower heavy–element abundances significantly disagree with the helioseismological determinations of the depth of the solar convective zone, the surface helium composition, the internal sound speed and the density profile.

Such discrepancies need to be removed, in particular as far as the characteristics of the convective zone are concerned, because the dynamo mechanism, which originates the magnetic fields emerging in the solar atmosphere, acts right there. In fact, the presence of a meridional flow near the base of the convective zone is the key ingredient of new MHD flux-transport models recently developed to provide a picture of the solar dynamo which reproduces many basic features of the solar cycle (e.g., Bonanno et al. 2002, 2005; Dikpati 2004). These numerical codes, based on a positive $\alpha$–effect, adopt the meridional circulation and velocity fields deduced by helioseismological observations and by the study of UV tracers. They are able to describe the behaviour of the solar plasma with high magnetic Reynolds numbers (~1000), providing solutions with correct cycle periods, butterfly diagrams, magnetic helicity, magnetic field intensity, and consistent with the results of helioseismology (Dikpati & Gilman 2001; Bonanno et al. 2002, 2005).

Given the crucial role played by magnetic fields in structuring the solar atmosphere and causing its dynamic behaviour, the research efforts devoted to this field of investigation appear extremely useful and can give a significant contribution also to the studies of stellar structures and of other astrophysical objects where the magnetic field action is important.

## 3. Sun and heliosphere as a system

The challenge of the physics of the Sun's atmosphere is in understanding the processes leading to a hot, variable solar corona and its expansion into the interplanetary space to form the magnetized solar wind and the heliosphere. A major step forward in this field is important 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 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 gather different lines of research into a cooperative effort.

### *3.1. 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. 2002, 2004; Del Moro et al. 2004; Spadaro et al. 2004; Zuccarello et al. 2005). Hence an in–depth study of the photospheric and chromospheric dynamics in quiet regions and emerging active regions is highly required: the efforts carried out by the groups of Catania, Florence, Naples and Rome can lead to interesting results on 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 in the various atmospheric layers 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. This is somewhat difficult by means of the solar instruments available at the moment.

### *3.2. 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, ...). In fact, a direct detection of these processes is difficult at the moment, since it requires EUV and X–ray observations with spatial resolution $\sim$0.01 arcsec, temporal resolution $\leq$1 s and spectral resolution sufficient to measure velocities $\sim$1 km s$^{-1}$, significantly below the values characterizing the present instruments.

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.

The groups of Florence, Palermo, Cosenza and Catania 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 (ionization 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 (see the contributions of the groups of Florence, Naples and Catania in this field). However, 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.

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 polarization 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 polarization 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 the Florence and Turin 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 such method deserves a greater attention, as pointed out by Franca Drago in the discussion following this review.

### 3.3. 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 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 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. 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 $\lambda$304 (Z/A=0.25), O VI $\lambda$1032 (0.31), H I Ly$\alpha$ (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 characterized 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. A significant contribution to this approach by the Italian community is expected, through the groups of Rome (INAF/IFSI), Cosenza and Florence, already working in this field (Velli, Bruno & Malara 2003).

## 4. Coronal activity and its interaction with the Earth system

The challenge of the physics of solar activity is in the understanding magnetic structures, their emergence in the solar atmosphere, eruption and energy release. Coronal activity evolves systematically over a cycle of eleven years: the activity cycle and magnetic cycle are strictly coupled and they are clearly driven by the subphotospheric solar dynamo. Hence any physical understanding of coronal activity needs to explicitily account for the dynamo injection of magnetic flux (see Sect. 2).

Coronal mass ejections and flares are the two most energetic phenomena on the Sun. The energy liberated in a coronal mass ejection, of the order of $10^{31-32}$ erg, is comparable to that of flares. The energy of flares results in intense heating of the corona and particle acceleration, whereas that liberated in the ejections is transformed in macroscopic work against gravity and bulk kinetic energy of the expelled mass. Flares and mass ejections are of paramount importance in understanding the huge disturbances occurring in the heliosphere and their impact on the Earth, and other planets, environment.

This stimulates studies with the purpose of identifying the mechanisms which give rise to the instabilities in the coronal structures, the consequent eruption of the structures and the release of energy connected to such events. The key element in all the possible scenarios of flare ignition and coronal mass ejections is again the magnetic field. Therefore, joint high temporal and spatial resolution observations of the coronal magnetic field and emission in the visible and UV can pinpoint the process/es triggering solar flares and leading to large–scale disruption and mass ejection.

A big effort in this way is important to address many open questions concerning the following aspects related to flares: energy storage in non–potential magnetic fields, magnetic structure instabilities, energy transfer from the magnetic field to the plasma and particles (formation of current sheets and/or magnetic reconnection), transfer of energy and particles through the magnetized solar atmosphere, role of MHD turbulence in distributing energy from larger to smaller scales, where its dissipation occurs, formation and evolution of post–flare loops and behaviour of the sub–arcsecond filaments making up them. Several Italian groups with a substantial experience in the field (Palermo, Turin, Florence, Cosenza and Catania) can undoubtedly play a significant role in carrying out this effort.

On the other hand, the beginning and the first evolution of coronal mass ejections (CMEs) in the inner coronal layers are still unclear: the identification of those events that can be considered as precursors of CMEs is strongly required. A possible candidate is the dimming in the EUV and X–ray emission noticed in the coronal regions where a CME has occurred. Since this reduction can be caused by the density decrease due to the plasma initial expansion, it is regarded as an important observational signature of the CME start. Moreover, the detection of waves in the coronal plasma can be taken as indicative of the CME launch, because they are generally a consequence of the eruption of filaments and prominences. However, it is quite difficult to determine from imaging data alone what exactly the bright wave front is, or what the dimming region behind the front is. Spectroscopic observations and diagnostic techniques are invaluable in understanding phenomena observed in imagers. They have been used, for instance, to determine that coronal dimming in active regions is actually depletion of material. Moreover, spectroscopic signatures in coronal waves can be used to gather further information in order to distinguish between an MHD shock wave and a coronal mass ejection lift-off.

It is important to note that both ground-based and space visible light coronagraphs typically image the corona beyond 2 $R_\odot$. Therefore mass ejections are observed as they originate in the inner corona, below 1.2 $R_\odot$, and further out beyond 2 $R_\odot$; thus it is not possible to follow their early evolution. An important requirement to understand the acceleration of CMEs is to fill the observational gap between the lower corona and 2 $R_\odot$, and this can be done by introducing ultraviolet imaging coronagraphs. The spectral results obtained by UVCS/SOHO at heliocentric distances around 1.5 $R_\odot$ (e.g. Antonucci et al. 1997; Ciaravella et al. 1997; Ventura et al. 2002) suggest that it is possible to get information on CME acceleration, morphology, dynamics and energetics by this kind of instruments.

The influence of these events on the terrestrial environment significantly depends on the characteristics of propagation of the related perturbations through the interplanetary medium. This is one of the main reasons for studying the MHD turbulence in the solar wind, both at distances close to the Sun and farther away. In fact it controls the energetic particle (1-100 MeV and beyond) transport from the Sun to the Earth. Recent investigations show that magnetic turbulence substantially broadens the region of space where the energetic particles can be found, depending on the level and anisotropy of the magnetic field fluctuations (Zimbardo et al. 2004). Therefore, in order to be able to make reliable predictions of energetic particle fluxes associated with flares and CMEs, as required for Space Weather forecasts, a more detailed knowledge of turbulence features in the solar wind is needed. In particular, it is necessary to know, beyond the spectral shape and the intensity of the fluctations, the degree of anisotropy, which influences in a fundamental way the transport properties. Also, the non-Gaussian features of the magnetic field fluctuations, especially at small time scales, could influence the transport. This knowledge should be gained both as a function of the distance from the Sun, and as a function of the heliographic latitude. It has a considerable importance for the studies on the perturbations of the terrestrial magnetosphere and ionosphere induced by solar activity, as well as on the modulation of cosmic rays penetrating into the heliosphere and, in case, the magnetosphere.

## 5. Future opportunities

What are the prospects of development for solar research according to the scientific drivers outlined in the previous sections?

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. For instance, the IBIS instrument (Cavallini et al. 2001) installed on a telescope equipped with a very efficient adaptive optics can acquire nearly monochromatic images of the photosphere and the chromosphere with high spatial resolution (~0.2 arcsec), high spectral resolution (R>200,000) and a temporal resolution of some frames per second. The instrument is already operative and the first results appear suitable to address some of the problems discussed in Sect. 3.1. Moreover, IBIS could be used as a bi-dimensional spectropolarimeter, thus allowing high spatial resolution measurements of magnetic fields.

The long-term prospect is given by the Advanced Technology Solar Telescope (ATST), currently under development in USA. The telescope, located in Hawaii Islands (Haleakala), will have a 4 meters primary mirror and the *first light* is expected within 2012. The advanced focal plane instrumentation should be suitable to perfom solar observations with very high spatial (∼ 0.03 arcsec), spectral and temporal resolution, as well as with high polarimetric accuracy. This ambitious project can be carried out only through an international cooperation, so that an Italian participation is possible (adaptive secondary mirror, a focal plane instrument, contribution to observations), and firmly hoped for the development of solar research in Italy. It is evident that these ground-based observations, mainly carried out in visible 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, are foreseen in the next decade: Solar-B, the follow-up to the very successful Yohkoh mission, whose launch is planned in 2006; 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, that will be launched in 2007; later on, Solar Orbiter and Solar Probe, very ambitious and challenging missions for the space technology presently available, designed to fly very close to the Sun (within 0.2 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. 3 and 4 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 through the Hanle effect and the abun-

dance of Helium in the solar corona. Note that 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 and its research activities should significantly benefit from this opportunity. On the other hand, a further opportunity is given by the operation in a coordinated scheme of the different and complementary ground-based instruments managed by various groups in Italy and since many years devoted to the continuous monitoring of the complex phenomena occurring on the Sun, in the heliosphere and in the Earth, from the magnetosphere to the ground level (see Amata et al. 2005). Due to its capabilities, this network allows to monitor solar activity at different wavelengths, to determine the evolution of interplanetary disturbances, their effects on the Earth magnetic field and the cosmic ray intensity changes. These measurements, all stored in the SOLARNET archive, besides being important for the comprehension of the phenomena occurring in each single field of research, also play a key role in the context of Space Weather studies.

## References


Abbo, L., & Antonucci, E. 2002, ESA-SP, 508, 477

Amata, E., Berrilli, F., Candidi, M., et al. 2005, these proceedings

Antia, H.M., & Basu, S. 2005, ApJ, 620, L129

Antonucci, E., Kohl, J.L., Noci, G., et al. 1997, ApJ, 490, L183

Antonucci, E., Abbo, L., & Dodero, M.A. 2005, A&A, 435, 699

Bahcall, J.N, Serenelli, A.M., & Basu, S. 2005, ApJ, 621, L85

Berrilli, F., Consolini, G., Pietropaolo, E., et al. 2002, A&A, 381, 253

Berrilli, F., Del Moro, D., Consolini, G., et al. 2004, Sol. Phys., 221, 33

Bonanno, A., Elstner, D., Rüdiger, G., & Belvedere, G. 2002, A&A, 390, 673

Bonanno, A., Elstner, D., Belvedere, G., & Rüdiger, G. 2005, Astron. Nachr., 326, 170

Cavallini, F. 1998, A&A, 128, 589

Cavallini, F., Berrilli, F., Cantarano, S. & Egidi, A. 2001, Mem. Soc. Astron. Italiana, 72, 554

Ciaravella, A., Raymond, J.C., Fineschi, S., et al. 1997, ApJ, 491, L59

Del Moro, D., Berrilli, F., Duvall, T.L. Jr., & Kosovichev, A.G. 2004, Sol. Phys., 221, 23

Dikpati, M. 2004, ESA-SP, 559, 233

Dikpati, M., & Gilman, P.A. 2001, ApJ, 559, 428

Domingo, V., Fleck, B., & Poland, A.I. 1995, Sol. Phys., 162, 1

Hassler, D.M., Dammasch, I.E., Lemaire, P., et al. 1999, Science, 283, 810

Kohl, J.L., Esser, R., Gardner, L.D., et al. 1995, Sol. Phys., 162, 313

López Ariste, A., Casini, R., Paletou, F., et al. 2005, ApJ, 621, L145

McComas, D.J., Elliott, H.A., Schwadron, N.A., et al. 2003, Geophys. Res. Lett., 30, 10

Spadaro, D., Billotta, S., Contarino, L., Romano, P., & Zuccarello, F. 2004, A&A, 425, 309

Spadaro, D., Ventura, R., Cimino, G., & Romoli, M. 2005, A&A, 429, 353

Velli, M., Bruno, R., & Malara, F. 2003, Solar Wind 10, AIP Conference Proceedings, Vol. 679

Ventura, R., Spadaro, D., Uzzo, M., & Suleiman, R. 2002, A&A, 395, 975

Zimbardo, G., Pommois, P., & Veltri, P. 2004, JGR–Space Physics, 109, A02113

Zuccarello, F., Battiato, V., Contarino, L., et al. 2005, A&A, in press