THE ACTIVELY QUIET SUN - THE VIEW FROM SOHO*

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ABSTRACT

After a little more than a year of the SOHO mission, one of the most striking conclusions is that even during the quiet depths of minimum the Sun is constantly and furiously changing. Furthermore, especially in the corona, every region is to some degree affected by what happens far away. What implications must this have for understanding the solar - terrestrial connection?

The complement of 12 SOHO instruments measures conditions from well beyond the spacecraft back to the solar interior. Coupled with WIND and other spacecraft observations, for the first time we can trace nearly the entire chain of events that causes solar activity: motions of fields and plasma at the photosphere and below, heating and acceleration in the lower atmosphere and corona, and finally continuous variations in structure and dynamic characteristics of the solar wind and heliosphere.

For making predictions, representative images from SOHO are available within minutes of taking the observations. Most of the rest can be had within hours; a small fraction take as long as a few weeks. Joint observing programs (JOPs) are frequently executed to coordinate the observations of various instruments.

Examples of useful one-year plus sequences are the time series of full disk magnetograms taken every 96 minutes from MDI, the frequent EIT images of temperature and density structures in the chromosphere and low corona, and the synoptic LASCO coronagraph observations from 1.1 to 30 solar radii. Particular events can be studied in great detail.

Now that the data are available, our challenge is how to practically analyze that information to make useful and reliable predictions.

Relevant WWW addresses:
SOHO: http://sohowww.nascom.nasa.gov/
MDI: http://soi.stanford.edu

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1. INTRODUCTION

The Solar and Heliospheric Observatory (SOHO) and its instruments have been described in some detail in a special volume of Solar Physics (Fleck et al., 1995). The major goals of the mission are to study the solar interior, determine the mechanisms of coronal heating, and investigate the solar wind and its acceleration. Since arriving at the L1 point a few months after its December 1995 launch, the 12 SOHO instruments have conducted both synoptic and campaign observations of the solar interior, photosphere, corona, solar wind and heliosphere. This time span includes the quietest part of the solar cycle. One of the most striking results of the mission is the realization that even at minimum the Sun is constantly and furiously changing on the small scale and that this has major implications for our understanding of the apparently stable conditions seen on larger scales.

Continuous observation of the Sun is one of the unique features of the SOHO mission. That ability, along with superb instrumentation, allows observers for the first time to trace unambiguously the origin, evolution, and transport of solar, coronal and interplanetary features on a wide range of time scales. This comprehensive array of instruments, together with those of other spacecraft (such as WIND, Yohkoh, and Ulysses) and ground based observatories, will provide insight into the mechanisms of the solar cycle, coronal heating, solar wind acceleration, and the triggering of coronal mass ejections. Some of the initial SOHO results have been presented in special issues of Solar Physics (Fleck and Svetska, 1997) including a CD-ROM that allows presentation of striking movies showing how even at solar minimum the Sun is active at all scales. Along with the observations themselves, the results of this work are crucial for understanding the inputs required for successful implementation of artificial intelligence systems for predicting space weather.

This paper presents a few examples of the types of data that are available from the spacecraft and briefly summarizes some of the early results from SOHO that are relevant to the application of AI to problems in solar-terrestrial physics. The SOHO instrument teams welcome collaborations and proposals for Joint Observing Programs (JOPs) to investigate interesting solar features and conditions.

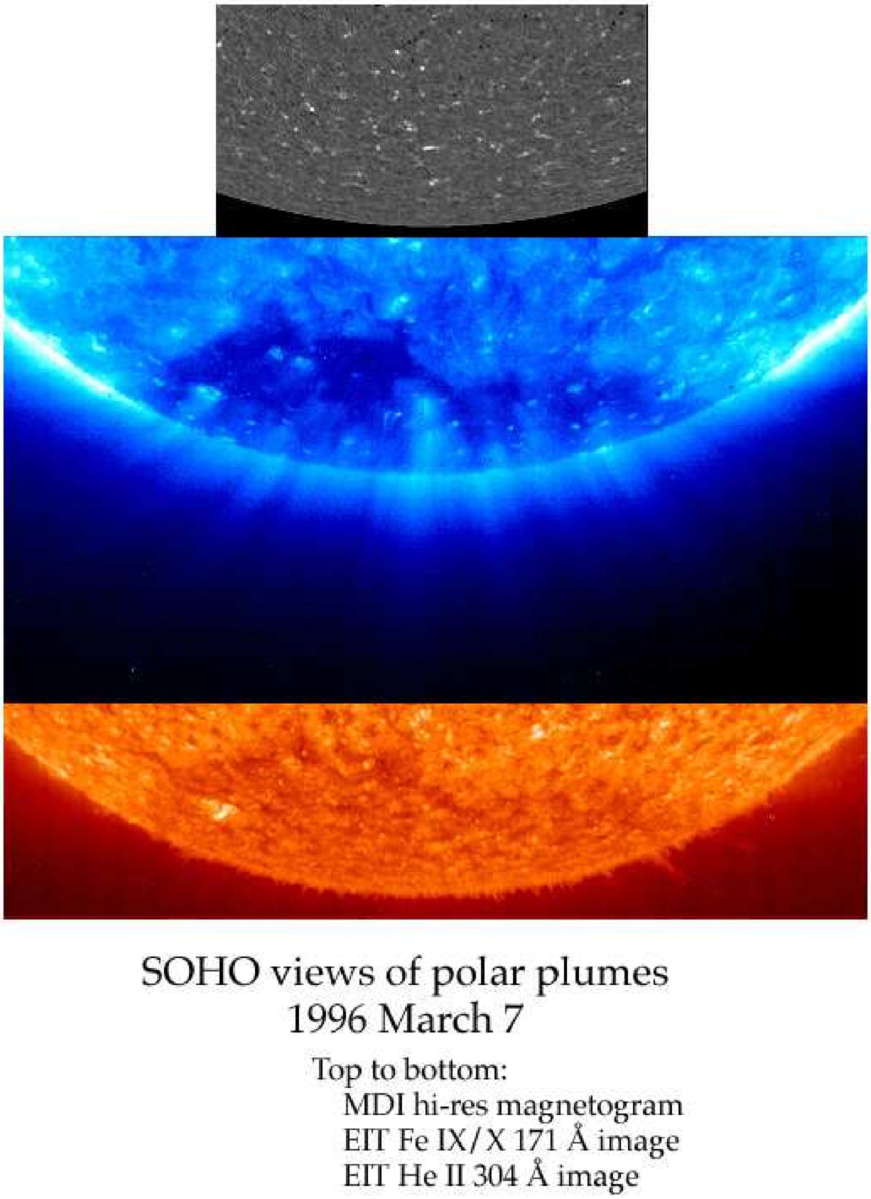

Figure 1. Plumes of outward flowing relatively cool gas in the Sun's atmosphere may be one source of the solar wind. These images, taken March 7, 1996, show (top) photospheric magnetic fields near the south solar pole; (middle) a 171 A image of the 1.3 million degree plumes from the same region; and (bottom) a 304 A EUV image of the "quiet" solar atmosphere at 80,000 K, closer to the surface. The top image was taken by the Michelson-Doppler Imager/Solar Oscillations Investigation instrument. The center and bottom images were taken by the Extreme-ultraviolet Imaging Telescope (EIT). These images provided the first opportunity to see the detailed development over time of the polar plume structures in which the solar wind is accelerated. Because of SOHO's continuous view of the Sun, movies have been constructed that help us understand the relationship between the magnetic field and the polar plumes. [Images courtesy of the SOHO/EIT and SOHO/EIT consortia.]

2. SOHO Observations

The SOHO instruments can observe conditions from the photosphere out to 1 AU and beyond. Here we present observations of plumes in a polar coronal hole, a case of early detection of a CME directed at Earth, evolution of the photospheric magnetic field over several months, and the temperature profile of a coronal loop system. Each has implications for structures observed in the solar wind at Earth

2.1. Plumes in Coronal Holes

Low- and mid-latitude coronal holes are the main source of high speed solar wind streams observed at Earth during the declining and maximum phases of the solar cycle. High speed streams are uncommon in the ecliptic during minimum because coronal holes are normally confined to the polar regions. Coronal holes overlie nearly unipolar regions in the photosphere where many field lines are open to the inter-

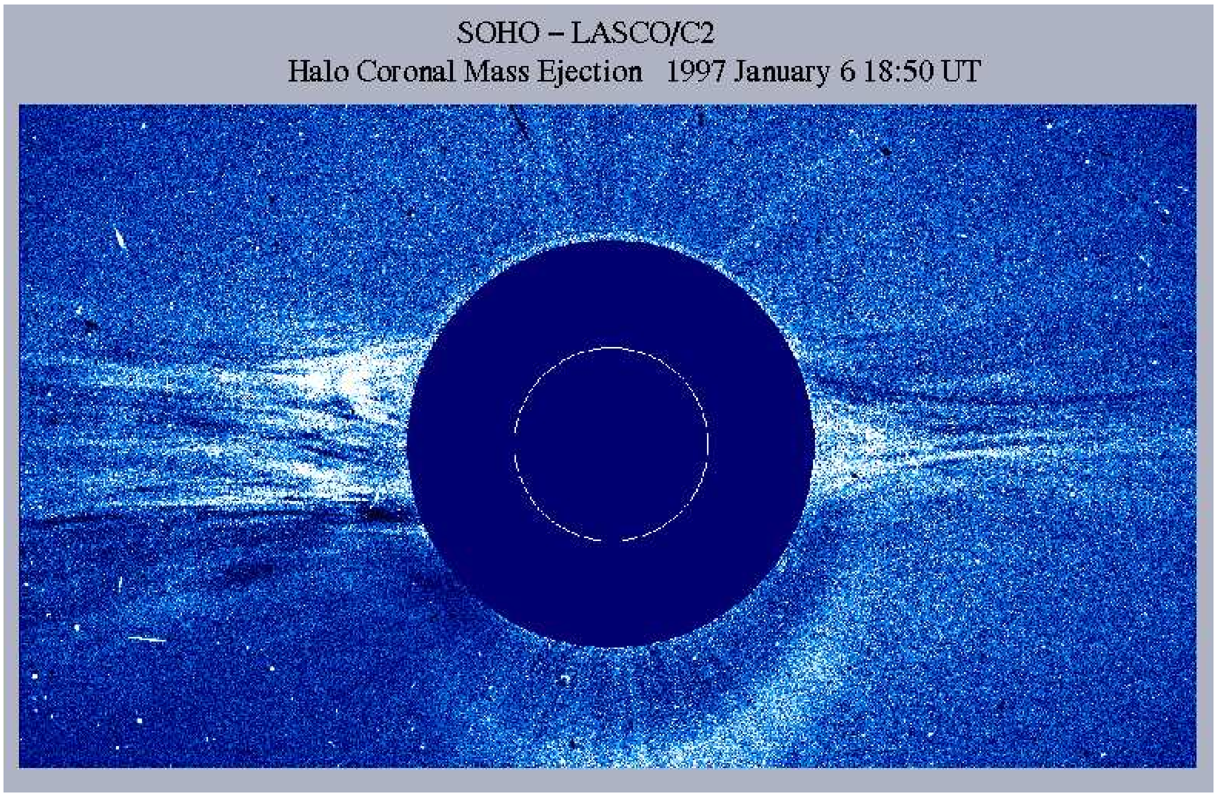

Figure 2. A halo coronal mass ejection as recorded by LASCO on board SOHO on January 6, 1997, at 18:50 UT. This event, seen most clearly in the southern quadrant, resulted in a giant magnetic magnetic cloud that traveled to the Earth and it caused a severe magnetospheric storm. Observations such as these are crucial to the understanding of the magnetic clouds, their origin on the Sun and future predictions of geomagnetic storms, as long as 4 days before their occurrence. [Image courtesy of the SOHO/LASCO consortium.]

planetary medium. Within coronal holes, most of the material comes from relatively cool plumes (DeForest et al., 1997). The plumes resemble blunt pencils that expand rapidly with a few tenths of a solar radius (Rs), and above that continue to expand superradially to fill most of the coronal hole volume within the first several Rs. Plumes originate in photospheric magnetic flux concentrations at chromospheric network boundaries that are typically more complex than other concentrations. The small flux concentrations cover at most a few percent of the solar surface below coronal holes. Figure 1 shows a sample of the SOHO observations of polar plumes recorded near solar minimum in March 1996.

The more commonly experienced lower speed solar wind originates either near the boundaries of coronal holes or, as recently proposed by Woo and Habbal (1997), from small filamentary ray-like structures originating all over the Sun. These ray-like structures have been identified with plumes as well. It may in fact be the case that nearly all of the material in the solar wind comes from plumes.

Plumes have relatively long lifetimes, up to several weeks in the polar regions, but vary on fine scales with periods of a few minutes. This may be due to emergence of mixed polarity flux on the smallest scale interacting with the larger concentrations of flux at the bases of the plumes. It may eventually become possible to identify the sources of plumes from magnetic field observations. If the magnetic field variations near disk center can be linked to the sources of plasma that eventually reach the Earth, a prediction of solar wind conditions may be possible.

2.2. Coronal Mass Ejections

Coronal mass ejections and the magnetic clouds they cause are the source of all major geomagnetic storms. Thus predicting CMEs and the details of the clouds associated with them are crucial elements of space weather forecasting. Coronagraphs are most sensitive to conditions over the limbs of the Sun. Because coronagraphs use a fairly large disk to block out the bright photosphere and innermost corona, events moving directly toward the Earth cannot be seen directly. Because of the increased sensitivity of the LASCO coronagraphs, in some cases as Earth-directed CMEs move outward and expand they become visible as a faint ring or halo around the occulting disk. Figure 2 shows such a feature observed by the LASCO/C2 instrument on SOHO. This halo event was first seen on 6 January 1997 at 17:30 UT. The figure shows the fully developed event as observed by the intermediate coronagraph at 18:50 UT. The outer coronagraph (LASCO/C3) detected the cloud about 3.5 hours later (see http://sohowww.nascom.nasa.gov-/gallery/LASCO/las009.gif). This event and another that took place on 7 April, 1997, have been

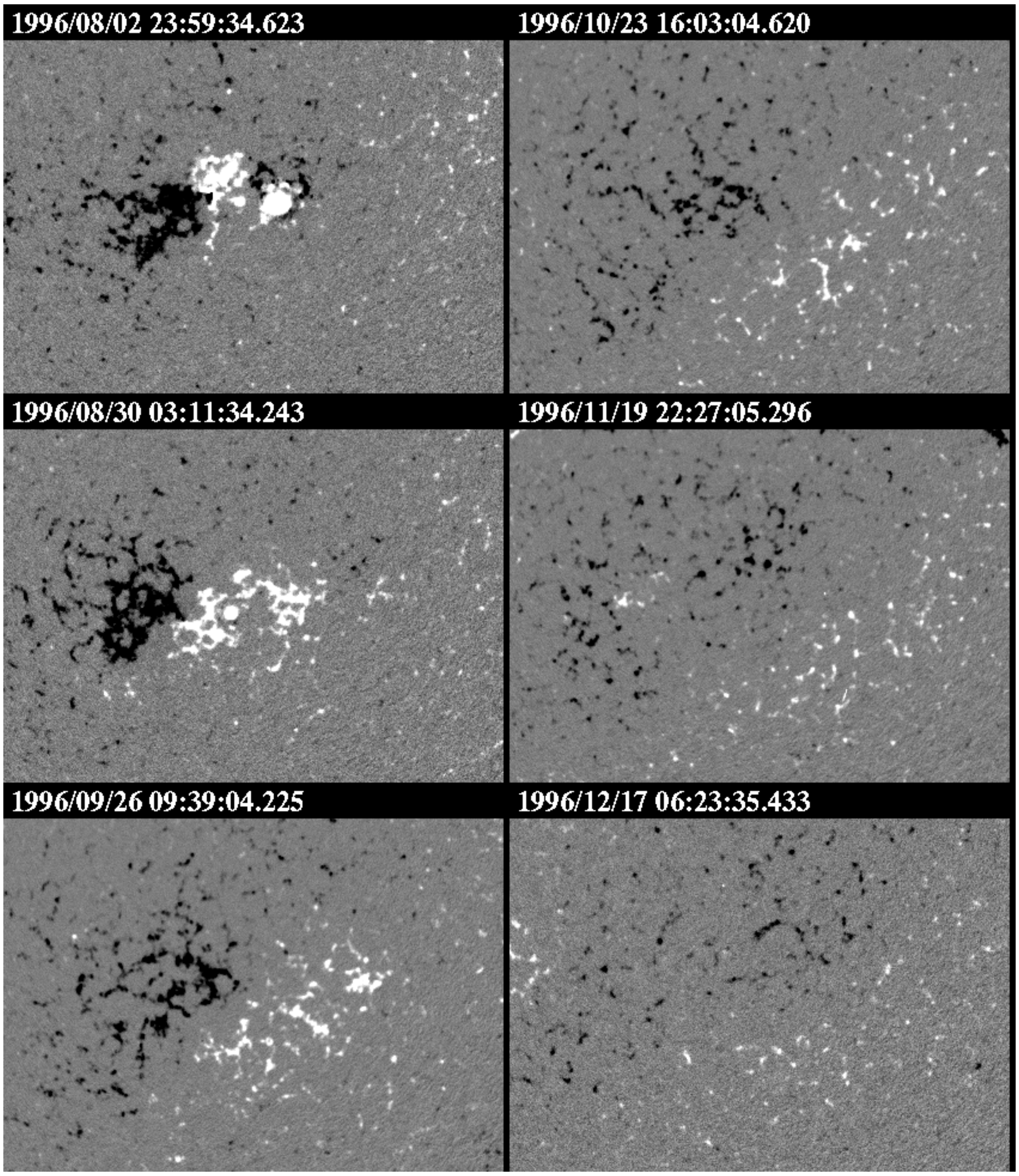

Figure 3. *At solar minimum decaying active regions can last for several months without being disturbed by new flux emergence. The magnetic field that emerged prior to 2 August 1996 gradually diffused in these views of the same region of the Sun near central meridian over 6 solar rotations. A positive polarity (white) sunspot was present only in the first panel. The plot saturates at a relatively small value (50 G) and so emphasizes the pattern of flux concentrations at supergranular boundaries. Outside of the plages associated with the active region, the individual flux concentrations live for only a few days. The polarity pattern evolves slowly and persists for many months. [Image courtesy of the SOHO/MDI consortium and B.T. Thompson.]*

studied in some detail as part of the ISTP program (see http://www-istp.gsfc.nasa.gov); much of this information comes from that site.

Most CMEs are associated with magnetic clouds. The relatively strong magnetic field of the CME forms a bubble. Ahead of the rapidly moving bubble a shock wave develops. Inside the cloud the stronger magnetic field pressure displaces some of the gas resulting in a lower density. At the edges of the cloud the density is higher and can be seen as a faint ring. From the expansion speed of the cloud, the LASCO team estimated that it left the solar surface near 15:50 UT on 6 January. SOHO/CELIAS and WIND observed signs of the cloud at 0.99 AU on 10 January at 04:45 UT and determined a speed of 450 km/second. Assuming a constant velocity, that implies a departure time from the photosphere of 9:00 UT on 6 January. The 4 hour time difference is very small compared to the 92 hour travel time.

Unfortunately (for forecasters) not all Earth-directed CMEs produce geomagnetic storms. In fact, only those that cause extended intervals of intense southward IMF component, or -Bz events, generate geomagnetic storms. Nearly all -Bz events are associated with the effects of CME in interplanetary space, especially magnetic clouds and bidirectional electron events. However, not all CMEs cause -Bz events. Zhao and Hoeksema (1997a,b) have made some progress predicting the characteristics of the subset of magnetic clouds associated with disappearing filaments at the Sun.

The solar filaments and associated clouds display a similar magnetic flux rope structure, i.e., a cylindrical configuration with a strong axial field in the center and weaker and more azimuthal fields away from the center. Furthermore, there is a good correlation between the axial field direction of the magnetic cloud and the filament. From this we infer that the rope's orientation remains basically unchanged while propagating through interplanetary space.

We have gone on to determine that there is a close relationship between the axial field direction in a filament and the duration and intensity of the associated -Bz event. Thus one important factor affecting the occurrence, intensity, and duration of -Bz events is the initial orientation of the rope. This suggests that it is the axial (rather than azimuthal) field direction of the cylindrical rope in the disappearing filament-associated CMEs that determines the characteristics of the -Bz event and that determines whether the CME will be geoeffective.

2.3. Photospheric Magnetic Field Evolution

The large-scale photospheric field determines the coronal and interplanetary field configuration. Models of the coronal field based on such data quite successfully reproduce the observed polarity patterns and field magnitudes observed in the interplanetary medium throughout the solar cycle (e.g. Zhao and Hoeksema, 1995). The photospheric field patterns themselves can be explained, or at least very well modeled, solely in terms of the distribution of flux that emerges in active regions. The active region flux diffuses and is transported by differential rotation and meridional flow (e.g. Sheeley et al., 1985; Sheeley, 1992). Figure 3 shows the evolution of an isolated active region over a 6 month time period. Flux that had emerged by early August 1996 gradually diffuses and is transported to form the large-scale polarity pattern observed in subsequent frames. Using only the flux in the largest 10% of the active regions, the flux transport model has reproduced the reversal of the solar polar fields and the large-scale photospheric field pattern in several 11-year cycles. The emergence of new flux is not explained. Until recently the mechanism for diffusion of the flux was not understood either.

The slowly evolving structure near solar minimum suggests that not much is happening on the Sun. Observations of the fine scale field show this not to be true. Using SOHO/MDI data, Schrijver et al. (1997) show that all of the flux concentrations in the chromospheric network outside of active regions are constantly changing, with essentially 100% of the flux being replaced on a time scale of a few days. The small elements are not simply the result of repeated emergence and submergence of the same flux, but are manifestations of presumably locally generated field that interact on the scale of supergranules. Their relationship to the larger-scale longer-term solar cycle field is not yet clear, but their motions and interactions with active region flux are of the right sort to result in the kind of diffusion coefficients required for the model described above.

Perhaps the most interesting and important consequence of this discovery, however, is that the energy involved in the cancellation of these small flux elements is more than enough to heat the solar corona. This is a big step toward a solution of the long-standing problem of how to heat the solar atmosphere. These small bipolar elements appear to be generated locally and fairly uniformly over the Sun; they have no preferred polarity. The large-scale field pattern results from local imbalance of flux dispersed from active regions. This has far-reaching implications for understanding the structure of the coronal field and the origin of the solar wind.

2.4. Comprehensive Observations

One demonstration of the capabilities of the SOHO project is the Whole Sun Month Campaign (Biesecker et al., 1997; see also http://sohops.gsfc.nasa.gov/whole_sun/). The campaign was organized to study the corona near solar minimum. The SOHO instrument teams and many other spacecraft and ground observatories cooperated to produce a comprehensive set of synoptic measurements during the interval from 10 August - 8 September, 1996. The goal of the campaign was to provide measurements of the magnetic field, velocity, temperature, and density in the photosphere, corona, and solar wind and to compare those observations with models of the conditions throughout the heliosphere.

An unexpected result of the campaign was the discovery of a transequatorial coronal hole reaching from the north pole well into the southern hemisphere during the depths of solar minimum. Effects of the feature were seen in intervals of high speed solar wind at the Ulysses and the WIND spacecraft. There were other times of elevated solar wind velocity during the month that were not associated with observed coronal holes; those intervals may have been related to smaller regions where coronal field models indicate open magnetic flux. The active region in Figure 3 was near the southeastern tip of the coronal hole. This underscores once again the Sun's unexpectedly dynamic and active nature.

In addition to synoptic charts in many wavelengths, detailed observations were made throughout the month. Figure 4 shows the appearance of a loop system rotating onto the visible disk two rotations before whole sun month. The loops evolve rapidly in time and can be followed as they cross the disk. Spectroscopic observations provide insight into the temperature and velocity in such regions. Understanding the changes of such active regions will result in better predictions of solar particle events and perhaps of coronal transients.

It is perhaps interesting to note that we have made a careful analysis of the MDI photospheric field mea-

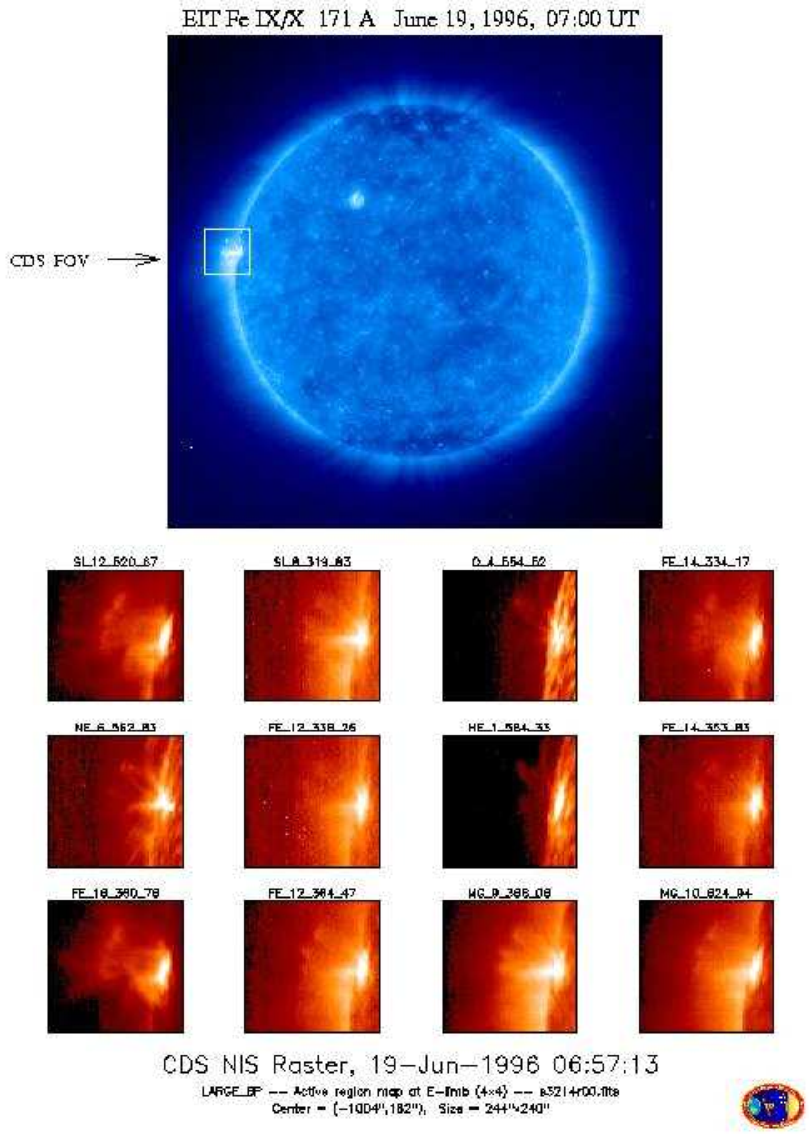

Figure 4. The temperature profile of a loop system rotating over the east limb on June 19, 1996. The upper figure shows the 171 A SOHO-EIT Image at 1.3 million K and indicates the SOHO Coronal Diagnostic Spectrometer field of view. The smaller panels show the intensity at different temperatures, as measured by the normal incidence spectrometer. Each panel shows the intensity determined from the complete spectrum for a particular element, ionization state, and wavelength. For example the upper left panel shows an image in Silicon XII at 520.67 A. [Image courtesy of the SOHO/CDS and SOHO/EIT consortia.]

surements at the time of the January 1997 CME shown in Figure 2. There was no evidence for a sudden localized change in the photospheric field at the time the CME began. At least in this case, the immediate trigger was apparently coronal rather than photospheric, even though the ultimate cause was the evolving configuration in the photosphere.

Comparison with longer time series from Yohkoh and ground-based observations will allow extension of results to other parts of the solar cycle. Observations continue to be made with SOHO and the teams welcome collaborations, both in the analysis of existing data and in the design of new observing programs to investigate particular questions. Much of the SOHO data can be made available quickly for predictive investigations.

3. CONCLUSIONS

Conditions in the solar wind and corona depend on what happens in the photosphere. SOHO observations have revealed a Sun that changes rapidly and completely on the small scale even at solar minimum. This is true both in the photosphere and in the corona. There is real progress toward detailed understanding of the nature of steady coronal heating and solar wind acceleration. It is also becoming possible to detect the launch of Earth-directed coronal mass ejections and to make predictions of how geoeffective those events will be from solar observations. With the reliable and rapid availability of high quality observations of the solar magnetic field from SOHO/MDI and of the corona from SOHO/EIT and SOHO/LASCO and other sources, those wishing to implement AI or other schemes for predicting solar-terrestrial conditions can have timely access to the inputs required.

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REFERENCES

Biesecker, D., D. Alexander, R.C. Altrock, C. DeForest, A. Fludra, B. Forsyth, T. Galvin, S. Gibson, D. Hassler, T.W. Henry, J.T. Hoeksema, C. Korendyke, A. Lazarus, A. Lecinski, R. Lepping, A. Panasyuk, P. Riley, J. Steinberg, L. Strachan, B. Thompson, T. Summanen & A. Szabo 1997, Proc. 5th SOHO Workshop, Published by ESA, Noordwijk, The Netherlands, in press.

DeForest, C.E., J.T. Hoeksema, J.B. Gurman, B.J. Thompson, S.P. Plunkett, R. Howard, R.A. Harrison, & D.M. Hassler 1997, Solar Phys., in press.

Fleck, B., V. Domingo, and A. Poland (eds), 1995, The SOHO Mission, Kluwer Academic Publishers and in Solar Phys., Vol. 162.

Fleck, B. and Z. Svetska (eds.), 1997, The First Results from SOHO, Kluwer Academic Publishers and in Solar Phys., Vols. 170/1 and 175/2.

Schrijver, C.J., A.M. Title , A.A. Van Ballegooijen, H.J. Hagenaar, & R.A. Shine 1997, Astrophys. J. 487, 424.

Sheeley, N.R., Jr., C.R. Devore, & J.P. Boris 1985, Solar Phys. 98, 219.

Sheeley, N.R., Jr. 1992, in The Solar Cycle, A.S.P. Conf. Ser. 27, ed. K. Harvey, 1.

Woo, R. & S.R. Habbal 1997, Geophys. Res. Lett. 24, 1159.

Zhao, X.P., & J.T. Hoeksema 1995, J. Geophy. Res. 100, 19.

Zhao, X.P., & J.T. Hoeksema 1997a Geophys. Res. Lett., in press.

Zhao, X.P., & J.T. Hoeksema 1997b, J Geophys. Res., in press.