2001 Senior Review proposal for *TRACE*
N.B. Science section onlyl

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Contents

1 Insights from *TRACE* data

The dynamics of the magnetic field in the solar atmosphere, and the associated non-radiative energy transport from the interior of the Sun into its tenuous outer layers, are important fields of study because

1. they are the only examples of fundamental magnetohydrodynamic prosesses that occur in the universe that we can observe in detail in a truly astrophysical environment, and

2. they are responsible for space weather and are therefore of direct societal significance.

Detailed observations of the processes in the solar outer atmosphere are essential to advancing our understanding, because the detailed modeling of the physics of the Sun is far beyond current numerical capabilities. To make significant progress, we need observations with high angular, temporal, and thermal resolution. The *Transition Region and Coronal Explorer, TRACE*, is uniquely suited among existing and near-future solar observatories to meet these requirements.

The primary objective of the Small Explorer mission *TRACE*, as stated in the "Phase III & IV proposal" (August 1994) is "to explore both morphologically and quantitatively the connections between fine-scale magnetic fields and the associated plasma structures." To do this, the *TRACE* investigation was designed to focus on the study of the 3-d field structure, its temporal evolution in response to photospheric flows, the time-dependent fine structure and thermal topology of the corona and transition region.

TRACE has been addressing these problems since its launch on 2 April 1998 by obtaining sequences of coaligned images (totaling close to 6 million to date) of photosphere, transition region, and corona (see Table 1 for the wavelengths observed), with an angular resolution of 1.25 arcsec FWHM (Golub et al., 1999), and uninterrupted viewing of a field of view spanning $0.53\,R_\odot$ for over eight months of the year. The instrument characteristics have been described in detail by Handy et al. (1999).

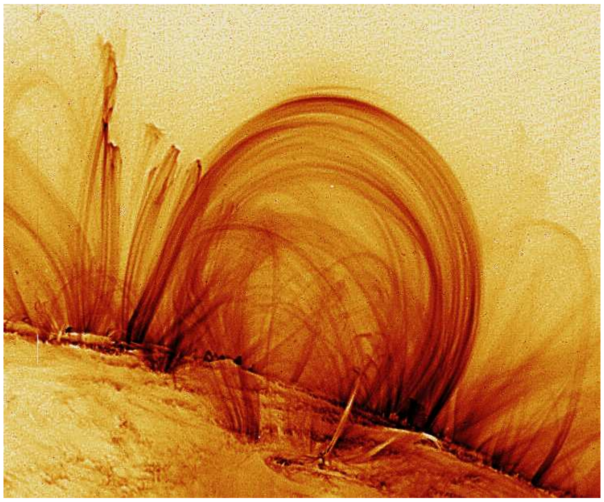

Figure 1: TRACE*'s high-resolution images allow the estimation of, e.g., loop cross section, measurements of loop deformations, and determination of density stratification if the temperatures fall within the range of the EUV passbands. This negative (otherwise unprocessed) of a* TRACE *171 Å image (1 MK), taken on 6 November 1999 over the eastern limb, shows the multitude of high coronal loops over an active region.*

Among the biggest surprises produced by the *TRACE* science investigation is the general lack of braids and twists in the coronal field (except around filaments), even though *TRACE* now observes it with a resolution close to the scale of the granulation that drives the coronal field. Moreover, *TRACE* is uniquely suited to observe the 1-1.5 MK loops that form between distant active regions within hours of a new emergence. Based on these and other findings, it turns out that magnetic reconnection in the quiescent corona is much faster and more common than assumed before *TRACE*.

Prior to *TRACE*, the prevailing view of the solar corona was that it was a magnetically-dominated environment, primarily made up of slowly evolving loop atmospheres, heated rather uniformly and persistently to a narrow temperature range, in which rapid changes occur only by field emergence, flares, and filament eruptions. *TRACE* has shattered that traditional

Table 1: *TRACE* spectral regions and characteristic exposure times

Central wavelength	Ion	Region of solar atmosphere	log(T)	T range (FW at 2%)	Characteristic exposure time (s)		
					Quiet Sun	AR	Flare
2500Å	Cont.	Photosphere	3.7	3.6-3.8	0.003	0.003	0.003
1700Å	Cont.	$T_{\rm min}$/Chrom.	3.8	3.6-4.0	5	3	1-3
1600Å	CI,FeII,cont	$T_{\rm min}$/Chrom.	3.8	3.6-4.0	1	1	0.01-0.1
1550Å	CIV	Trans. region	5.1	4.8-5.4	15	10	1-5
1216Å	H Ly α	Chromosphere	4.2	4.0-4.5	3-30[1]	3-30[1]	1-2[1]
284Å	Fe XV	Corona	6.3	6.0-6.7	60	30	1-10
195Å	Fe XII	Corona	6.1	5.0-6.4	20	30	1-10
171Å	Fe IX/X	Corona	5.9	5.3-6.3	20	30	1-10

1 The two values are for on-disk and off-limb observations, respectively. Off-limb exposure times are longer, because there is no significant continuum contribution there.

view of the quiescent corona: both the outer-atmospheric heating and the evolution of the magnetic field are much more dynamic than previously thought. In addition, *TRACE* is contributing significantly to our understanding of impulsive and eruptive processes, and also uncovered the phenomenon of coronal loop oscillations. The most important discoveries are outlined in Table 2, which also lists key references (not repeated in the text); some of these findings are discussed in more detail in the remainder of this section.

1.1 Thermal structure and coronal heating

TRACE shows us a corona comprised of thin loops that continually change in shape, and that are filled with atmospheres that are intrinsically dynamic. The corona over both quiet and active regions comprises loops with a range of temperatures in close proximity to each other, even in non-flaring conditions; based on the appearance of the images, we estimate that the volume filling factor for a given temperature range peaks around 1.5-2 $\times 10^6$ K for the quiet corona and around 3-5$\times 10^6$ K over active regions, as expected, but in each domain the range of temperature is wider than appreciated before.

The corona consists of thin strands, with widths that are often at, but also frequently above the resolution of *TRACE*. Yet there is no measurable expansion with height in these images (more than 25 times sharper than those of *YOHKOH/SXT* for which this result was first obtained), even though sets of neighboring loops diverge with height. There is no explanation for this phenomenon.

Many coronal loops appear to be heated for only minutes to tens of minutes, after which the heating changes significantly in magnitude, or ceases altogether. The multiple passbands of *TRACE* allow us to conclude that cooling occurs as fast as radiation and conduction allow (see the example in Fig. 3, from Schrijver, 2001). It appears that active-region loops experience such dramatic cooling on average once every few days. Such dramatic events, and the many much more gradual events that are also observed, probably contribute significantly to the ubiquitously observed transition-region redshifts (although the velocities of $\sim 40-80$ km/s measured with *TRACE* are significantly larger than the typical redshift of no more than 10 km/s).

Emission profiles as a function of height above

Table 2: The solar corona seen by *TRACE*: a selection of key findings

Finding	Select reference(s)
Loops of significantly different temperatures exist side by side, probably because heating is variable and sensitive to the details of the coronal field.	Schrijver et al. (1999)
Many, if not all, coronal loops are incompatible with the traditional quasi-steady, uniformly-heated loop (Rosner-Tucker-Vaiana model).	Lenz et al. (1999), Aschwanden et al. (2001)
Loop cross sections lie near the instrumental resolution, without significant expansion with height, even for those loops that are significantly wider than the instrumental resolution.	Watko and Klimchuk (2000), Klimchuk (2000)
Relatively cool 1-2 MK loops tend to arch over the hotter 3-5 MK loops within active regions, suggesting a hot core and cooler shell in quiescent phases.	Schrijver et al. (1999)
Coronal heating occurs predominantly low in coronal loops, with a scale height of 10-20 Mm.	Aschwanden et al. (2000, 2001)
Coronal heating in active-region coronae frequently drops by more than an order of magnitude for up to an hour or more, leading to coronal rain and bright loop-top sources.	Schrijver (2001)
Twists and braids in the corona rarely exceed one half turn, even on the scale of the granulation that should drive such braiding. Long-range reconnections between active-region field occur within hours of emergence. Both findings suggest unexpectedly efficient reconnection.	Schrijver et al. (1999)
The downward conducted energy from the corona seen in the transition-region moss is not spatially correlated with chromospheric emission on small length scales, perhaps reflecting distinct heating mechanisms, or strong sensitivity to local conditions.	De Pontieu et al. (1999)
Transverse coronal loop oscillations, first discovered by *TRACE*, open the field of coronal seismology. Their damping is unexpectedly rapid; apparently, we do not understand the coronal environment, the dissipative coupling to the lower, denser chromosphere, or the means to amplify small surface effects in the corona.	Nakariakov et al. (1999), Wills-Davey and Thompson (1999), Schrijver and Brown (2000), De Pontieu et al. (2001)
Hot plasma above post-flare EUV arcades appears diffuse as a consequence of its multi-temperature nature rather than that the source itself is diffuse.	Warren (2000)
Cool material in filaments is extremely dynamic, commonly accelerated and decellerated, exhibiting counterstreaming on nearby field lines.	Schrijver et al. (1999)
The energy spectrum of small-scale brightenings was extended with *TRACE* observations to 10^{24} ergs, a factor 10 below the earlier *SOHO/EIT* result. It remains uncertain whether the extrapolated distribution of these small brightenings contains enough energy to explain quiescent coronal heating.	Parnell and Jupp (2000), Aschwanden et al. (2000)
Canceling flux most likely retracts into the solar interior.	Harvey et al. (1999)
Fast flows (up to several hundred km/s) and wave-like phenomena occur commonly over magnetic plages and in association with spots and filaments.	Ireland et al. (1999), De Moortel et al. (2000), Shine (2000)
Coronal mass ejections are often associated with significant amounts of material that falls back to the surface. In fact, many filament destabilizations lead to confined eruptions in which material is thrown upward up to some 100 Mm, only to fall back after the field restructuring ceases.	

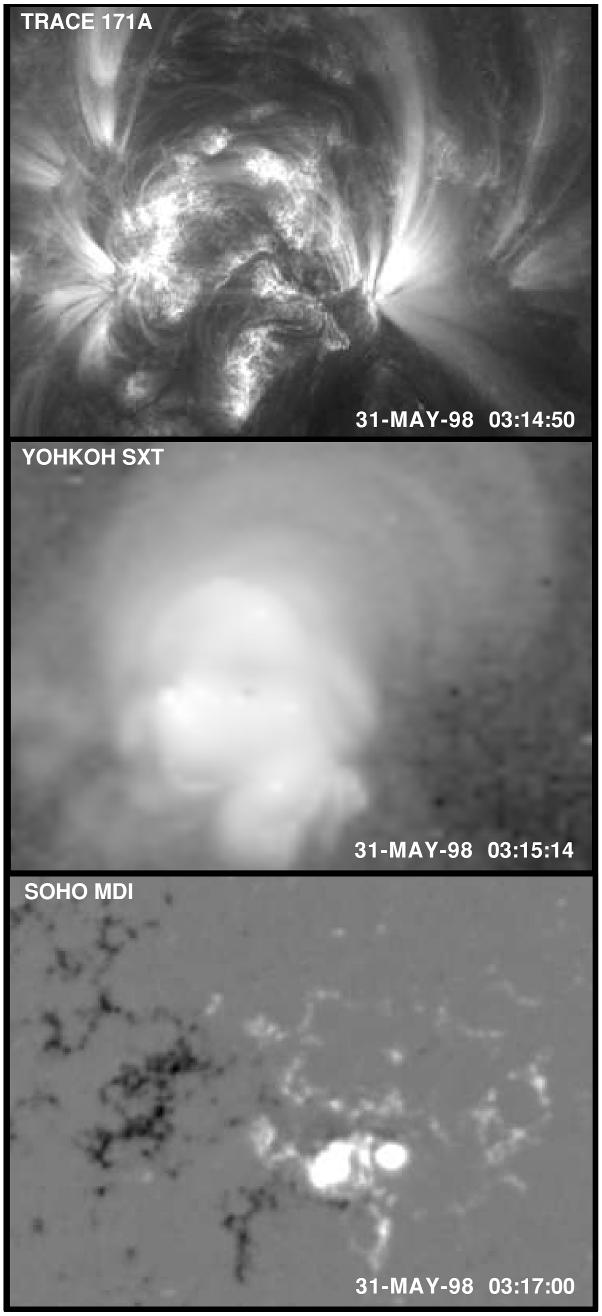

Figure 2: *The 1 MK active-region corona seen by* TRACE *(top panel) is dominated by high-arching, cool loops and the low-lying "moss." The moss corresponds to the top of the transition region, over which* YOHKOH*'s* SXT *observes - at much lower resolution - the 3-5 MK coronal emission (central panel). The bottom panel shows the corresponding* SOHO/MDI *magnetogram.*

the limb in the *TRACE* 171 Å and 195 Å passbands demonstrate that most, if not all, loops that are visible in those passbands do not agree with the standard model for the quasi-stationary, uniformly-heated loop that was introduced by Rosner et al. (1978). Those loops that are compatible with a quasi-stationary stratification require that the heating occur primarily in the first 10 to 20 Mm of the coronal segments of the field lines (many loops in the sample that was studied may be rapidly evolving loops, including post-flare loops, which require a dynamic model to explain their structure). Upward moving pulses of hot material observed in cool loops suggest that the low–altitude heating is in fact strongly modulated on time scales of minutes or less.

Coronal images are particularly crisp when the thermal passband is narrow, and even more so when the formation temperature of the line observed is relatively far from the peak in the emission-measure distribution. Hence, in active regions, loops with temperatures near 1-1.5 million Kelvin stand out in relative isolation (cf. Fig. 1). One particularly conspicuous trend that was discovered by *TRACE* is that the coronal loops over active regions tend to be cooler than lower-lying ones, resulting in a hot coronal core embedded in a cooler outer shell (Fig. 2).

TRACE observations often show EUV-bright loops shifting through the corona. Two mechanisms contribute to that. First, there is often a strongly amplified response of coronal loops to displacements of photospheric magnetic charges. This is particularly the case for loops near separatrix surfaces: as the photospheric field evolves, coronal loops are seen to shift along what may well be separator surfaces, sometimes in opposite directions in close proximity, as expected from models (e.g., Priest and Schrijver, 1999).

Second, the shifting of coronal loops is compatible with significant modulation of the heating whenever there is a relatively smooth shift of the location of the heating over periods of at least some tens of minutes. Such an evolutionary pattern is compatible with braiding–induced current heating, but that interpretation

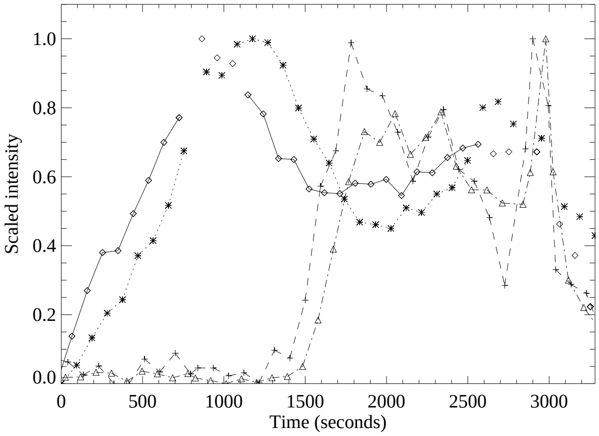

Figure 3: *Sequences of* TRACE *images, cycling from one wavelength to another, allow the study of, e.g., the thermal evolution of loop plasma. This diagram shows an example of a loop cooling event: the light curves for 195 Å (◇; 1.5 MK), 171 Å (∗; 1 MK), C*IV *1550 Å (+; 0.1 MK), and chromospheric Lyman α (△).*

needs further observational confirmation.

The currents responsible for heating would presumably form primarily at interfaces between fields from neighboring flux tubes. That the bright patches in the EUV–bright transition region (the so–called moss) are uncorrelated with the locations of the photospheric flux concentrations supports this notion. These currents are, moreover, expected to be more intense in regions of high field strengths, i.e., low in the outer atmosphere, which may explain the relatively low heating scale height.

The EUV observations by *TRACE* reveal not only material at coronal temperatures moving upward from as low as a few thousand kilometers above the photosphere. *TRACE* also sees cool material in jet-like spicules and mottles, no hotter than about 20,000 K, both in the quiet Sun and in the active-region moss (where earlier ground-based observations had not revealed their existence). New spicule models are being developed to reflect this finding. Understanding the details of these processes leading to these injections of hot and cold plasma into the outer atmosphere may well be key to solving the riddle of coronal heating; how little we know of these processes is reflected by the fact that we cannot at present construct a consistent cartoon that shows spicules and mottles, chromospheric brightenings, and channels of thermal energy that are conducted down from the corona in a proper relationship to the magnetic field configuration.

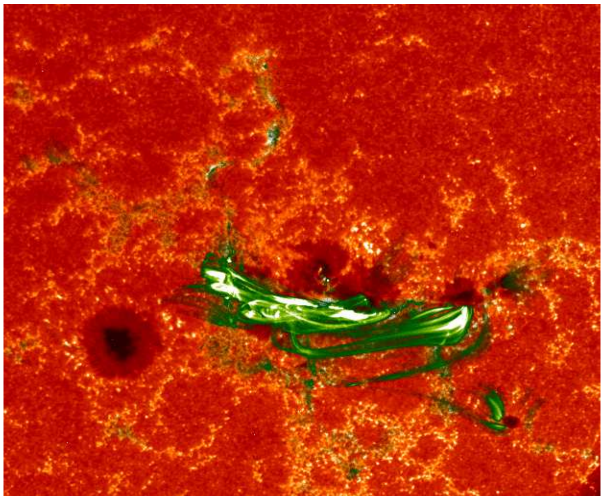

Figure 4: *The use of multiple wavelengths allows comparison of the coronal loops with the (near-)photospheric boundary conditions, as in this example: a composite image of an X-class flare on 6 June 2000. In red, it shows the ultraviolet continuum (1600 Å passband), which shows the small-scale magnetic fields at the surface as yellow/orange dots; a white-light image was blended in to show the location of the sunspots. The green-white overlay is the 171 Å image, showing the location of the bright coronal loops cooling after the initial flaring phase. The UV channels can be used for accurate alignment with, e.g., magnetograms.*

Combination of *TRACE* with chromospheric and photospheric magnetograms demonstrated that at least in the quiet Sun most canceling flux appears to be retracted back into the convective envelope rather than escape into space. This has important consequences for the global and any local dynamo action, and needs further study and extension to active-region environments.

1.2 Explosive and eruptive events

TRACE images UV ribbons in most large flares (e.g., Fig. 5), reflecting the impact sites of non-thermal particles. It also provides high-resolution images of the pre-flare magnetic configuration and, by studying loop cooling down to chromospheric temperatures (e.g., Fig. 6), the post-flare configurations (compare Fig. 4). The complexity of the events delay publication of the interpretations, but as the flare sample and observer experience build up, new trends are being recognized. For example, often very compact flare kernels are imaged, while the brightening of sometimes distant ribbons suggests that fast particles or magnetic shocks are involved.

The ability of *TRACE* to observe the Sun over a very broad range of temperatures (10,000 K - 20 MK) with high spatial resolution and at high cadence make it a unique instrument for observing solar flares. *TRACE* is sensitive to high temperature flare plasma because of the presence of the Fe XXIV 192 Å line in the 195 Å bandpass, in addition to Fe XII 195 Å. Thus *TRACE* can observe the buildup of magnetic energy in the corona, the response of the chromosphere and transition region to energy deposition from magnetic reconnection, as well as the hot, high density plasma that is such a prominent feature of the flare. In its first three years of operation *TRACE* has made substantial new discoveries in many areas of flare research.

One of the central questions in astrophysics is how magnetic energy is built up and released in solar flares. It is widely believed that the random motions of field line footpoints, which are driven by photospheric flows, lead to the formation of highly stressed magnetic field configurations. But what triggers the relaxation of the field? Antiochos et al. (1999) have proposed that the overlying magnetic fields play a central role in this process by constraining the highly sheared fields. When the overlying fields are weakened, the highly sheared field below it can relax. *TRACE* observations of the July 14, 1999 M3 flare have provided the first evidence in support of this framework. In this event the magnetic field, determined from a potential field extrapolation, shows a null point in the corona above the delta spot (Aulanier et al., 2000). The *TRACE* EUV images show clear evidence for reconnection associated with the null point just prior to the main phase of the flare.

Understanding the temperature structure of flares is another key problem in solar physics. *YOHKOH* observations suggested that some regions in a flare have elevated electron temperatures relative to the bulk of the flare plasma. These hot regions have been interpreted as a signature of the slow mode shock which is expected to form in front of the reconnection region. Because of potential inconsistencies between *SXT* and spectrally resolved observations as well as between *SXT* and hard X-ray images, this result has been questioned. *TRACE* observations, however, have demonstrated the existence of the regions. Comparisons between *TRACE* and *SXT* observations of a limb flare have shown that the bulk of the flare plasma is at about 10 MK while the hotter thermal flare plasma is confined to a region above the brightest flare loops (Warren et al., 1999). *TRACE* observations of a very compact X-class flare have provided direct evidence for a highly localized region where the electron temperatures are as high as 20 MK (Warren and Reeves, 2001). Furthermore, the *TRACE* observations show an enrichment of Fe in this region, consistent with in situ heating of coronal material.

TRACE observations emphasize a remarkable property of the solar corona in which nearby regions can appear to be largely decoupled while in contrast distant regions may be closely linked: regions up to several hundred thousand kilometers away frequently respond (often within the same exposure) to flares or eruptions, while at other times loops nearby a substantial explosive event appear unaffected.

The high sensitivity of *TRACE* has allowed the extension of the short-term variability (microflaring) spectrum from active regions to very quiet Sun at a level of 10^{24} ergs. The sensitivity of the results reported on by various research groups to assumptions about the geometry of

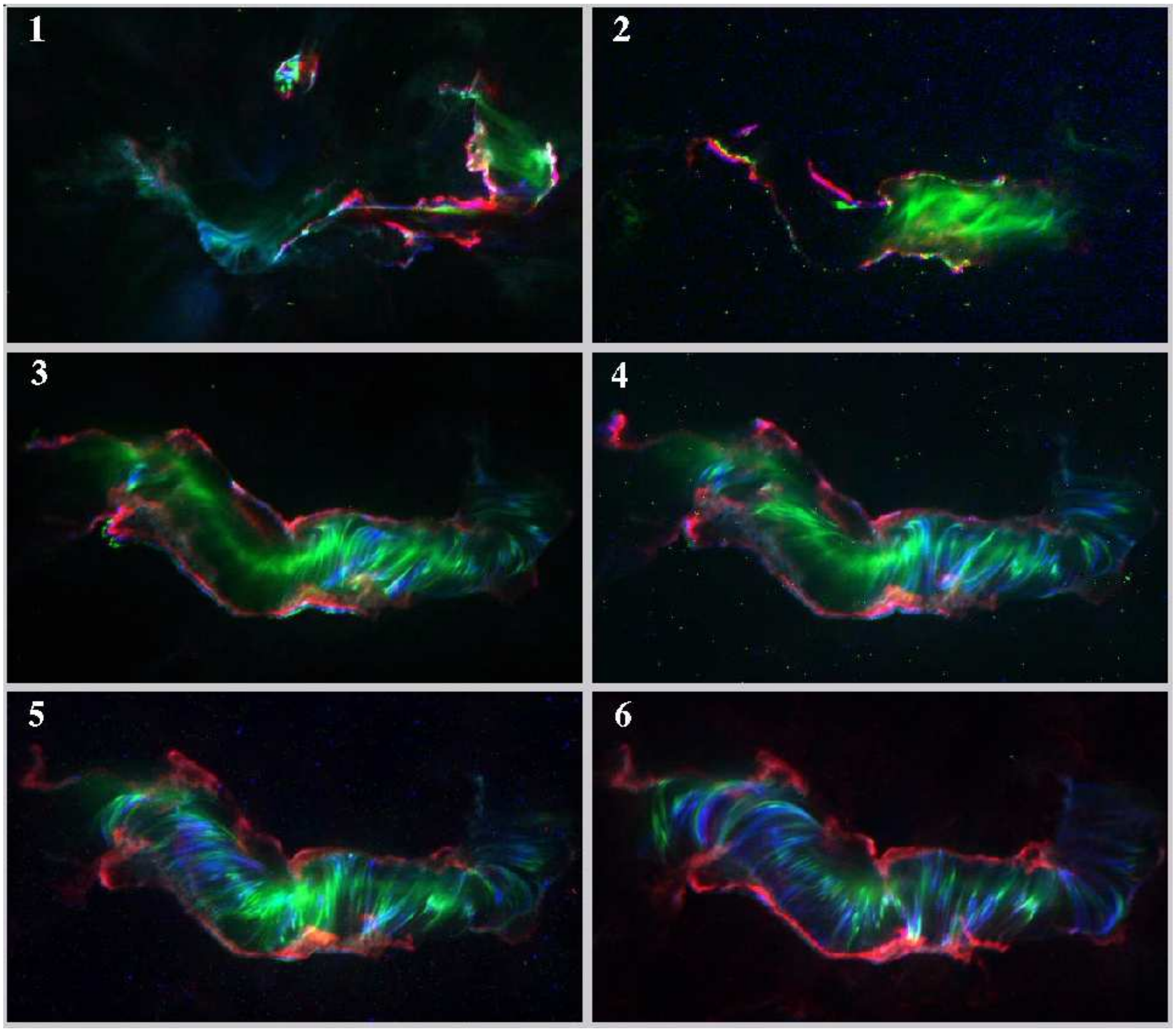

Figure 5: *High-cadence EUV imaging during flares can be alternated with lower-cadence UV images, allowing for example the study of flare ribbons and flaring and post-flare arcades. This set of composite images shows a very large flare that occurred on 14 July 2000. The red channel shows the ultraviolet continuum (1600 Å); the blue image shows the 171 Å pass band (1 MK); the green channel (195 Å) shows material hotter than about 1.5 million degrees up to approximately 10 million degrees. Frame 1, right after the onset of the flare, shows very bright, rapidly evolving kernels in the flare ribbons. Frame 2, taken 22 minutes later, shows a phase in which the ribbons have developed to their full extent, and loops connecting them are showing up on the right-hand side of the arcade. Frame 3 shows a bright ridge of presumably very hot material between the ribbons. Frame 4 shows 2 MK (green) loops forming on the left-hand side, that cool to 1 MK (blue) in frames 5 and 6.*

the brightenings and about the temperatures involved results in uncertainties that still leave it uncertain whether an extrapolated microflare spectrum to very small energies can explain all of the quiescent coronal heating.

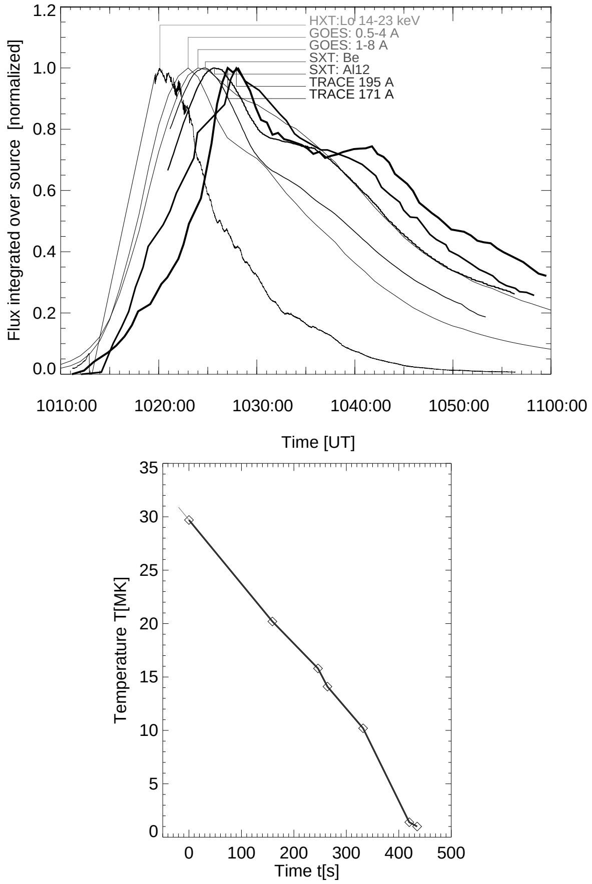

Figure 6: TRACE *complements flare observations by other instruments, not only offering high-resolution imaging, but also allowing light-curve timing analyses of, e.g., flare-loop cooling. Top: Light curves of the flare on 14 July 2000, observed - in order of spectral hardness or characteristic temperature - YOHKOH/HXT, 2 GOES channels, 2 YOHKOH/SXT filters, and 2* TRACE *filters. Bottom: The estimated characteristic temperature of the emission at peak brightness as a function of time.*

2 Filaments

Filament/prominence configurations are dynamic and unstable: *TRACE* has observed evolving twists in the filament field, and many filament destabilizations and eruptions, including coronal mass ejections. Among the many surprises we find the following:

Filaments are more transparent to the EUV radiation than to, for example, Hα. As a result, what appears as an almost solid wall of cool gas in ground-based observations, reveals separated, thin strands of continually moving cool gas that shows up in extinction against any brighter EUV-emitting background. The material appears to slosh back and forth on the nearly horizontal field. The filament barbs are particularly puzzling, exhibiting what sometimes looks like whirling motions when seen from the side. The long-term continuity of *TRACE* observations also reveals interesting details of how small filaments and fibrils align to form fila-

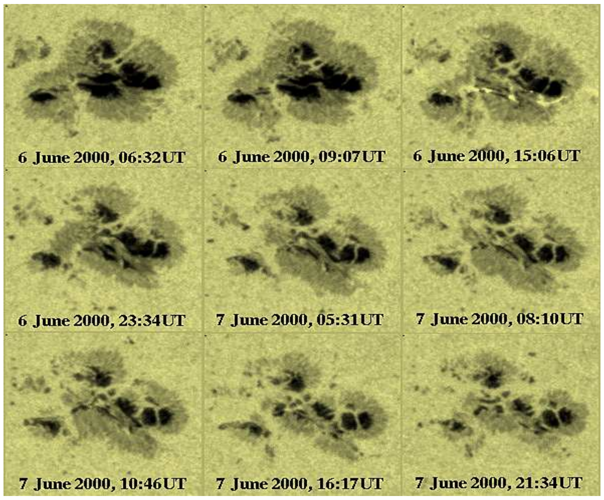

Figure 7: *Continuous observing not only has advantages for the study of coronal evolution, but also allows the study of phenomena in the photosphere that can only be observed with great difficulte and a lot of fortuitous weather conditions over a series of observatories. For example, this composite of nine white-light images taken by* TRACE *of the central spot complex that produced three X-class flares on 6 and 7 June 2000. The spot, in which two polarities are combined, evolves so that the lower-central umbral region (the darkest part of the spot) contracts, resulting in a flare (visible even in white-light as a faint whisp in the upper right panel). The umbrae open again briefly, then to disappear altogether. Once that process is completed, the spot evolves rapidly into a decaying cluster of small spots and pores.*

ments stretching over hundreds of thousands of kilometers.

Filament configurations often show fleeting brightenings in the 1 MK passband of *TRACE*. These brightenings temporarily envelop the cooler material. Interestingly, such ephemeral EUV-bright veils sometimes show up in regions where there is no filament visible in $H\alpha$; apparently, the filament field configuration can exist without appreciable cool material filling it.

TRACE has observed many examples of the initial filament destabilizations (examples are shown in the *TRACE* DVD to be included in the 200th volume of Solar Physics in the summer of 2001), and the subsequent eruptions: matter is seen to be thrown up with velocities of up to some 500 km/s, much of it sliding back to the surface. Sometimes trains of shock waves are seen propagating perpendicular to the magnetic field as the eruption progresses.

2.1 Coronal seismology

The high cadence and resolution of *TRACE* have allowed the discovery of transverse coronal-loop oscillations in response to (sometimes distant) filament eruptions and flares. The fact that loop oscillations are rare (we are now aware of six well-observed examples), and that they damp very quickly (within 3-4 oscillations), requires an unexpectedly high energy dissipation. Competing models argue whether that happens in the corona (which would mean our estimates of viscosity or resistivity are up to a factor of 10^9 off the mark) or in the chromosphere (in which case resonance-based wave-heating models could almost surely be ruled out), or whether photospheric motions are being amplified by a sensitive dependence to the details of the configuration.

Whatever the correct interpretation is, these oscillations, and coronal blast waves previously detected by *SOHO/EIT*, have taught us that we do not at all understand the solar outer atmosphere at a very fundamental level. Coronal seismology promises a significant breakthrough in the near future.

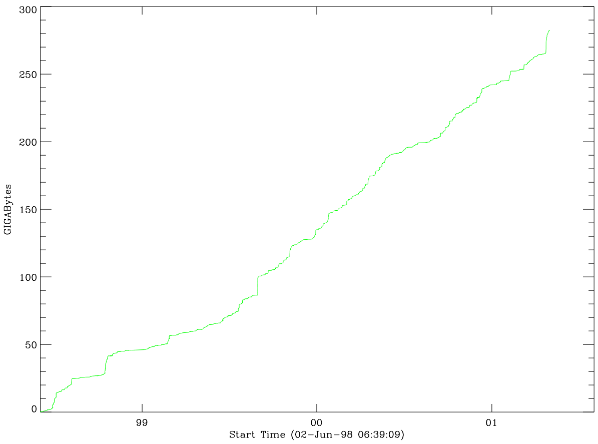

Figure 8: *Cumulative number of Gigabytes transferred from* TRACE*'s primary data archive at Lockheed Martin since the start of normal operations. A fairly steady stream of data has been delivered from the archive the past two years at an average level of* ~ 300 *MB/day.*

3 Data archiving and access

The *TRACE* project has had a completely open data policy from the very first day of observations: there are **NO** restrictions on the use of *TRACE* data. As soon as the spacecraft telemetry has been reformatted and archived, the data are accessible - normally well within 12 hours of observing. In order to allow faster access to the large amounts of data, the archive files are mirrored to Goddard Space Flight Center, and further transferred electronically or by tape to mirror archives at Rutherford-Appleton Laboratories in the U.K., the Kiepenheuer Institute in Germany, ISAS in Japan, and Meudon in France.

The primary *TRACE* archive at Lockheed Martin is frequently accessed via the internet; a total of $\sim 2.9 \times 10^{11}$ bytes in 310,000 images has been transferred (cf. Fig. 8). The average rate of data requested has remained steady over the past 1.5 years, having doubled from the usage in the first year following a successful *TRACE* science conference in August 1999. The archive site at GSFC shows similar trends at approximately 1/4 the Lockheed Martin level.

TRACE analysis software is available on the web, embedded within the widely used and openly available SolarSoft package of IDL routines, as well as a special (much faster) image-viewing package called BROWSER. Descriptions of how to use these packages, and where they can be retrieved, are given in an on-line, up-to-date *TRACE* Analysis Guide (at http://www.lmsal.-com/ bentley/guides/tag/tag_top.html).

4 Collaborations

The *TRACE* project closely coordinates with other observatories, both in space and on the ground. The coordination with SOHO is given particular emphasis, with a *TRACE* representative present at the various planning meetings. Of the 30 Joint Observing Programs run by SOHO in 2000, 23 (77%) included *TRACE*. Particular efforts are made to coordinate during campaigns of continuous contact for *SOHO/-MDI* (both in full-disk and in high-resolution mode), campaigns involving *SOHO/SUMER* and *CDS*, or when observing as a complementary instrument to *SOHO/EIT*. We have, moreover, coordinated with *YOHKOH/SXT*, continue to coordinate with Max Millenium campaigns, and have defined a JOP for close coordination with the High Energy Solar Spectroscopic Imager, *HESSI*, after its launch later this year.

TRACE coordinates with the Very Large Array in the radio/microwave domain, with the microwave observatory in Nobeyama, with coronographic observations from Norikura, with vector-magnetographs at Sacramento Peak and on Hawaii, with solar observatories on La Palma (Swedish and Dutch Telescopes) and Tenerife (Themis and the German telescopes), with the NSO telescopes at Sacramento Peak and Kitt Peak (including chromospheric magnetographic studies), and with observatories at Big Bear Solar and Meudon.

Special efforts to coordinate are made whenever unique observing opportunities occur, including a Mercury disk passage, rocket flights (*SPARTAN, VAULT, SERTS, Celias* and other calibration rockets, *TXI*), the *Galileo* passage behind the Sun, Whole Sun Month observing campaigns, the Antarctic balloon flight of the Flare Genesis program, Interplanetary Scintillation campaigns (with Ooty (India), Toyokawa (Japan), Merlin (UK), and Eiscat (Scandinavia) observatories), eclipse observations, major flare alerts (as announced in the Max Millenium program), and *Ulysses* at quadrature.

5 *TRACE* scientific effectiveness

The solar-physics community has embraced *TRACE* as a key observatory. The efficient implementation of a freely accessible data archive, and flexible, responsive planning by the team operating the science instrument, has resulted in broad community interest in *TRACE* data. As a result, there are now (1 May 2001) 148 papers or books already published in the scientific literature that are based entirely or in part on *TRACE* data. At least another 39 publications are in press (Fig. reffig:pubstats shows rate of publications per year) . A total of 242 different authors contributed to these publications (compare the membership of 570 of the AAS Solar Physics Division in 2000), from 80 institutions in 22 countries. This broad interest has led the publishers of Solar Physics to include for the first time a DVD entirely devoted to *TRACE* observations, in addition to a substantial segment on the CD-ROM that will be included in the same volume (scheduled for the March issue, to appear in the summer of 2001).

Some of *TRACE*'s discoveries are so fundamental they are even used for national press releases by NASA. NASA, moreover, has listed *TRACE* discoveries among its top-10 stories in 1998 and in 2000.

6 Public outreach

The spectacular images and movies of the *TRACE* project have found their way to tens of millions of people around the world. The broadest audiences were reached during two national NASA press conferences; one of these is estimated to have reached over 35 million people in the US

Figure 9: *A collage of some of the* TRACE*-related coverage in the printed and electronic media, which includes the Washington Post, New York Times, Time, and CNN.*

either during prime time newscasts or in printed media.

The *TRACE* images are found in many publications around the world (Fig. 9), including graduate-level textbooks, an encyclopedia, popular science journals (including Science, Scientific American, Popular Science, Sky and Telescope, and National Geographic), newspapers (including the Washington Post and New York Times) and news magazines (including several cover images and a two-page spread in the year-2000 overview of LIFE Magazine). A partial listing of *TRACE* in the media resides at http://vestige.lmsal.com/TRACE/Science/ScientificResults/ (Fig. 9). The most interesting images are regularly posted on the web (at http://vestige.lmsal.com/TRACE/POD/TRACEpod.html), where they are regularly found by the media. *TRACE* images, and the science of the Sun in general, were given attention in two cover stories of Sky and Telescope, with a readership of over 200,000. Five thousand educational CD-ROMs (contents accessible at http://vestige.lmsal.com/TRACE/Science/ScientificResults/trace_cdrom/) and fifty thousand posters have been distributed at meetings, in science musea and planetaria, and to interested teachers at high schools. A multipanel movie of the rotating Sun at the full resolution of *TRACE* features as one of the eye catchers in the newly released IMAX movie "Solar Max," while other sequences have been shown in PBS and other educational specials about the

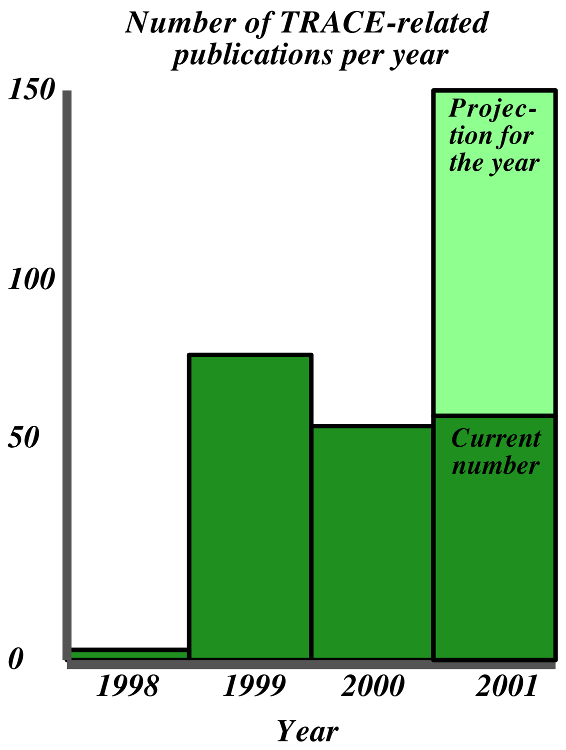

Figure 10: *Number of scientific publications per year (and projected value for the current year), from http://vestige.lmsal.com/TRACE/-Science/ScientificResults/tracepubs.html*

Sun, including "Live from the Sun" and "Solar Blast." Television programs with *TRACE* data have been produced at least in the USA, UK, Australia, and Japan. We have recently produced 5,000 DVDs with *TRACE* movies, to be distributed to our colleagues and the general audience.

The *TRACE* web server at Lockheed Martin logs a steady stream of, on average, 500 visitors, requesting 10,000 web pages, each day. In days following a major press release, the number of visitors reached over 8,000, requesting over 300,000 files (see also Fig. 8).

7 The role of *TRACE* in the long term health of solar physics

One of the main challenges in Solar Physics for the present decade is to develop a comprehensive understanding of, and numerical model for, the generation and ejection of magnetic fields by the Sun; from their formation in the overshoot layer, their rise through the convection zone and emergence through the photosphere, to their evolution and destabilization in the corona, and their transport through the heliosphere up to their impact on the Earth's magnetosphere. Such a comprehensive understanding and numerical model is a necessary prerequisite for a physics-based predictive capability of space weather.

This requires coordinated multi-wavelength observations to study the evolution and eruption of magnetic fields in and above the photosphere in full detail. *TRACE* currently provides an EUV microscopic view of the upper transition region and cooler parts of the corona, and will remain the only mission to do so for the next six years. In an ongoing collaboration with Yohkoh (soft and hard X-rays), SOHO (magnetograms, coronagraph images, UV and EUV spectroscopy, EUV full disk context), and soon HESSI (high resolution soft and hard X-rays, X-ray spectroscopy), as well as with constantly improving ground based observatories (e.g., Themis, SVST, and some day ATST), *TRACE* will continue to provide an important part of "the full picture" of solar magnetic activity in the visible layers of the Sun, because of its high-cadence capabilities.

Until the start of observations by Solar-B, *TRACE* will remain the highest resolution Solar telescope in orbit, and even after that *TRACE* continues to provide a unique EUV window on the Sun. *TRACE* offers angular and temporal resolutions in the EUV that exceed other current instruments (*SOHO/EIT*) by a factor of almost 30, making it an extremely valuable asset.

We are currently looking forward to coordination with *HESSI* on the study of solar flares. Two SOHO JOPs have been defined already in anticipation of the *HESSI*'s launch: JOP 136 (the Max Millenium program) and JOP 143 on impulsive flare dynamics (developed by the *TRACE* team). Coordination with *HESSI* will

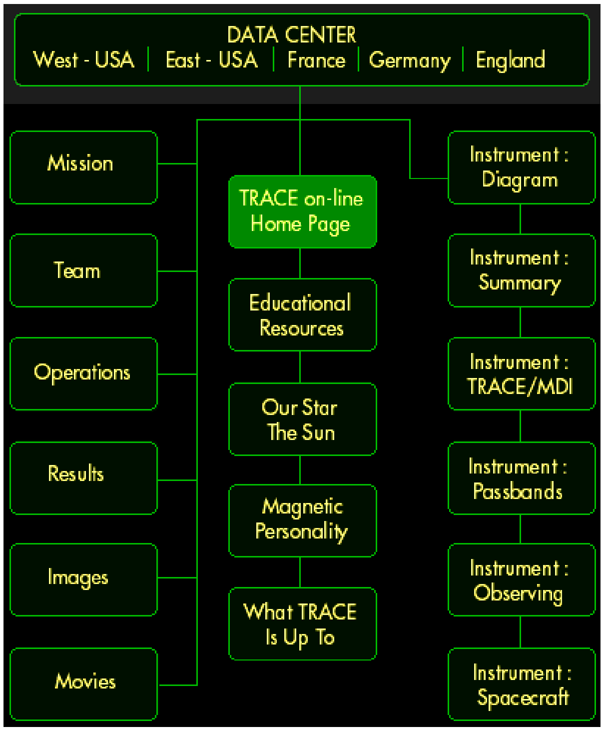

Figure 11: *Accessing* TRACE *data bases, instrument descriptions, operational plans, etc., is straighforward through the world-wide web (from http://vestige.lmsal.com/TRACE/-Public/siteinfo.htm).*

have priority during at least the first six months following its launch. Precedures have already been set up with the *TRACE* flight-operations team to allow us to respond to flare alerts even during weekends when normal operations otherwise require the definition of the entire spacecraft timeline of instructions from Saturday 0 UT through midnight on the following Monday, to be finalized by 18 UT on Friday. We have also initiated the organization of a joint *TRACE-SOHO-HESSI-* science workshop for the summer of 2002.

8 Proposed science investigation

TRACE contributes to Objectives 7 and 8 in NASA's Strategic Plan for the Office of Space Sciences: "Understand our changing Sun and its effects throughout the solar system", and "[c]hart our destiny in the Solar System", upon which both the Sun-Earth Connection Program and the Living-with-a-star Initiative are based. The study of the physics of the solar magnetic field is a key ingredient to these objectives.

In the coming years - likely until at least 2006 when the *Solar Dynamics Observatory* will be launched - *TRACE* will be the only high-resolution EUV observatory in space that can provide narrow-band imaging, at high cadence. Continued operation of *TRACE* is therefore crucial (a) to the study of the dynamic solar magnetic field that drives space weather, (b) the development of new models or validation of tentatively proposed models for some of the most interesting discoveries made with *TRACE* that at present are based on small sets of events or even a single event, and (c) to the interpretation of results from new missions, including *HESSI*, *STEREO*, and *Solar-B*. The most important categories of research include the following:

Filaments and CMEs: Close collaboration with *SOHO* (*MDI, EIT, CDS,* and *SUMER*) will continue in the study of filaments in order to understand their formation (including sigmoid structures within active regions), eruption, and demise utilizing the high temporal and angular resolution of *TRACE*.

Flare physics and rapid reconnection: A primary focus in the next years will be coordination with other missions on flare studies, in particular with *HESSI, SOHO/MDI,* and *SXT*. Focus areas include (1) understanding the relationships between the footpoint hard X-ray emission, the UV flare ribbons, and the structure of the photospheric magnetic field, and (2) understanding the properties of the hot thermal flare plasma (12-25 MK), which *TRACE* observes through continuum radiation in the EUV passbands, and Fe XXIV in the 195 Å channel, and its relationship to both footpoint and coronal hard X-ray sources. *TRACE* data can, moreover, be used to study white-light and UV data for weak flares to see how important non-thermal particle acceleration is in these flares. Note that the largest flares in a solar cycle often occur in period immediately following the cycle maximum, i.e., for this cycle in the period 2001-2002.

The launch of *HESSI*, which is currently scheduled for June 4 of this year, will significantly complement what we can learn from *TRACE* flare observations. *HESSI* will provide an unprecedented combination of high spatial resolution (~ 2”) and good energy discrimination (> 1 keV) at energies above 3 keV. The ability of *HESSI* to image both the hottest thermal plasma, as well as non-thermal emission, will be particularly important to coordinated *TRACE-HESSI* flare observations.

For example, by combining observations from the two missions, we will be able to study the relationship between the footpoint hard X-ray emission and the flare ribbons. *TRACE* UV observations show the flare ribbons to be complex structures with many compact bright points within them, whereas previous, low-resolution hard X-ray images suggested much simpler conjugate footpoint brightenings. Thus, the relationship between the precipitating energetic electrons and the global structure of the flare ribbon is not well understood. Furthermore, by including magnetograph observations we will be able to study the relationship between energy deposition into the chromosphere and the structure of the photospheric magnetic field.

Combined *TRACE-HESSI* observations will greatly advance our understanding of the hot thermal flare plasma and its relationship to both footpoint and coronal hard X-ray sources. *HESSI* will be very sensitive to plasma above about 15 MK, which will allow us to study the formation and evolution of the hottest flare plasma in great detail. *TRACE* 195 Å observations will be required if we are to be able to relate this plasma to the bulk of the flare emission. *HESSI* will have a dynamic range of about 100:1, which will allow for the detection of relatively faint coronal hard X-ray sources. Thus, we will be able to relate the formation of these regions with the evolution of the flare ribbons and the formation of the hottest thermal plasma.

In general, *TRACE* can respond to targets of opportunity of particular importance to *HESSI* science within a day; for weekends operations, the *TRACE* FOT have agreed to send special pointing commands to the spacecraft if the target is deemed of particular importance.

Focus areas for the TRACE *investigation*

Filaments and CMEs
Flare physics and rapid reconection
Coronal seismology
Loop physics
Geometry and evolution of the field
Coronal response to surface driving
Flux emergence and retraction
Coronal heating properties

Coronal seismology: At present, only six well-observed cases of coronal-loop oscillations are known, half of those having been observed as recently as March 2001. Despite the rarity of the events, this newly discovered phenomenon is potentially of pivotal value in our understanding of coronal physics, as explained earlier. Other observations of rapid deformations (known as coronal-Moreton, EIT, or Thompson waves) also contribute to that topic. Continued observations, close inspection of the data, and collaboration with theory groups (for example, the group at St. Andrews) are part of the proposed future *TRACE* investigation.

Loop physics: The fact that there appear to be no uniformly heated, quasi-static loops requires fundamental changes in loop modeling. Guidance to the development of these models (likely to involve flows, variable heating, and sub-resolution structuring) will be derived from continued loop analyses.

Geometry and evolution of the coronal field: high-resolution *TRACE* images are crucial to validate field extrapolations based on vector-magnetographic observations (such as at SPO, Mees, and on Solar-B), and to apply statistical tomography to the corona. Both are important in studies of the large-scale field and the propagation of disturbances (including CME’s) through them. Such *TRACE*-validated field extrapolations will be the lower boundary condition for *STEREO* observations. Close coordination with *SOHO/MDI* and the ability to compare *MDI* magnetograms easily with *TRACE* data are crucial in this effort.

Coronal response to photospheric driving: Coordinated continuous observations with *TRACE* and *SOHO/MDI* allow the analysis of the coronal response to photospheric evolution. *TRACE* has a unique data set of four nearly complete disk passages of active regions, coordinated with *SOHO/MDI*. The analysis of this data, and further examples, will advance our understanding of the coronal magnetic field.

Flux emergence and retraction: TRACE has observed numerous flux emergences within active-region nests and ephemeral regions in the quiet Sun, but only one emergence of an isolated active region has been observed seen in detail, plus a few active-region emergences that occurred within or next to existing active regions. The loops rising, the rapid reconnections to distant fields, and the dynamic mixture of plasma at chromospheric and coronal temperatures tens of thousands of kilometers above the surface require further examples in order to be better understood. Moreover, flux retraction within active regions, in filament-channel polarity-inversion zones, and at the edges of (polar and mid-latitude) coronal holes also need observations.

Coronal heating properties: TRACE observations can be used to study variability of coronal heating (both in time and space along a loop to test the microflare theory for active-region loops at *TRACE*'s sensitivity) and the evolution in position (to study coherence lengths and evolution patterns in the heating in comparison with model predictions).

To facilitate all of the above new observations and to stimulate their analysis and interpretation, we will moreover *(i)* organize a joint workshop with *SOHO* and *HESSI* in the summer of 2002, and *(ii)* work to include the *SOHO/MDI* magnetograms in *TRACE* analysis programs, in particular to provide easy access from the ANA-browser, while having a substantial subset of *MDI* magetograms available on-line in parallel to the *TRACE* archive.

How much of the above science can actually be successfully addressed will, of course, depend on the magnitude of the funding that will be available in the coming years. This is discussed in Section [**??**].

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