Transition Region and Coronal Explorer (TRACE)

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Executive summary

The Transition Region and Coronal Explorer, *TRACE*, provides the highest-resolution images of the solar corona obtained with any past, existing, or near-future observatory. The *TRACE* EUV images, together with its UV and visible images of the corona-photosphere interface, enable or support crucial research on each of the three Strategic Objectives in the SSSC Roadmap. The *TRACE* data support research topics that range from flare-CME physics and the measurement of magnetic free energy and helicity to the turbulent dynamo and coronal heating. The next few years promise an exciting new era of solar research as new resources and an increase in solar activity will stimulate quantitative studies based on EUV spectroscopy, vector-magnetography, stereoscopy, and multi-wavelength coronal imaging. *TRACE* provides the highest spatial and temporal resolution for (E)UV imaging in support of the interpretation of spectrographic observations with SOHO and Solar-B, reveals complementary thermal domains to the Solar-B/XRT/EIS and GOES/SXI telescopes, images the initial development of CMEs observed by STEREO, allows detailed mapping of coronal field configurations during flares observed with RHESSI and radio and microwave observatories, and provides coronal-field data to complement SOLIS and Solar-B vector-field data. The new resources will, in turn, improve interpretation of *TRACE* EUV data.

TRACE therefore continues as an essential component of the SSSC Great Observatory, and is a key resource to the success of Solar-B and STEREO in the International Heliophysical Year 2007 and beyond. With these new resources, *TRACE* is expected to increase its science output even compared to that of the past 12 months, which saw ~ 55 refereed publications based on *TRACE* findings (including two Nature papers), sparked three major press events, and logged over one million images exported from the archive.

Through FY 2008, we will stimulate frequent multi-mission Joint Observing Programs much as we have for SOHO (with *TRACE* participating in 70% of its JOPs) and RHESSI in recent years, as well as organize multi-mission science workshops. We request that NASA allocate funding for a GI program on joint observing and analysis of solar eruptive events, specifically focused on buildup, initiation, evolution, and consequences of high-energy eruptive events.

This proposal assumes the successful launch of SDO and operation of SDO/AIA around the start of FY 2009. After AIA commissioning and several months of coordinated observing for calibration purposes, *TRACE* would be terminated. *TRACE* data will then be transitioned into a Resident Archive as part of the SDO/AIA data system, extending SDO's records by almost a solar cycle.

TRACE continues to be in good health after taking 17 million images of the Sun since its launch in April 1998. Multiple annealings have rejuvenated the detector back to its mid-2001 EUV sensitivity. All mechanisms function adequately and are used as science requires. Upgrades in the data system now make *TRACE* data available $10\times$ faster than before, typically within ~ 1 h of receipt at the EOF.

TRACE observations capture the interest of the general public. It is hard to find a popular science article or television special on the Sun that does not show *TRACE* images. *TRACE* catches the public's attention particularly during special events, such as three solar eclipses, Mercury and Venus transits, and two unique periods of extreme activity with record flares and CMEs since the previous Senior Review. On the day of the Venus transit, for example, a dedicated web site received over one million hits. During these two years, six thousand posters and twelve thousand calendars have been distributed, while *TRACE* images are on display throughout the U.S. from an exhibit in the Hayden planetarium in New York to the Chabot science center in California where a 20-foot full-disk composite dominates the exhibit. A DVD set of illustrative and educational *TRACE* observations was completed for distribution to scientists and the general public.

Contents

1 Science section

The *TRACE* team looks forward to a period of exciting scientific advances during the period covered by this proposal, FY 2007-2010: new instruments in space and on the ground - including Solar-B, STEREO, GOES/SXI, SOLIS, and SDO – will enable new research avenues for the highest-resolution coronal imager in existence. These new avenues address each of the three research Objectives formulated in the recently-completed NASA/SSSC strategic Roadmap (see Table 1). *TRACE* will continue to be a significant contributor to the SSSC Great Observatory because of its unique capabilities: high-resolution imaging at high cadence from chromosphere to corona (Tables 2 and 3) of phenomena that cover the evolution of the Sun's atmospheric magnetic field from emergence, through stress buildup, to the release of magnetic energy and the subsequent evolution of explosions that lead to space weather.

TRACE data enable an enormously wide spectrum of research areas. They have, for example, been used for quantitative comparisons with models of 1) high-frequency wave power entering the solar outer atmosphere, 2) the heating of the coronal plasma, 3) the development of instabilities in filament and field eruptions in CMEs, 4) coronal field and plasma properties during coronal oscillations, 5) magnetic free energy available in flares, and 6) the coupling of photosphere and heliosphere. Key recent achievements are highlighted in Sec. 1.4.

The period FY 2007-2010 will see new research avenues open as new resources become available. These offer spectroscopy, multi-wavelength imaging, and even stereoscopic imagery. This will markedly increase the ability of *TRACE* images to (a) allow detailed mapping of the coronal field during flares that are observed with RHESSI and with radio and microwave observatories, (b) provide imaging context for the spectrometer raster observations with SOHO and the future Solar-B, neither of which image their slit jaws, (c) reveal thermal domains that are essentially complementary to those seen by the Solar-B/EIS/XRT and GOES/SXI telescopes, (d) image the initial development of CMEs observed by STEREO from a third viewpoint, and (e) observe the coronal field well above the photosphere to provide data complementary to vector-magnetographic measurements with SOLIS and Solar-B. These research topics are discussed in Sec. 1.1.

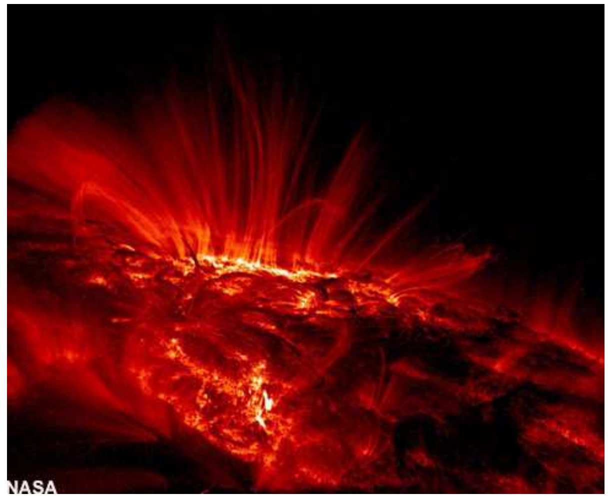

Figure 1: *High-resolution* TRACE *images such as this reveal the striking fine structure of the corona at the limb, with loops clearly displaying their still unexplained nearly constant cross section. This image was voted 4th place in a poll by space.com on 'Most Amazing Galactic Images Ever'; 18 out of the top 20 images were taken by the Hubble Space Telescope, with only one other solar (SOHO/EIT) image in the list.*

The variety of research topics for which *TRACE* data are used demonstrate how essential *TRACE* is to the SSSC Great Observatory. *TRACE* will also contribute in essential ways to the success of the future Solar-B and STEREO missions in the International Heliophysical Year 2007 and beyond. Even after seven successful years of operations, *TRACE* continues to yield discoveries that are published in refereed publications at an essentially constant frequency of ~ 50/yr starting shortly after its launch. These studies are based on a rapidly increasing use of *TRACE* data recovered from its archive (section 1.6).

This proposal is written assuming that the Solar Dynamics Observatory will be launched successfully in the second half of 2008. We propose a period of joint observing of *TRACE* with SDO/AIA to take place after SDO's initial three-month commissioning phase. Cross-calibration of the overlapping 171 Å, 195 Å, and UV channels of *TRACE* and AIA will enable continuation of an (E)UV data base from

Table 1: TRACE *within the primary Sun-Solar-System Connections science Objectives, Research Focus Areas (RFAs), and Investigations. Only RFAs and Investigations are listed to which* TRACE *contributes in a primary role as identified explicitly in the SSSC roadmap (July 2005).* TRACE *contributes indirectly to many other SSSC Investigations.*

SSSC objective	SSSC priority RFA	Investigations with *TRACE* in primary role
Open the frontier to space environment prediction	• F1: Understand magnetic reconnection as revealed in solar flares, coronal mass ejections, and geospace storms • F2: Understand the plasma processes that accelerate and transport particles • F4: Understand the creation and variability of magnetic dynamos and how they drive the dynamics of solar, planetary, and stellar environments	• F1.2: What is the magnetic field topology for reconnection and at what size scales does magnetic reconnection occur on the Sun? • F2.1: How are charged particles accelerated to high energies? • F4.2: How are open flux regions produced on the Sun, and how do variations in open flux topology and magnitude affect heliospheric structure?
Understand the nature of our home in space	• H1: Understand the causes and subsequent evolution of solar activity that affects Earth's space climate and environment	• H1.1: What are the precursors to solar disturbances? • H1.2: How do solar wind disturbances propagate and evolve from the Sun to Earth? • H1.3: Predict solar disturbances that impact Earth.
Safeguard the journey of exploration	• J2: Develop the capability to predict the origin and onset of solar activity and disturbances associated with potentially hazardous space weather events.	• J2.1: What are the observational precursors and magnetic configurations that lead to CMEs and other solar disturbances, and what determines their magnitude and energetic particle output?

one solar cycle into the next. If SDO/AIA works as designed, and if no further launch delays occur, we anticipate that *TRACE* can be terminated in the spring of 2009. This proposal also includes a transition for *TRACE* data into a Resident Archive, as well as the first full year of that archive's operation.

1.1 Proposed science program

The requirements of the Living With a Star program within the era of the Exploration Vision are focused on learning how to forecast space weather events (see Table 1). Within the broader scientific context, the successful prediction of explosive and eruptive events and the associated particle and electromagnetic radiation, is the ultimate test for our understanding of solar activity that drives space weather and climate. Our path towards that ultimate test requires that we understand the conditions under which such impulsive events either do or do not occur, that we measure the evolution of the energy available to the event, that we know the instability that initiates the event, and can map the pathways for energetic particles through the Sun's extended magnetic field. Obtaining this knowledge requires a significant investment in fundamental solar physics.

The years ahead promise new ways to address the science behind solar magnetic activity with new facilities such as Solar-B and STEREO, with new analysis tools for multi-spacecraft data from the SSSC Great Observatory, and new numerical tools to compare models and observations. Our plans for coordinated observing and analysis are outlined in Sec. 1.1.1. Sections 1.1.2 - 1.1.5 address these opportunities in four steps - forecasting, evolution, consequences, and fundamental solar physics - and shows the roles that *TRACE* plays in the advancement of our quantitative understanding of solar activity. Each of these steps discusses two characteristic examples of recent, ongoing research that illustrate the value of *TRACE* observations in some detail. These are followed by an outline of proposed research. The relevance to the SSSC goals and objectives and the promise of future impact and productivity are summarized in Secs. 1.2 and 1.3. Past scientific achieve-

Table 2: *TRACE* spectral regions and characteristic exposure times

Central wave-length	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	C I, Fe II, cont, C IV	$T_{\rm min}$/Chrom.	3.8	3.6-5.4	1	1	0.01-0.1
1550Å	C IV, cont	Trans. region	5.1	4.8-5.4	15	10	1-5
1216Å	H Ly α, cont	Chromosphere	4.2	4.0-4.5	3-30[a]	3-30[a]	1-2[a]
284Å	Fe XV	Corona	6.3	6.0-6.7	60	5-30[b]	2-20
195Å	Fe XII (XXIV[c])	Corona	6.1 (7[c])	6.0-6.4	30	5-30[b]	1-10
171Å	Fe IX/X	Corona	5.9	5.3-6.3	30	5-30[b]	1-10

a 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.
b The lowest values are for 2×2 binned imagery.
c Fe XXIV line, and sometimes a high-temperature thermal continuum, visible during flares.

ments are highlighted in section 1.4.

1.1.1 Coordinated observing and analysis

New discoveries with existing instrumentation often occur when observations are combined with other, complementary instruments, or when they are analyzed with the joint expertise from multi-disciplinary science teams. The *TRACE* team will organize and participate in such joint analyses, as it has done in the past, in order to optimize the scientific return from the continuation of *TRACE* operations.

Coordinated observing:

The *TRACE* team will continue to coordinate closely with other space- and ground-based observatories in the coming years to obtain multi-wavelength spectral and imaging data on a variety of solar events, from photosphere into heliosphere. The physical proximity of principal investigators and co-investigators on the *TRACE*, Solar-B, STEREO, and SOHO missions at the Lockheed Martin Advanced Technology Center (LMATC, part of Lockheed Martin's Space Systems Company), at GSFC's mission operations center, and at the Harvard-Smithsonian Astrophysical Observatory ensures effective coordination between the instrument teams as well as the science teams. The coordination with La Palma SST campaigns for approximatly 40 days each summer will also continue efficiently by these overlapping science teams. Coordination with other space missions, such as RHESSI, and with ground-based observatories around the world will continue to be organized based on (joint) observing requests.

The *TRACE* planning team has a very strong record in responding flexibly and efficiently to requests for observing. They will continue to place particular emphasis on coordinated observing, assigning the highest priority for special events such as Major Flare Watches, eclipses, transits, and multi-observatory campaigns. We estimate that outside of the three months each year that the *TRACE* orbit experiences Earth-atmospheric absorption, we are involved in coordinated observing 70% of the time. Another 20% of the time is filled with observing requests for *TRACE* data only, and 10% of the time is filled with either target-of-opportunity observing or observing runs for the *TRACE* planner at the time.

The close coordination of the *TRACE* team with SOHO planning has earned *TRACE* a reputation as SOHO's 13th instrument. The rapid response to Major Flare Watches in the context of RHESSI coordination has resulted in *TRACE* observing 18 out of 30 (60%) of the X flares between 2004/01/01 and 2005/09/18, and 81 of 205 (40%) of the M flares.

Table 3: *Coronal and chromospheric instrumentation on the future Solar-B and STEREO spacecraft, and the complementarity of* TRACE *in contributing to their science goals.*

Solar-B (launch: fall 2006)	*TRACE* compared to Solar-B
XRT (Kano et al., 2004): 1 arcsec pixels, 34×34 arcmin fov, $< 1 - 30$ MK thermal range observed with 9 broadband filters with peak sensitivities at $\sim 3 - 15$ MK; characteristic programs: 200 s cadence for pairs of full fov images, 40 s cadence for pairs of images of ARs, or 5 s cadence for AR image pairs for one hour, assuming 100% duty cycle	*TRACE* has $2\times$ higher resolution, and is primarily sensitive to the cooler ($0.5 - 2$ MK) coronal emission for which XRT filters have a sensitivity of $5 \times -1000\times$ below their peak sensitivity around 3 MK; *TRACE* has comparable image cadence for sustained observing of quiescent conditions and for high-cadence observing of flaring regions.
EIS (Hara, 2004): $170 - 210$Å and $250 - 290$Å, $0.02 - 20$ MK, slit widths 1, 2, 4, or 266 arcsec, slit length 1024 arcsec; a 4×4 arcmin scan takes ~ 1 ksec; no slit-jaw imaging	*TRACE* EUV passbands lie within the EIS range, enabling straightforward co-alignment and EUV context imaging during area scans in one or more (E)UV passbands. This allows separation of flows and loop displacements, provides information on the existence and structure of multiple line-of-sight emission structures, and enables direct calibration of the contributions to the *TRACE* passbands
FPP (Shimizu, 2004): vector-magnetic field and Doppler velocities in low chromosphere in Na I D and Mg I b; magnetic connectivity and flows in narrow-band Hα; chromospheric dynamics in Ca II H and Hα	*TRACE* observes the base of hot coronal loops in the transition-region moss and its interaction with embedded chromospheric spicules; UV passbands provide access to compressible waves to beyond 50 mHz.

STEREO (launch: April 2006)	*TRACE* compared to STEREO
SECCHI/EUVI (Howard et al., 2000): 1.6 arcsec pixels, 3.4 $R_\odot$ fov; 171, 195, 284, and 304 Å; standard synoptic program with two parts: (1) 3 min. cadence for pairs of 1024^2 images, and (2) 30 min. for pairs of 2048^2 images	*TRACE* observes at $> 60\times$ higher cadence with 10 pixels per EUVI pixel at EUVI high-res. synoptic, or $> 10\times$ higher cadence with 40 pixels per EUVI pixel at EUVI low-res. synoptic; *TRACE* thus allows high-resolution studies of the initial evolution of the eruptions as well as measurement of time delays between high, low, and distant coronal fields reflected in EUV loop motions. *TRACE* provides this imaging from a 3$^{\rm rd}$ viewpoint for stereoscopic reconstruction.

This high success rate reflects our dedication to coordination on these targets of opportunity; that it is not higher, is mainly because flare sites (and thus pointings) are difficult to forecast while the *TRACE* field of view contains only 1/8 th of the activity belt, and because *TRACE* has an effective duty cycle of approximately 70% (owing to radiation zones and eclipse periods), and because occasionally data are lost in transmission to the ground station.

Note that *TRACE* observed the largest flares on record, in October and November 2003. These observations formed the basis of the widely distributed 2005 *TRACE*-team calendar. That calendar showcased observations of the large flares made by the various observatories throughout the heliosphere, illustrating the power of the SSSC Great Observatory.

Multi-disciplinary data analysis:

Scientific conferences and workshops are particularly efficient ways to reach out to a broad scientific community, to demonstrate software that helps users to find and use *TRACE* data, and to spark discussions between scientists of different backgrounds. We plan, therefore, to stimulate multi-disciplinary data analyses by organizing (or participating in the organization of) joint workshops such as the successful workshop for the RHESSI, *TRACE*, and SOHO communities held in Sonoma, CA, in December 2004.

In the recent solar maximum, an enormous range of remarkable new observations of solar explosions and eruptions and their energetic consequences has become available from ACE, RHESSI, SoHO, TRACE, Wind, and other missions of the SSSC Great Observatory. The buildup, initiation, evolution, and consequences of explosive and eruptive events are topics of particular relevance to NASA's future in this era of the Vision for Space Exploration and the Living With a Star initiative. From FY 2007, STEREO and Solar-B will add new types of observations. Each of these missions contributes fundamental new insights, but a global integration and analysis of these observations will provide the real pay-off in our understanding of these phenomena. Since the in-guideline funding levels of the individual missions are inadequate to cover such integrated studies, the science teams of many of the SSSC Great Observatory missions (including, alphabetically, ACE, RHESSI, SOHO, TRACE, and Wind) propose that NASA allocate $1.5 million/year in Guest Investigator (GI) funds in the coming years to stimulate rapid advancement of our understanding of the buildup, initiation, evolution, and consequences of explosive and eruptive events. A multi-mission GI program would stimulate analysis of data from joint observing campaigns as well as stimulate coordination between instrument and analysis teams. Multi-disciplinary science workshops, focused on specific aspects of these tasks, will provide additional stimulus to discover new processes, phenomena, and correlations in archival and newly-obtained data.

1.1.2 Forecasting: where, how large, when?

Where will flares and coronal mass ejections occur? Major advances in answering this question will come from the routine use of vector-magnetograms that will be provided by ground-based facilities NSO/-SOLIS and HAO/ASP and by the Solar-B/FPP vector-magnetograph with even higher resolution and full continuity. These facilities will provide essential observations needed to model the coronal field over active regions and filament channels. These data form the basis of any extrapolation of the field into the corona. Such extrapolations are, however, subject to the significant observational uncertainties and biases in the observables, mostly because the chromosphere is not force-free and because of observational noise and a 180° ambiguity in the component of the field normal to the line of sight. Coronal loops in the high-resolution *TRACE* images outline part of the magnetic field. This enables a quantitative validation of the model field extrapolation. Ideally, as described below, we will learn how to use *TRACE* observations to iteratively guide the field modeling from surface to corona (cf., studies by van Ballegooijen, 2004; Mackay and van Ballegooijen, 2005; Wiegelmann et al., 2005). The resulting field models will allow us to measure the available free energy and the stored helicity, to map where that energy resides, and to establish how that energy came to be stored there.

TRACE data are particularly useful for tracing the coronal field in quiet and active Sun: *TRACE* observes the EUV corona with at least 10 pixels for every pixel in the STEREO/EUVI instrument and 4 pixels for each in Solar-B/XRT images, while routinely operating at a cadence that is at least 10 times higher than STEREO/EUVI and comparable to Solar-B/XRT. The Solar-B/XRT filters have responses at 1 MK which are $5\times$ to $1,000\times$ lower than their peak responses around $3-5$ MK (cf., Table 3). Hence, Solar-B/XRT will have difficulty to effectively image the relatively cool coronal plasma to which *TRACE* is most sensitive.

One example of core research into coronal field geometry and energy started with a study of *TRACE* and SOHO/MDI data. The pilot study compared *TRACE* EUV images to potential field models to find that large flares preferentially occur within a day of new field emergence into existing active regions with sufficient complexity, flux, and incompatibility with the field pattern already at the solar surface (Schrijver et al., 2005a). The electrical currents that power these large flares were shown to deflect the magnetic field of the entire active region, and are therefore likely to affect even the global magnetic configuration of the corona, including the corona-heliosphere coupling. We plan to expand this pilot study to non-potential fields, utilizing both *TRACE* and Solar-B data.

Sequences of *TRACE* images enable the quantitative study of the evolution of the magnetic field by comparing fields and coronal loops. For our understanding of flares and CMEs, for example, the measurement of reconnection rates is particularly relevant. This is now coming within reach, as illustrated by a recent study by Longcope et al. (2005). They demonstrated that it is possible to trace the evolution of the coronal field as seen in *TRACE* images as newly emerging field reconnects with pre-existing field. They argue that the field is transferred in bundles of typically 4×10^{18} Mx each. These reconnections occur up to a day after the emergence of the new flux, which is entirely compatible with the 1-day decay time scale of large-scale coronal currents found by Schrijver et al. (2005a). During flares, the tracking of flare ribbons across magnetograms provides measurements of reconnection rates (e.g., Fletcher et al., 2004).

Observations need to be compared to models if we are to improve our understanding of coronal field dynamics; we believe that the numerical and observational resources are well matched to stimulate significant progress in the coming years. In particular, we need to learn what determines the timing and magnitude of flares and CMEs. We know these depend on the magnetic free energy or (relative) helicity within the active region or filament field configurations. These quantities can only be measured after computing non-potential models for the coronal magnetic field. The non-linear force-free (NLFF) field computations or MHD simulations that are required for this type of measurement require at least vector-magnetographic data of the photosphere in large areas centered on the regions of interest.

Vector-magnetograms are currently measured infrequently, subject to Earth-atmospheric conditions, at only a few facilities (including SOLIS, Mees IVM, and HAO/ASP). Following the launch of Solar-B in late 2006, however, vector-magnetic maps will be routine products for entire active regions at subarcsecond resolution. The application of NLFF or MHD field extrapolations to these vector-magnetograms is not straightforward, however, because (1) the magnetic data are measured in the photosphere well below the high chromosphere where the field becomes force free, and because (2) there is an intrinsic 180° ambiguity in the direction of the vector-field component perpendicular to the line of sight

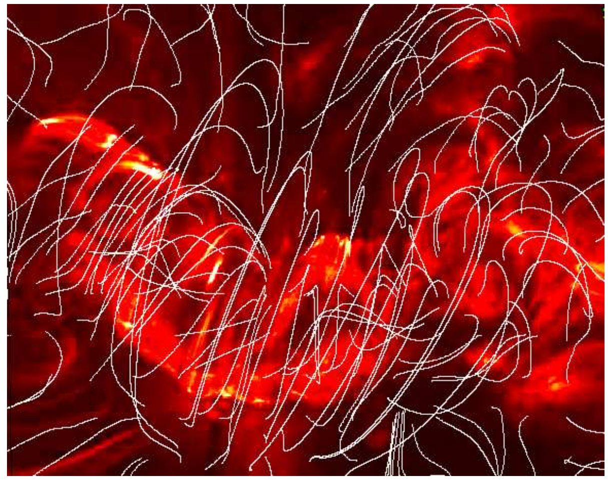

Figure 2: *Overlay of a* TRACE *image of a pre-flare active-region field configuration and a nonlinear force-free field extrapolation (white field lines). Although there is a general agreement of the model field arcade with the coronal arcade, the disagreements are substantial. The main problem appears to be that photospheric vector-magnetography by itself does not entirely specify the coronal field because of Lorentz forces that act up to the top of the chromosphere. We anticipate significant improvement from a modeling technique that utilizes the* TRACE *images as complementary information to the photospheric vector field observed (here observed by Mees/IVM; in the future by Solar-B/FPP and SOLIS), possibly including Solar-B/FPP Hα images.*

which often cannot be unambiguously resolved. Thus, coronal field models based on vector-magnetographic data have a considerable degree of uncertainty. Combining photospheric vector-field measurements with high-resolution coronal observations promises to resolve much of this uncertainty. If successful, this would yield much more accurate determinations and mappings of free energy and helicity in active regions. In that approach, the photospheric field vector is used as an approximate lower boundary condition in an iterative process that uses traces of coronal loops to find the appropriate coronal model field. We have formed a world-wide consortium of NLFF field modeling groups to pursue this concept with promising first results for a comparison of methods (Schrijver et al., 2005b). At present, such models fail to perform adequately (see the example in Fig. 2) because the photospheric measurements of the vector field cannot specify the coronal field owing to Lorentz forces that act throughout the lower atmosphere. *TRACE* and Solar-B/FPP data together, however, will guide modelers to appropriate and fast methods to establish the 3-D coronal field configuration that is required to understand the drivers of space weather. Solar-B/FPP will also image chromospheric features in its Hα bandpass; these features trace the near-horizontal field at the coronal base, which can in principle be used as added information for coronal field modeling.

Continuation of the *TRACE* mission in the coming years is essential to improved understanding of the conditions that lead to flares and CMEs:

- As Solar-B and SOLIS vector-magnetograms become available, the coronal effects of emergence, transport, and disappearance of photospheric field can be observed with *TRACE* at over twice the resolution available to the XRT coronal imager on Solar-B. Moreover, *TRACE* images of the $1-2\,\mathrm{MK}$ plasma, to which XRT is relatively insensitive, can be used successfully to study the coronal topology and dynamics. Quantitative measurements of free energy and helicity can then be based on models that use the complementary surface vector field and projected coronal loop patterns.
- Our understanding of quiet-Sun field that is involved in CMEs or forms the base of coronal holes will also expand as future vector magnetographs come on line. The transverse components of the quiet-Sun vector-field will continue to be subjected to very substantial noise, however. Hence, the the geometry of the cool corona, best observed with *TRACE*, will provide key information to guide coronal field models.

TRACE will coordinate closely with Solar-B (see section 1.1.1) thus stimulating the development of field modeling techniques.

1.1.3 Evolution: magnetic topology, event precursors, configuration destabilization

The destabilization of magnetic configurations has been observed with *TRACE* for both flares and coronal mass ejections. The destabilization of CME-related field configurations is at the core of STEREO science, and *TRACE* will support that by providing observations of the filament and low-coronal field involved in the eruptions. *TRACE* observations will provide 10 or more pixels for every STEREO/EUVI pixel, and the standard full-fov observations will provide a cadence that is $\sim 10-60\times$ faster (cf. Table 3). These high-resolution observations will, moreover, be taken from a perspective in between those provided by the two STEREO spacecraft.

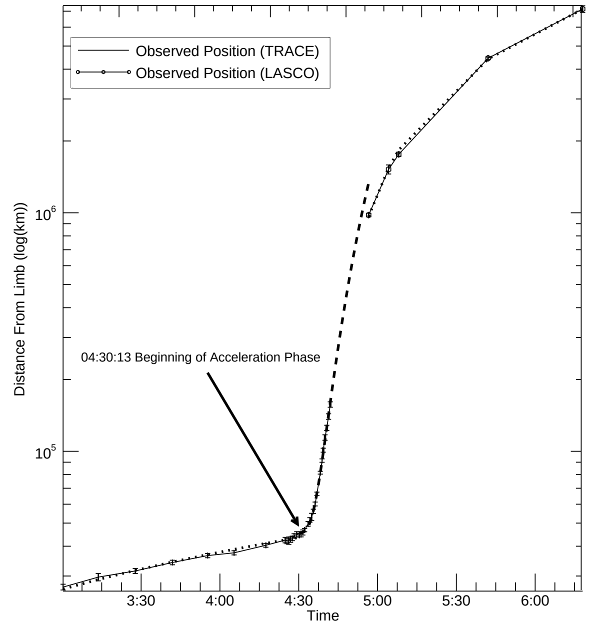

Figure 3: TRACE *data provide high-cadence information on the initial phases of CMEs and the filaments they contain. The figure shows the slow initial increase in height, h, of a CME filament, followed by a rapid acceleration observed with* TRACE. *The best fit, shown as a dashed line, has* $\mathrm{d}^3h/\mathrm{d}t^3 = \mathrm{const.}$ *This is followed by a phase at constant velocity observed in the Hawaii-based MLSO/Mk4 coronagraph (upper solid lines). Figure from Elmore et al. (2005).*

The higher cadence and resolution of *TRACE* relative to STEREO/EUVI (and to SOHO/EIT) is crucial in measuring, for example, the initial phases of the filament rise and of the evolution of the surrounding field. An example of the power of such observations is shown in Fig. 3: Elmore et al. (2005) measure the rise of the filament from the pre-eruption phase, through the low corona, into the heliosphere by combining *TRACE* observations with ground-based and space-based coronagraphic observations. The high cadence and resolution of the *TRACE* image sequence leads them to conclude that the eruptive phase occurs at a constant rate of increase of the acceleration, which ultimately transitions into a near-coasting phase in the inner heliosphere. Their preliminary finding is that an exponential rise phase, as expected for, e.g., kink-mode instabilities, does not provide a statistically acceptable fit to the observations (but see section 1.4 for other studies).

Elmore et al. (2005) also study time differences between the evolution of the rising filament and of the overlying high coronal loops. Suitable observations for these studies are rare because they require optimal coverage of a filament near the limb at a cadence of 40 s or better (see Table 4 for selected other references). The optimal data sets selected by Elmore et al. (2005) suggest in one case that the filament rises before the high loops deform while in the second case no significant temporal difference is seen. Such observations are of great importance: phase differences between filament rise and the evolution of the overlying field allow us to differentiate between models for what drives the CME (e.g., kink instabilities, tether-cutting reconnection below the flux rope, or field breakout by reconnection above the filament configuration; e.g., Moore et al., 2001; MacNeice et al., 2004), while the acceleration profile reveals the forces involved in the destabilization itself (e.g., Williams et al., 2005).

Continued observing of *TRACE* in conjunction with ground-based coronagraphs and SOHO/LASCO will increase the number of suitabley-observed events, particularly as the new cycle increases in strength in the coming years. The combination of *TRACE* data on the initial phases of CMEs with STEREO observations of the interplanetary behavior will enable comprehensive studies and model testing.

The LWS and Exploration Vision requirements also dictate an intensified search for precursors to flares and CMEs. This is not only of importance to forecast, but may actually provide clues on what causes the destabilization. Such precursors thus include 1) the emergence of new field and its interaction and reconnection with pre-existing coronal field, 2) moderate activations of filament-related field configurations that *TRACE* observes as high-velocity, short-lived events that travel along or around filaments, and 3) early signs of particle acceleration which are frequently observed with *TRACE* as compact, fleeting footpoint brightenings that occur in the minutes prior to the flare. The combination of *TRACE* imaging with Solar-B/EIS spectroscopy will enable measurement of plasma and flow properties, while the combination of *TRACE* and Solar-B/XRT imaging will provide comprehensive thermal coverage, with a cadence and resolving power that is much better in joint observing than when observing with either instrument separately.

An entirely different type of precursor behavior may be found in the large-scale structure of active regions: an analysis of *TRACE* EUV images and SOHO/CDS spectra of active regions near the limb by Cirtain et al. (2005b) suggests that there may be an observable change in the total EUV intensity and stratification behavior before the onset of a flare. All of this precursor behavior needs to be studied for large samples of flaring regions using archival data as well as new data observed by *TRACE* once Solar-B and STEREO are operational.

TRACE will coordinate closely with SOHO, Solar-B, STEREO, and RHESSI to observe flares and CMEs, from the buildup to the eruptive phases, at high resolution. Measurements of the coronal-field deformation, of reconnection rates inferred from flare ribbon motions, and reconnection in and around filament and flare sites in response to emerging and moving magnetic flux will further our understanding of flare and CME processes.

1.1.4 Consequences: heating and acceleration

The generation of energetic particles and photons is of key importance to the Living With a Star program and the Exploration Vision. *TRACE* observations of the indirect effects of particle acceleration and energy deposition will continue to be decisive in understanding the sources, pathways, and evolution of these events. One illustrative example is that of a γ-ray flare observed by RHESSI, SOHO, *TRACE*, and other observatories that include INTEGRAL, CORONAS, GOES, and radio observatories

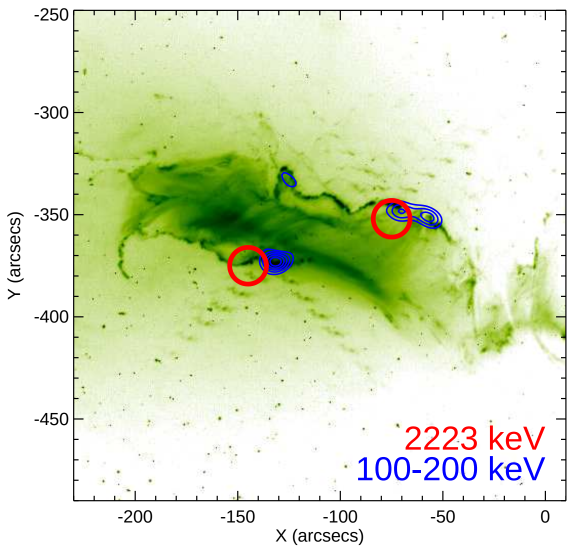

Figure 4: *High-resolution* TRACE *image sequences show the evolution of particle precipitation sites and of the coronal plasma and field during flares, complementing hard X-ray and γ-ray RHESSI observations. The background image is a* TRACE *195 Å channel exposure, taken at 11:07:41 UT. The red circles show the centroids for the 2.2 MeV neutron-capture line, and the blue contours the locations of the* $100-200$ *keV electron-impact bremsstrahlung, both observed around 11:06:46 UT. Image courtesy of Säm Krücker, Space Sciences Lab., Univ. of California at Berkeley.*

(Fig. 4). This outstanding example of the power of the SSSC Great Observatory illustrates how important high-resolution imaging observations are to understand the properties of, e.g., the 511 keV positron-annihilation γ-ray line. The *TRACE* observations show that the dominant sites of particle acceleration are less than 1,400 km in diameter while precipitating energy at rates that are thousands of times larger than in the rest of the flare ribbons. These precipitation kernels move across the magnetic field traveling across their own diameter in less than ~ 40 s, shorter than the relaxation time of the heated atmospheres. The integrated spectra seen at lower resolution, such as by RHESSI, are thus sums of spectra from rapidly evolving atmospheres and energetic-particle populations. These observations suggest, for example, that a narrowing of the 511 keV γ-ray line occurs because of the rapid collapse of a heated umbral near-photospheric plasma at the very end of the impulsive phase of the flare (Schrijver et al., 2005c). High-resolution *TRACE* observations are essential to reveal such details.

The study of the energy conversion in solar flares as well as in quiescent active regions will be facilitated by the Solar-B EIS spectrograph. The *TRACE* EUV channels are included in the EIS wavelength range (Table 3). This allows the calibration of the *TRACE* channels relative to the EIS, which strengthens the quantitative basis of studies of coronal loops performed thus far. The future potential is particularly formidable: the shared wavelength ranges allow the use of *TRACE* images as context images for the EIS which does not have a slit-jaw imaging capability. Thus the spectral signatures seen in EIS (raster-scan) spectra can be correlated with flows, loop movements, or multiple line-of-sight emission features in the *TRACE* images.

1.1.5 Fundamental solar and plasma physics

The preceding three sections focus specifically on the strategic priorities of the SSSC research programs as reflected in the Roadmap and the needs of the LWS and Exploration programs. At their base lie many more research topics that address the fundamental aspects of solar physics. This incudes the plasma physics of coronal heating; wave diagnostics; flux emergence, interaction, reconnection, and retraction or expulsion; loop-atmosphere physics and the dynamic fine structure of the corona, etc. All of these will benefit from the combination of high-resolution, high-cadence imaging provided by *TRACE* in conjunction with the imaging and spectroscopy provided by Solar-B and STEREO (see Table 3).

For example, Solar-B/EIS spectroscopy will enable a detailed study of the contributions to the *TRACE* EUV passbands as well as reveal the thermal properties of the plasma within *TRACE* pixels, thus helping to resolve an ongoing debate about loop atmospheres (as described and referenced in the 2003 Senior Review proposal[1]). The spectroscopic information will also enable a better interpretation of MHD wave modes that have been observed in a multitude of solar coronal features, and help separate flows

[1] http://chippewa.nascom.nasa.gov/TRACE/senior.pdf

from waves, and perhaps compressible from transverse wave types.

The combination of Solar-B/XRT high-temperature imaging and *TRACE* imaging of the $1-2$ MK plasma in combination with Solar-B spectroscopy will improve our understanding of any small-scale fluctuations in coronal heating (micro- or pico-flaring), and the subsequent response of the loop atmospheres in their entirety. The combined observations will, for example, reveal how loops migrate from one thermal domain to another. That, in turn, constrains the spatio-temporal properties of coronal heating and helps separate real from apparent loop motions when studying field topology and reconnection.

The more comprehensive coverage in temperature space by combined *TRACE* and Solar-B/XRT and EIS data will help us study the properties of the Sun's atmosphere by utilizing wave phenomena. Observations of magneto-acoustic modes at a large range of temperatures, for example, will give us better insight into the thermal structure of the corona down to sub-resolution scales. The new observations can extend the work by, e.g., Robbrecht et al. (2001) and King et al. (2003) to analyze propagation speeds in the 171 Å and 195 Å channels. That work suggests that loops contain sharp temperature gradients below the instrumental resolution. Spectroscopy and a wider thermal range will help us understand what makes this possible, thus providing a deeper insight into the solar coronal fine structure and its physical processes. The same instrumental complementarity will help us exploit the high-temperature longitudinal oscillations observed by SOHO/SUMER (Wang et al., 2003) contrasted to the lower-temperature ones seen by *TRACE* to understand the coronal structure.

The complex and dynamic chromospheric interface between solar surface and corona can also be studied using travelling and evancescent wave phenomena observed by *TRACE* (e.g., Goossens et al., 2002; De Moortel and Hood, 2003; Roberts and Nakariakov, 2003; Klimchuk et al., 2004; De Pontieu et al., 2004). These observational constraints guide modeling of the atmospheric and field structure in this complex yet crucial atmospheric domain. The *TRACE* data provide higher-frequency and long-wavelength information that supplements Solar-B/EIS and SOHO/CDS and SUMER spectral data.

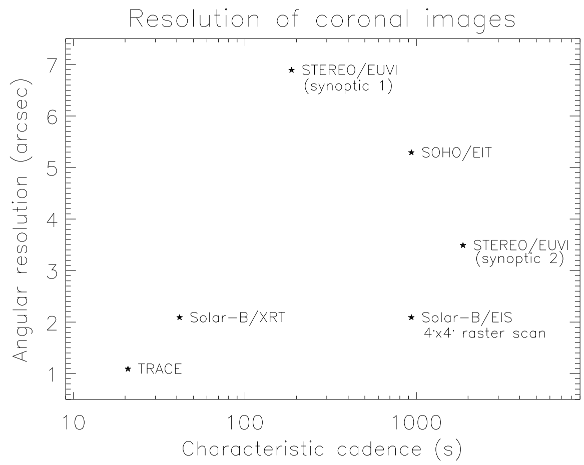

Figure 5: *The figure compares the characteristic cadence and resolution of current and future imaging (incl. rastering) instrumentation for the solar corona prior to the launch of SDO. A large and important domain of high cadence and angular resolution is accessible only by* TRACE *and Solar-B.* TRACE *provides unique access to the highest resolution at $1-2$ MK which can be approached otherwise only by Solar-B/EIS in raster scans or is seen mixed with higher-temperature plasma in Solar-B/XRT images.*

1.2 Relevance to SSSC goals and objectives

The *TRACE* science investigation supports each of the strategic Objectives formulated in the recently-completed SSSC roadmap. Table 1 lists the Objectives, Research Focus Areas (RFAs), and the Investigations that explicitly list *TRACE* as a key contributing mission. The Roadmap Investigations that call out *TRACE* as a key contributor require *TRACE* observations because:

- F1.2: The coronal field topology is observed with *TRACE* at the highest available resolution (cf. Fig. 5); the topology, and its evolution, constrain the magnetic free energy, helicity, and reconnection rates.
- F2.1: *TRACE* images show coronal pathways for high-energy particles, and - in particle precipitation sites - show how particle acceleration sites evolve during flares and CMEs at the highest available resolution.

- F4.2: *TRACE* observations of the coronal field, and the field modeling that is guided by these observations, aid in understanding how field opens into, and closes off from, the heliosphere.
- H1.1, J2.1: The continuous high-resolution coverage of *TRACE* enables the detection and study of precursors to solar disturbances.
- H1.2: The evolution of the field at the base of the solar corona and wind by high-resolution EUV imagery provides the input of solar disturbances into the solar wind.
- H1.3, J2.1: *TRACE* helps quantify magnetic free energy and helicity, and thus helps forecast the occurrence of solar events. *TRACE*-guided field models will help us understand the pathways of solar energetic particles to geospace. *TRACE* also observes the early evolution of coronal mass ejections.

Background to these scientific rationales are given in sections 1.1.2 – 1.1.5. *TRACE*, of course, also supports the deepening of our general understanding of the physics of the star that we live with; examples of that research are given in section 1.4.

1.3 Future impact and productivity

The period FY 2007-2010 promises unique opportunities for exciting new research based on *TRACE* observations as a new solar cycle starts:

1. Continuous high-resolution vector-magnetographic data with Solar-B/FPP and SOLIS in combination with *TRACE* data allow the measurement of energy and stress buildup and release in flares and CMEs.
2. Spectroscopic data by the Solar-B/EIS enables (1) calibration of relative contributions from spectral lines to *TRACE* observations, and (2) spectroscopic studies of *TRACE* loop atmospheres, their hydrodynamic evolution, their fine structure, and the role of up and down flows as heat input evolves.
3. High-resolution, high-temperature coronal imaging with Solar-B/XRT allows the study of the full thermal range of the corona, clarifying why $1-2$ MK loops occur where they do, how they evolve into and from higher-temperature loops, and how the heating fluctuates along field lines.
4. Stereoscopic data with STEREO/EUVI aids in the understanding of the dynamic 3-D coronal magnetic field, helps resolve line-of-sight ambiguites, and helps quantify the large-scale and core coronal configuration around CMEs and their associated filaments.
5. High-fidelity numerical simulations of real coronal conditions and instabilities will allow us to validate our understanding. These realistic models will be driven by horizontal flows derived from Solar-B/FPP image sequences and may include vertical velocities derved from Solar-B/EIS spectra. *TRACE* data provide the coronal touch stone for model validation.

The *TRACE* project will continue to participate in, and stimulate, multi-mission joint observing campaigns. As a result of the science needs as much as our dedication to support Joint Observing Programs (JOPs), *TRACE* is a participant in 80% of the 100 most-recently defined SOHO JOPs, and has participated in 70% of the JOPs actually implemented by SOHO over the past two years. Particular efforts continue to be made to coordinate during campaigns of continuous contact for *SOHO/MDI* (both in full-disk and in high-resolution mode), *SOHO/-EIT* shutterless campaigns, intermittent campaigns with *SOHO/SUMER*, when observing as a complementary instrument to *SOHO/EIT*, or making full-disk composite images during the extended EIT bakeouts implemented after SOHO's antenna problems developed. Coordinations with SOHO and RHESSI are given top priority, and *TRACE* responds to all Major Flare Alerts. In future years, close coordination with the Solar-B mission and STEREO missions will be implemented.

Since the launch of *RHESSI* on 5 February 2001, *TRACE* closely coordinates with the RHESSI team and the associated Max Millenium campaigns, to obtain optimal data for flare studies. Such data include (a) EUV observations to see pre- and post-flare configurations, as well as the hot plasma component visible in the Fe XXIV line in the 195 Å channel, (b) UV observations to study the impact of high-energy particles on the high chromosphere (in flare ribbons), and (c) white-light studies to see

Table 4: A selection of recent discoveries (2003-2005) about the physics of the Sun's atmosphere that are based in large part on *TRACE* observations.

Finding	Select reference(s)
• Acoustic wave power through the upper photosphere is insufficient to power the chromospheric radiative losses; if proven correct, this implies that magnetic heating dominates everywhere, and thus indirectly proves the existence of a small-scale turbulent dynamo in Sun and other cool stars	Fossum and Carlsson (2005); also DeForest (2004)
• Inclined chromospheric magnetic fields help channel otherwise evanescent acoustic waves into the solar corona, and may explain spicules	De Pontieu et al. (2004, 2005)
• Multi-instrument spectroscopic and imaging studies reveal that filaments seen as dark structures in *TRACE* may, in some cases, be caused by non-emitting voids rather than absorption by cool plasma.	Schmieder et al. (2004)
• Reconnection between emerging and existing field occurs with typically a 1-day delay and in small bundles of $\sim 4 \times 10^{18}$ Mx.	Longcope et al. (2005)
• Significant non-potentiality of coronal configurations is driven by flux emergence, likely carrying electrical currents, and decays within typically one day through coronal reconnections	Schrijver et al. (2005a)
• Ab initio MHD models of coronal heating over a small active region by braiding of field lines is quantitatively consistent with the coronal emissions and qualitatively with the coronal appearance. Coronal heating appears to be more effective for lower filling factors of footpoints within active regions	Gudiksen and Nordlund (2005b, 2005a); Katsukawa and Tsuneta (2005)
• Photospheric motions may, in some cases, be more important than new flux in adding helicity to a filament about to erupt.	Romano et al. (2005)
• Erupting filaments in CMEs show acceleration profiles that appear to include exponential, constant acceleration, and constant rate of change of acceleration	Elmore et al. (2005); Goff et al. (2005); Williams et al. (2005); Sterling and Moore (2005)
• Twisted helical flux ropes form because of reconnection in some eruptive events; the inferred reconnection appears consistent with the breakout model	Li et al. (2005); Gary and Moore (2004)
• Twist and writhe in pre-eruption state of CME-related filaments have the same sign, supporting the kink instability	Rust and LaBonte (2005)
• Multi-strand impulsive heating and cooling models appear consistent with the appearance of coronal loops in EUV and X-ray images	Winebarger and Warren (2005)
• Emission profiles and filter ratios suggest that 'monolithic', isothermal loop strands have been observed with widths of 1.5 ± 0.3 Mm; most lines of sight, however, contain many temperatures, perhaps often within the same loop strand.	Aschwanden and Nightingale (2005); Schmelz et al. (2005)
• Particle acceleration during flares, as reflected in the ribbon precipitation, is related to the reconnection rate as measured by (*TRACE*) footpoint motions across the (SOHO/MDI) magnetic field	Fletcher et al. (2004)
• Models of twisted flux-rope emergence into the corona appear consistent with observations. Rotation of flux patterns reflect twist, and is thus related to large flares if the twist is large enough.	Gibson et al. (2004)
• Simulations of a kink-unstable flux rope match the appearance of a destabilizing filament very well (Fig. 6)	Török and Kliem (2005)
• The solar wind properties (such as the charge state) can be correlated to properties of wave travel times in the near-photospheric and low-chromospheric layers, suggesting a deep source region of the solar wind	McIntosh et al. (2004); McIntosh and Leamon (2005)
• An eruption of a small active region, with $100\times$ less flux than a large active region, was observed to have a signature in the solar wind; this is the smallest 'CME' thus far traced plausibly from the Sun to a near-Earth magnetic cloud	Mandrini et al. (2005)

flare-related consequences close to the photosphere. Image cadences in WL/UV are often as high as 1 frame per 1.5-2 s, and in the EUV 1 frame per 5-10 s, or faster during bright flares.

TRACE coordinates with ground-based optical observatories in the U.S., including the observatories of NSO (SPO, KPNO), BBSO, and Mauna Loa, as well as with international observatories, including THEMIS and Pic du Midi (France), SST (Swedish Solar Telescope at La Palma), DOT (Dutch Open Telescope at La Palma), and the Japanese Hida observatory. We also coordinate with radio observatories, including VLA (U.S.A.), Ooty (India), Nagoya (Japan), and EISCAT (Norway). With JOP 136 (the Max Millenium RHESSI coordination), we further participate in a world-wide flare program with 40 ground-based observatories. The *TRACE* team (co-)authors or supports many of the publications based on these joint programs.

1.4 Scientific accomplishments and impact

Scientific advances that are based on *TRACE* observations span a broad range of research areas. The publication list maintained by the *TRACE* team contains all publications known to us that are based on either *TRACE* observations directly or on *TRACE* findings from other studies. At the time of this writing, the list contains a total of 550 publications, of which 371 are in refereed journals. The number of papers per year is relatively constant, if not slightly increasing with time, at ~ 55 refereed publications per year (Fig. 7). Discoveries continue to be made that warrant broad national or even international attention: in the past 12 months, for example, *TRACE* observations lead to two publications in Nature (both on wave propagation into and through the lower outer atmosphere), a Nature Highlights entry (on kink instabilities in filament), three NASA and AAS press events (on corona-heliosphere coupling, rotating sunspots and X-class flares, and forecasting of major flares), and multiple smaller events. Invited and contributed talks based on *TRACE* data occur at many solar-physics meetings, and in particular at the following meetings in whose organization the *TRACE* team was significantly involved or part of the initiating group:

- "SOHO-13: Waves, oscillations and small scale transient events in the solar atmosphere: A joint view of SOHO and *TRACE*," held on Mallorca in Sep./Oct. 2003[2].
- SOHO 15, on solar coronal heating, held in St. Andrews, UK, August 2004[3].
- A workshop on solar coronal loop fine structure and dynamics, in Palermo, Italy, September 2004[4]. The problem of loop fine structure that was debated during that workshop continues to engage researchers.
- A joint RHESSI/SOHO/*TRACE* workshop with special emphasis on high-energy processes in the solar atmosphere, held in December 2004 in Sonoma, California[5]

In addition to scientific publications, the *TRACE* team have completed a set of 5 DVDs with particularly illustrative or spectacular events: three DVDs focus on filaments, flares, and active regions, respectively, a fourth presents educational materials on magnetic fields from the deep solar interior into the heliosphere, while a fifth shows the 1996-2005 SOHO/MDI magnetogram sequence and the 1990-2001 YOHKOH full-disk image set. These DVDs are being distributed to the community, and the movies are being made available on the *TRACE* web pages[6].

A sampling of scientific findings published in the past two years has been compiled in Table 4. Here we highlight a few of these discoveries in their broader context:

Flares: Reconnection rates during flares and quiescent conditions have been measured, either by mapping the particle precipitation sites in flare ribbons (Fletcher et al., 2004) or by comparing observations and models of field geometries (Longcope et al., 2005). Studies such as these, relying on the high spatio-temporal resolution of *TRACE* images, bring the difficult task of quantifying coronal field reconfigurations within reach.

[2] http://soho13.uib.es/
[3] http://www.soho15.org
[4] http://www.astropa.unipa.it/EVENTS/LOOPW/
[5] http://sprg.ssl.berkeley.edu/RHESSI/rst/
[6] http://trace.lmsal.com/Public/Gallery/Movies/

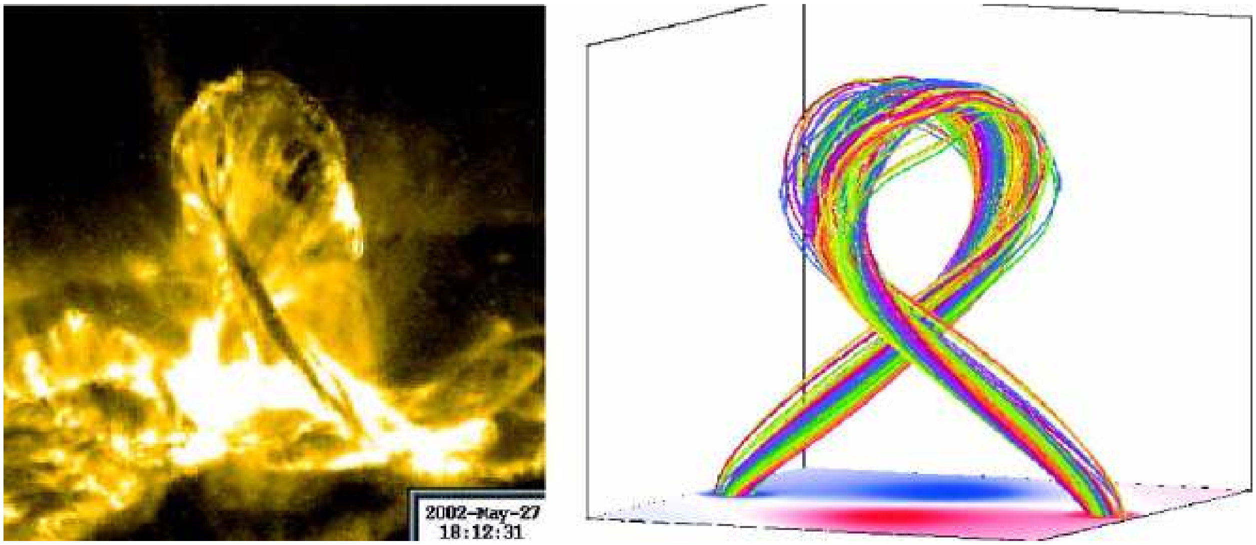

Figure 6: *Left:* TRACE *195 Å images of the confined filament eruption on 2002 May 27. Right: Magnetic field lines outlining the core of the kink-unstable flux rope as modeled by Török and Kliem (2005), shown over the projected model magnetogram. The model matches this eruption throughout its evolution. This work was discussed in a Nature Physics Highlight (2005/09/01).*

Filament eruptions: The study of filament eruptions yields results that support multiple mechanisms, including the kink instability, the breakout concept, and the tether cutting (compare some of the entries in Table 4). Perhaps this implies that all of these mechanisms operate on the Sun, but with different strengths under different conditions. Comparisons of models and observations stimulate research, as some models begin to reproduce observations remarkably well (see the example the evolution of a kink-unstable filament in Fig. 6).

Waves: Fossum and Carlsson (2005) simulate UV signals for the *TRACE* 1600 Å and 1700 Å channels for various power spectra of acoustic waves traveling into the lower solar atmosphere. By comparing these with actual observations of waves in the quiet Sun, they conclude that there is between 10 and 100 times less acoustic power than predicted from theoretical approximations. That means, for one thing, that convective simulations need now be made to understand why this is the case. The implications for solar dynamo action are exciting: if, as they claim, the quietest chromosphere is not heated by acoustic waves, then the so-called basal chromospheric emission from the centers of supergranules and from entire inactive Sun-like stars (e.g., Schrijver, 1995) must be generated by magnetic processes. The emission levels are the same for the present-day Sun as for a very old main-sequence star, so that the Sun's local dynamo should generate a turbulent intranetwork field independent of the activity level of the global cyclic dynamo.

Coronal field and electrical currents: The comparison of potential fields and active-region loop observations by Schrijver et al. (2005a) suggest (1) that large-scale electrical currents exist in active-region coronae only because of flux emergence (likely even because the currents are carried into the corona by the emerging flux), and (2) that despite theoretical arguments to the contrary, these currents disappear on a time scale of approximately one day (supported by other studies referenced in their paper). That study supports multiple earlier findings that the dynamics of the field is essential to measure the field's energetics in order to forecast when flares of what magnitude can be expected.

Coronal heating and magnetic field: Numerical experiments of entire active-region coronae are now possible, and the work by Gudiksen and Nordlund

(2005a, 2005b) shows that a simulated corona resembles *TRACE* observations both in the amount and appearance of emissions. In their model, the braiding induced by footpoint motions caused by the granular convection provide the power that heats the corona. *TRACE* observations have also provided views of the coronal field that add to the puzzle, however, such as, for example, the near-constant cross section of coronal loops which appears incompatible with our understanding of the magnetic field (e.g., Klimchuk, 2000; Bellan, 2003; Lopez Fuentes et al., 2005).

Loop atmospheres: Loop atmospheres continue to challenge modelers, and differences in opinions sparked a series of papers by authors that include Aschwanden, Cirtain, Martens, Peres, Schmelz, Testa, Warren, and Winebarger. This merited a dedicated international workshop in Palermo, after which the discussion continued in a series of papers in the literature. Spectroscopy with the relatively low-resolution SOHO/CDS suggests a multi-temperature structure, while *TRACE* 3-filter studies suggest a single temperature at least in some of the sharpest structures (e.g., Schmelz et al., 2005; Aschwanden and Nightingale, 2005; Cirtain et al., 2005a and references therein).

1.5 Productivity and vitality of the team

The *TRACE* team continues to be active in stimulating and carrying out science, despite the fact that purely scientific investigations are not funded by the *TRACE* project or by an associated GI program. The Investigator team is active in defining or organizing international scientific meetings, disseminating the results to scientific colleagues as well as the general public. The core *TRACE* team will continue to oversee, guide, and stimulate research performed by guest investigators that use the data under a variety of grant programs. Members of the *TRACE* team (co-)author or support many of the *TRACE*-related studies in the literature.

The vitality of the *TRACE* team benefits from the involvement of multiple (under-)graduate students, both in our core institutes (see Sec. 5), as well as in other institutes around the world. *TRACE* thus plays an important role in the education of the next generation of solar physicists.

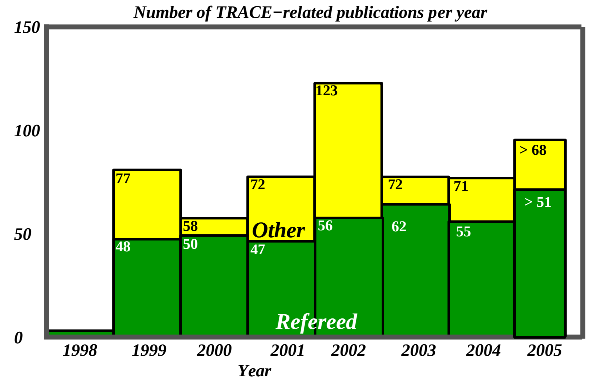

Figure 7: *Number of research publications per year (up to 2005/09/01) based directly on* TRACE *data or on findings derived from it (full listing at http://trace.lmsal.com/tracepubs.html). The short green bars show the numbers in refereed journals (ApJ, A&A, PASP, PASJ, Nature, Physics of Plasmas, Science, and Solar Physics). Abstracts published in AGU and AAS meeting booklets were not counted. The bar lengths for 2005 were scaled to reflect that only 9 months had passed at the final count.*

1.6 Data use, accessibility, and usability

Scientists from around the world use *TRACE* data. The data are obtained either directly for them in (joint) observing campaigns or they request existing observations from the data archive. In total, 2.4 million images (or 2,250 GB) had been exported from the primary *TRACE* data archive at Lockheed Martin to external users by September 2005 (Fig. 8). The mirror archive at GSFC has exported approximately one quarter of that volume. Interestingly, the daily data volume being exported from the archive through user requests has exceeded the rate at which *TRACE* obtains data since early 2003. The average rate of data requested continues to grow, doubling every 1.4 years over the past five years. *TRACE* data are being used in studies spread over many areas in solar physics. Requests for *TRACE* archival data span the entire mission duration, with clearly enhanced interest in times of major flares and in the most recent data. Data requests are significantly more frequent around times of international coronal-physics meetings, which motivates frequent involve-

Table 5: *A selection of web resources for the* TRACE *investigation*

Home page	http://trace.lmsal.com
Scientific results	http://trace.lmsal.com/Science/ScientificResults/
U.S. data centers	US (West) http://trace.lmsal.com/trace_cat.html
	US (East) http://sohowww.nascom.nasa.gov/sdb/trace/DCE/
Analysis Guide (TAG)	http://trace.lmsal.com/tag/
Flare catalog (being updated)	http://hea-www.harvard.edu/SSXG/TRACE/flares/flares.html
“Picture of the day” collection	http://trace.lmsal.com/POD/TRACEpod.html
Movie collection	http://trace.lmsal.com/Public/Gallery/Movies/
Loop oscillation data and movies	http://trace.lmsal.com/POD/looposcillations
Active-Region data base	http://zorak.lmsal.com/ar/
Operations and recent images	http://trace.lmsal.com/TRACErecent.html
Long-term plan	http://chippewa.nascom.nasa.gov/TRACE/current_plan.txt
Potential-field overlays	http://www.lmsal.com/forecast/TRACEview/
Venus transit	http://trace.lmsal.com/transits/venus_2004/
Educational material	http://trace.lmsal.com/Science/ScientificResults/trace_cdrom/

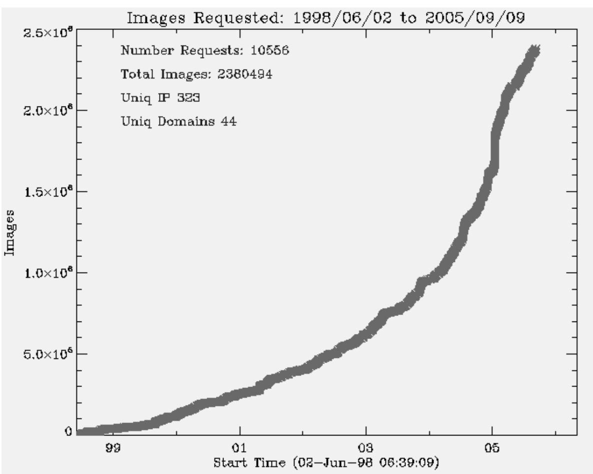

Figure 8: *By September 2005, a total of 2.4 million images (or 2,250 GB) were exported from the archive at LMATC to external users. The second-most active mirror archive at GSFC has exported roughly an additional 25% of that volume. Note the strong increase in the cumulative number of exported images around the RHESSI/*TRACE*/SOHO workshop in December 2004, after which the data exports resumed their exponential increase, doubling the export rate every 1.4 y.*

ment of *TRACE* team members in their organization.

Investigations based on *TRACE* data are a mixture of studies requesting tailored observations and studies based on archival data. The *TRACE* project has had a completely open data policy from the very first day of observations, with no restrictions whatsoever. As soon as the spacecraft telemetry has been reformatted and archived, the data are accessible - normally well within 6 h of observing and 1 h of receiving the data from the ground station.

Faster access to the large amounts of data is provided by mirroring the archive files to Goddard Space Flight Center, and further transfer them electronically or by tape to mirror archives at Rutherford-Appleton Labs in the U.K., the Kiepenheuer Institute in Germany, JAXA in Japan, and Meudon in France.

TRACE analysis software is available on the web, as part of the widely used and openly available SolarSoft[7] suite of IDL routines, as well as a special (much faster) image-viewing package called “browser”. Information on this software is provided in an on-line, up-to-date *TRACE* Analysis Guide (TAG; see Table 5 for the URL). Apart from the TAG, the *TRACE* team maintains web pages with interesting images, observed flare events, loop oscillation events, etc.; some of these resources are listed in Table 5.

1.6.1 Data-center & web-interface enhancements

The *TRACE* Data Center in Palo Alto has undergone several significant improvements over the past year. In response to the increasing traffic of data requests and public outreach efforts, the connection to the

[7] http://www.lmsal.com/solarsoft/

internet was increased from 6 Mbps to 45 Mbps, a seven-fold improvement. The *TRACE* data server, trace.lmsal.com, was upgraded, delivering a CPU performance $14\times$ greater than the original server, and a doubling in data throughput.

The increase in computing and network capacity has in turn enabled further enhancements in data services. The 12 h cycle of the data processing pipeline for incoming data has been reduced to 1 h. The pipeline control has been implemented using the Collaborative Sun-Earth Connector (CoSEC[8]) framework, which continually polls the *TRACE* EOF at Goddard for new data, mirrors it to Palo Alto, reformats and catalogs the images, and updates the recent movies web pages. As a result, observations collected by *TRACE* are available on the web generally within one hour of its receipt at the EOF.

The recent spate of large flares from Active Region 10808 in September 2005 provided the first stress test of the new system. Unlike previous events, the network capacity did not saturate due to community interest, even though the Apache web server software did reach saturation at over 65,000 requests per hour at peak demand. We are currently investigating the best method for handling such situations, including upgrading the web server or perhaps off-loading the latest-events pages (typically the most popular) to an external host.

Other enhancements to the *TRACE* data services include the option of requesting calibrated images directly from the data center, rather than requiring researchers to apply SolarSoft IDL calibration routines themselves. This option can be computationally expensive, so we apply reasonable default parameters to the calibration to avoid overloading the server. The second data center at GSFC has recast the raw images to accommodate the current version of the Virtual Solar Observatory[9], and is providing those images through the VSO. We are working with the CoSEC project to develop tools for more sophisticated mining of *TRACE* data, including connections to event lists, external databases and other missions. Finally, we have revamped the *TRACE* website to increase the visibility of current *TRACE* operations and most-recent data, the *TRACE*-related scientific literature, the updated *TRACE* Analysis Guide, and other documentation aimed at improving the usability of *TRACE* data.

[8] http://cosec.lmsal.com/

[9] http://umbra.nascom.nasa.gov/vso/

1.6.2 Data-center plans for 2007-2009

An important objective for the final years of *TRACE* observations is to provide context imaging and unique complementary observations to Solar-B, STEREO, and components of the SSSC Great Observatory. *TRACE* observations moreover provide a test bed for developing SDO/AIA data operations. With that in mind, improvements to the data center will focus on providing data-fusion capabilities, which should seamlessly link *TRACE* images to these newer missions. Using tools developed under the CoSEC project, we plan to provide and support enhanced services to the Virtual Solar Observatory as well as to the other Virtual Observatories that are under development. CoSEC-enabled services will permit researchers to integrate *TRACE* observations into cohesive data operations for integrated data analysis.

1.6.3 Data-center plans for a Resident Archive

Once *TRACE* completes its cross-calibration with AIA, we will begin the transition from an active mission archive to a Resident Archive. A Resident Archive is a transitional stage between an active mission and the final, permanent archive: the data are maintained by members of the original mission team and continue to be served to the research community by them. During this phase, data may be reprocessed and prepared for the eventual transition to a true archive, or perhaps for their merging with data from a follow-on mission (perhaps the SDO/AIA in this case).

Using the final calibrations, we will reprocess the entire decade of *TRACE* images to produce a final, fully calibrated, data set. This will require reprocessing the 1.6 TB Level 0 archive to produce approximately 10 TB of near-lossless compressed Level 1 archive, which would include the assembly of all full-disk mosaic images. This archive would be hosted by the AIA Visualization Center (where its volume would be equivalent to approximately 10 days of AIA data). Data would then be served to the solar community through the VSO or its descendants.

2 Technical section

2.1 Overview of mission operations and data analysis

TRACE was launched into a near-perfect orbit on 2 April 1998, and first light was achieved on 20 April. Science observing began with a 30-day plan that had been formulated in detail well before launch. *SOHO* collaborated extensively with nearly all *TRACE* observations during this period, and the pre-planned program was over within two months. After that, we began observing in a flexible manner, essentially as an additional *SOHO* instrument. In early November, 1998, *TRACE* went into its 3-month period with eclipses interrupting the continuous solar viewing. We had planned to turn the instrument off, but the observatory power margin was so good that it was left on; this was safer and allowed science observing to continue. However, observing was kept quite simple, since the potential for outstanding observations was reduced due to the eclipse interruptions (one per orbit, up to 24 minutes long, plus $\sim$15 additional minutes of atmospheric EUV absorption). This pattern of modest yet still productive observing during the eclipse season has been followed ever since.

Aside from the pleasant surprise of eclipse season observing, the pre-flight plans for both science operations and data handling have been closely followed throughout the mission. A small Flight Operations Team (FOT), working at the SMEX Mission Operations Center (MOC) at GSFC, handles all satellite operations. *TRACE* data is collected typically during six telemetry passes per day (four over Poker Flat, two over Wallops Island), which are normally fully automated. The FOT attends one pass every weekday to send commands that contain the observing timeline for the next day (or three days, on Fridays). The support staff for flight dynamics, telemetry pass scheduling, computer maintenance, etc., are shared among multiple missions.

Every week, one *TRACE* scientist is designated as planner. General priorities for each week are decided by email and in a telecon the previous Thursday, using a calendar of proposed observations similar to the *SOHO* calendar[10]. In consultation with *SOHO* planners and other collaborators, the planner chooses the target region(s) on the Sun and makes a timeline of detailed observations for the instrument to execute. The timeline is given to the FOT every weekday afternoon for the daily uplink. During most of the eclipse season, the timeline rate is decreased to three per week, and fixed programs are run for weeks at a time.

During the extended mission since 2000, *TRACE* science operations have become more efficient but no less effective. In the first observing season (1998), we maintained an operations team at the Experiment Operations Facility (EOF) at GSFC of three scientists, a data technician, and a computer systems administrator; and frequently scientists visited GSFC for a week to act as *TRACE* planner. In 2000, we switched to remote science planning, using improved connectivity and software tools which enable routine operations from the home institutions. Flurries of email have largely replaced the daily and weekly meetings. Now scientists only travel to GSFC by choice to interact with scientists there, not by necessity to do planning and operations. The EOF staff has been reduced to one part-time science planner/operator. The daily planning activity takes 1-3 hours depending on the complexity of the plan. We have never missed a deadline for providing the science timeline to the FOT for uplinking.

Although some operations have become routine and simple, such as fixed programs during eclipse season or flarewatch with RHESSI during a Major Flare Alert, the *TRACE* planners still provide individual attention and customized observing programs for JOP's and ground-based observatory collaborations. For example, for one program in September, 2005, there was daily email traffic for a week from scientists in Norway, La Palma, Japan, GSFC, and LMATC optimizing the on-board table loads, target selection and scheduling of the observations.

Telemetry data is collected at the ground stations and sent by ftp to the level-zero Data Processing System (DPS), a workstation located in the MOC at GSFC. This sorts and catalogs the data, saves it on disk and tape, and sends it by ftp to one of our workstations in the EOF; this is the official

[10] http://chippewa.nascom.nasa.gov/TRACE/current_plan.txt

delivery of data by NASA to the science team. The FOT maintains the DPS and tracks down missing data files from the ground station.

Once the data is delivered, it is sent LMATC in Palo Alto for cataloging, reformatting and archiving. The data are generally available for the entire science community online from the LMATC data center within 4 hours of receipt by the ground station. Within a day, the reformatted data is mirrored to the GSFC data center (part of the SDAC) and to SAO and MSU. The entire mission data set is online on disk at both the LMATC and SDAC facilities for immediate access; partial mirror sites also exist in Europe and Japan. All data is available to anyone via a web interface with capabilities for searching the catalog, either in raw or (since 2005, see Section 1.6.1) calibrated form. Data-analysis software is also available on line (Section 1.6). This data distribution system has been very well received by the solar physics community. It is being considered as the model for the Solar-B Data Distribution system which will be implemented at ISAS and mirror sites in the US and Europe. *TRACE* is fully compliant with the draft "Rules of the Road" for SEC mission data handling.

Since the second month of the mission, the *TRACE* science team, FOT, and data flow technicians have worked a nominal 8 hour day five days a week in order to minimize costs. This has proven to be an adequately safe policy which is far more cost effective than 24/7 staffing. The robustness and autonomy of the observatory, combined with ground software which automatically pages the FOT in event of an observatory anomaly and frequent web monitoring of the instrument telemetry by the science team, make this possible. Special arrangements have been made so that the *TRACE* planner will be notified anytime day or night, should RHESSI declare that a region has high potential for a γ-ray flare. The planner, our local operator, and the FOT then work together to ensure that *TRACE* is observing the proper target region.

2.2 Observatory & ground system status

The health of the *TRACE* Observatory remains excellent. We are confident that *TRACE* can continue

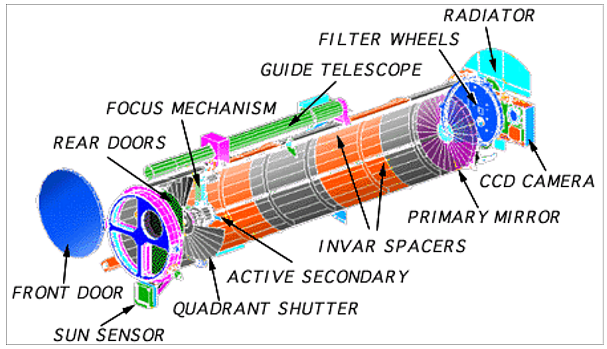

Figure 9: *Cutaway figure of the TRACE instrument*

to collect outstanding solar data until it is superceded by SDO/AIA early in 2009. Neither the spacecraft nor the instrument contain any consumables that would lead to a predictable end of mission life before this. Some limited signs of aging are discussed below.

Orbit predictions show that the sustained solar activity of the last two years has caused more atmospheric drag and orbital decay than expected. At the last Senior Review, the Flight Dynamics prediction showed full sun orbits would continue past 2009. The original orbit had 267 days of uninterrupted Sun-viewing per year, and in 2003 the total was still 267 days. For 2005 and 2006, the predictions are 247 and 228 days, respectively. In 2007, there will be a period with short eclipses during the orbits in summer as well as winter, reducing the total number of days with continuous observing to 132 days. Starting in the spring of 2008, all orbits will have an eclipse. These eclipses will be as short as 10 minutes (10% of the orbit duration) in the spring and summer; this allows observing to continue without concerns about the spacecraft power budget. The eclipses may last as long as 30 min. (30% of the orbit) during the winter months. We propose that our last observing will occur in the spring of 2009, to overlap with SDO after its launch in late 2008 and a 90-day commissioning period and during *TRACE*'s last season with eclipses shorter than 15 minutes.

The spacecraft is in fine shape in all respects. The solar array output has changed very little since launch and had significant margin then. The reaction wheel glitches discussed in the 2001 Senior Review proposal have stopped occurring, and the attitude control system performance is excellent. Since

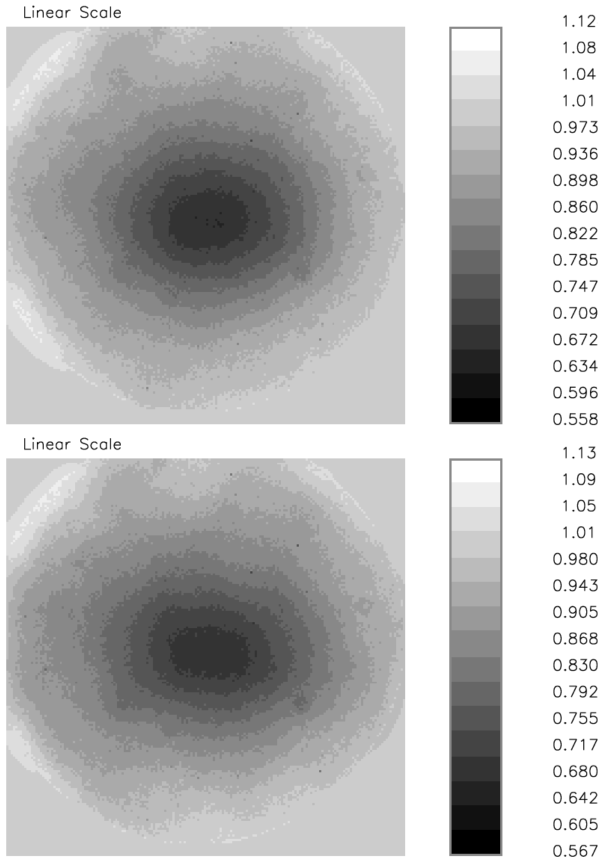

Figure 10: *The top image shows the 1700 Å flat fields (relative response) for 6 June 2005. This current flat field, after repeated CCD annealings, is very similar to the lower one for 1 May 2002 because of the increase in sensitivity caused by repeated CCD annealing. Flat fields for other wavelengths are qualitatively similar.*

launch, the spacecraft has gone into a safe-hold condition four times. Each time the FOT has promptly returned the spacecraft to normal operation and turned on the instrument within a day. Normal science observing has resumed within two working days, despite one of the events coming on Friday afternoon before a holiday weekend and another during a blizzard which shut down GSFC. With only four such occurrences in over seven years there is no meaningful prediction of how often such events may occur in the future, other than very infrequently. The battery still shows considerable margin during eclipse season, decreasing to about 79% of full charge during the longest eclipses (23 minutes) in 2004. The threshold at which the FOT would consider powering down the instrument is 70%, and this may happen during December 2008.

The closest thing to a consumable within the instrument is the lumogen coating on the CCD. This coating absorbs UV and EUV photons and re-emits visible photons which are then recorded by the CCD. The same EUV photons, which are our signal, gradually degrade the sensitivity of the lumogen. This happens particularly near the center of the CCD where active region images are usually recorded (Fig. 10).

Until 2004, the *TRACE* CCD experienced an exponential decay of EUV sensitivity with an e-folding time over most its surface of 5 years or more. Since then, we have found that annealing the CCD, warming to 40°C or more for several days, restores a significant fraction of the lost sensitivity. The annealings in March 2004 and February 2005, for example, restored the quantum efficiency at 171 Å to approximately 2001 levels. Figure 11 shows the sensitivity versus time for all wavelengths, UV and EUV, for the center of the field of view. Annealings increased the central sensitivity by more than 40% for some wavelengths. The CCD-averaged sensitivity for the most-often used 171 Å channel, for example, has increased by a factor of 1.4 from 31% of the launch value to 43%. Effective observing remains possible at all wavelengths with the limited loss of sensitivity. Most observations can use longer exposure times to compensate without real loss of temporal resolution, since cadence is frequently limited by on-board mass memory capacity; for other programs the planner chooses to reduce resolution and maintain high cadence and acceptable signal level. EUV intensity ratios for temperature estimates are not affected by the sensitivity loss since it is nearly identical for all three channels.

In the last review, we described the calibration of this sensitivity loss so that flat fielding of images is possible with about 5% accuracy and the overall sensitivity change is known to perhaps 20%. This is a complicated procedure relying (among other things) on synoptic disk center images in all UV wavelengths, in which quiet disk center is used as a "standard candle," and EUV "dosimeter" images (low-resolution records of total EUV flux on the CCD throughout the mission). Flat fields and calibration factors for all UV wavelengths were released for users in fall of 2002 in the IDL SolarSoft routine trace_prep and associated databases; and for EUV wavelengths in May, 2003. The improvement caused by annealings was measured directly for the UV wavelengths from synoptic images; the EUV improvement is more difficult to measure accurately due to the high contrast and variability of *TRACE* EUV images. Our suspicions that the EUV sensitivity calibration after annealing has not been correct since some time in 2004 were recently confirmed by a comparison with EIT images, and we are working to fix that now. We plan to continue annealing approximately twice per year. Annealing also temporarily reduces the number of “hot pixels” on the CCD, pixels with extra dark current caused by radiation damage.

Another sign of aging can be noticed in *TRACE* EUV and dark images with many particle hits. On the Eastern (left) side of the CCD, particle hits show faint trails to the East (left) due to decreased charge transfer efficiency in the CCD. This is a result of lattice damage caused by the integrated radiation dose to the CCD. The effect causes an asymmetric, spatially-dependent tail on the point spread function with amplitude of about 5% one pixel off the main peak. Thus it has minimal effect on the resolution of solar structures but is noticeable (and distracting) in particle hits. To reduce any artifacts caused by this, we have begun using better quality JPEG compression in our standard observing programs.

In terms of mechanisms (see Fig. 9, *TRACE* contains two filter wheels, a focal plane shutter, a quadrant selector mechanism, a pair of rotating pointing wedges, and a focus mechanism. Although the nearly 17 million images which have been taken by *TRACE* in the last seven years is an impressive number, it pales in comparison to the 90 million images that have been taken by MDI; and the focal plane shutter, filter wheels, and rotating wedges are basically copies of MDI units. The focus mechanism, which has made about 18 million steps, shows no sign of wear, but to be conservative we are now using it much less than before by taking the UV and white light images at the position of best EUV focus, except when they are the primary science images. Such UV/WL images are only about 1.5 depths-of-field out of optimal focus, which is hardly noticeable on such high contrast images.

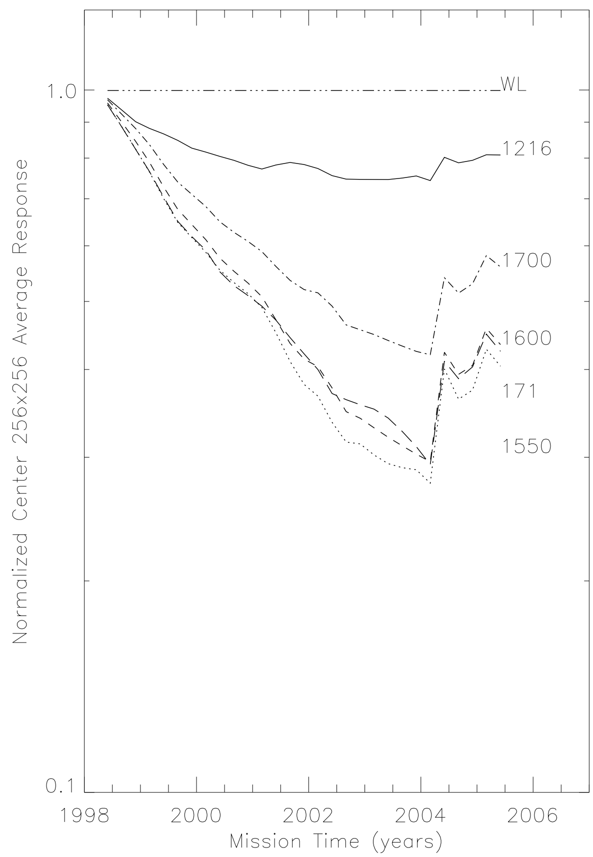

Figure 11: *Relative responses of the* TRACE *bandpasses at the center of the field of view. Several CCD annealings have rejuvenated the detector sensitivity to a level equivalent to early in 2001.*

The quadrant selector, which uncovers one of the four wavelength channels, is the only mechanism which has caused some concern and limited some science observing. Occasionally, it misses its destination by more than one step. Sometimes it recovers on its own, but other times it loses track of its position and does not recover until a reset procedure is run. We do not fully understand why this occurs but are convinced that the unit is not mechanically breaking down; rather its control system somehow “gets confused.” The last Senior Review proposal described our efforts to investigate this problem and devise a solution in on-board software. That solution has been implemented successfully, so now the instrument software senses when the quadrant selector misses its destination and signals the spacecraft to start a reset procedure. This relieves the FOT and science team from the burden of constantly monitoring and responding to the anomaly.

With this software mitigation in place, we have run many multi-wavelength observing programs. When resets take place, they interrupt observing for about a minute. The software also counts the number of resets during an observing sequence and can stop the program if that exceeds a threshold. So we always warn scientists requesting these observations that there is a risk of data loss. The problem is quite intermittent and appears to be seasonal to some extent. During some JOPs and campaigns we use the quadrant selector intensively and run for days without significant data loss, and on other days it is a real nuisance for multi-quadrant observing.

The *TRACE* ground system has been quite stable throughout the mission, the biggest changes being gradual adoption of security measures in accordance with NASA policy. The Level-0 DPS has moved from the EOF into a more secure area. EOF and LMATC computer systems have received considerable attention to plug security loopholes, and the *TRACE* Information Technology Security plan has been approved. The FOT and DPS operators have been cross-trained in the past two years, so that one integrated small team efficiently handles both spacecraft operations and ground data processing.

In summary, the *TRACE* observatory and ground system show only modest signs of wear. They will continue to perform very well during the STEREO and Solar-B primary missions, resulting in new and extraordinarily productive collaborative observations. They will certainly last into 2009 to overlap with SDO and provide a final calibration of *TRACE* with AIA and EVE. A direct calibration between SDO/AIA and *TRACE* for the overlapping 171 Å, 195 Å, 1600Å, and 1700 Å channels will make *TRACE* data serve as a record of almost a full solar cycle prior to the start of the SDO mission.

3 Budget section

3.1 In-guideline and optimal scenarios

The "In-Guideline" Scenario funding for FY-2007 and FY-2008 is the minimum level required for continued safe operation of the *TRACE* spacecraft and instrument, collection of valuable solar observations coordinated with other spacecraft and observatories, and archiving of the data for prompt access by the science community. The guideline results in budget cuts to the science team of 16% and 18% for FY-2007 and FY-2008, relative to the FY-2006 level; and level funding with a small inflation increase in each of these years for the FOT. In the "Optimal Scenario" for these years, we request more nearly level funding for the science team, to enable optimal collaborative observing with Solar-B and STEREO, to cross-calibrate *TRACE* with EIS and EUVI, and especially to serve the new users of *TRACE* data from these missions. In FY-2009, we are proposing a short period of simultaneous observation with SDO, to provide an accurate final calibration of *TRACE* EUV sensitivity, followed by the transition to Resident Archive status, which will be completed early in FY-2010. Following Dr. Holmes' instructions, the funds for FY-2009 and FY-2010 are listed in the in-guideline budget on the spreadsheet at the minimum tenable level.

Following the two previous Senior Reviews, we have streamlined mission operations and reduced the science data analysis effort supported by the TRACE project to a very low level, as requested. As a result, the mission funding for both the science team and the FOT is now more than a factor of two below the primary mission level, even with no inflation correction. The guidelines for the "mission extension paradigm" described in the call for this proposal are presently being followed precisely. The data archiving is highly automated and running in a cost-effective steady state. "Minimal science data analysis" to maintain understanding of the instrument performance, is being accomplished; and knowledge of the instrument calibration is applied to the data available to the science community at large. "Monitor[ing] progress toward accomplishing the objectives of science observations" goes on daily as part of the data monitoring and science planning by core team members. The goal "to involve the science community in formulating the mission observing program to make the best scientific use of NASA's missions," is being carried out very effectively, primarily as part of the SOHO planning process. These latter activities are labor intensive and require trained *TRACE* science planners for operations. Finally, most research with *TRACE* data is being supported by funds other than the *TRACE* project.

No additional funding cuts beyond those in the guideline can be accomodated without jeopardizing a safe and productive extended mission. Our strategy for dealing with the budget cuts in the guideline is to shift more of the science planning activities away from (relatively) senior scientists to students and recent graduates, especially at MSU. *TRACE* scientists at both LMATC and SAO will become heavily involved in Solar-B operations, starting in late FY-2006. During FY-2006 and early FY-2007, we will be training a new set of young *TRACE* planners who will take over the majority of routine science operations during the Solar-B and STEREO joint observing era. The core *TRACE* team of previous years will not disappear but will be supported primarily by other projects. They will still be available as necessary for specialized tasks such as observing program generation, engineering operations, and data analysis to maintain the instrument calibration.

Our optimal budget scenario asks for a small increase in funding to offset some of the cuts to the science team in FY-2007 and FY-2008. Both STEREO and Solar-B will be launched near the beginning of FY-2007, so that year will be an extremely exciting one for solar physics. Both spacecraft have instruments which share EUV passbands with *TRACE* so coordinated observing is extremely desirable. The STEREO EUVI instruments have full-sun fields of view but different aspect angles from *TRACE* allowing 3-D reconstruction of coronal structures. The Solar-B EIS instrument obtains spectra with spatial resolution comparable to that of *TRACE* so it will be fascinating to obtain simultaneous observations of a variety of solar structures. The added funding of the optimal scenario will support timely data analysis of these joint observations to benefit both missions, not only with "engineering" cross-calibrations but more importantly with scientific discoveries from their comparison. In addition, we expect large increases in requests for data from STEREO and Solar-B scientists, many of whom will not have previous experience with *TRACE* . We will use the additional funds to provide a higher level of support to these newcomers when appropriate, more like that of the prime mission phase. The "Solar Eruptive Events" GI Program (Sec. 1.1.1), if implemented, will also bring new users for the *TRACE* observatory and archive. In FY-2008, we will also use the optimal scenario budget increase to co-sponsor a workshop on Solar-B and STEREO science, similar to the RST workshop in 2004 (Sec. 1.4).

We have added continued observing in FY-2009 as part of our minimal scenario. SDO is now scheduled to launch in August, 2008, with a 90-day commissioning period following launch. Realistically, it may not launch before the fall or winter of 2008. Therefore, *TRACE* needs to continue observing into FY-2009 to avoid a gap in supporting observations for Solar-B, STEREO, and SOHO. In addition, SDO has two instruments which share EUV passbands with *TRACE*, namely the imager AIA and the irradiance spectrometer EVE. Simultaneous observations by *TRACE* and these instruments will enable the best possible calibration of *TRACE* EUV sensitivity, which will be applied retroactively to improve the entire 11-year archive. The best time for these simultaneous observations will be in March and April of 2009, when *TRACE* eclipses are shortest; indeed, observing may not be possible during the winter of 2008-2009 due to the length of the eclipses. We propose to "mothball' *TRACE* during that winter and then to have a last coordinated observing campaign with SDO (and Solar-B, STEREO and SOHO) during February to April of 2009. After this, *TRACE* operations will cease. The data will be analyzed to make the best possible calibration, and the *TRACE* mission will transition to a Resident Archive in late FY-2009 and early FY-2010.

3.2 Budget summary

The budget summary in the required spreadsheet format is appended to this proposal. The science team funding is shown in row 3, Science Center Functions, row 4, Science Data Analysis, and row 5, E/PO; and the total is shown in row III.1 *TRACE* Instrument. All other entries were provided by the Space Science Mission Operations Project (SSMO), which is the *TRACE* mission operations management organization at GSFC. They represent direct funding to GSFC for *TRACE* mission operations, funding to other branches of NASA for data services, and charges attributed to *TRACE* in multi-mission funding pools. In this section, we attempt to explain all these entries and to give a clearer sense of what the science team funding actually supports.

The science team provides some functions which are normally listed under the mission services category, including command generation and telemetry monitoring for the instrument; health and performance monitoring of the instrument and the ground system at the EOF; and flight software maintenance and engineering consultation for the instrument and the instrument simulator at LMATC. Row 3 Science Center Functions include science planning and observing program and timeline generation; instrument and observation performance analysis; science data calibration; master data archiving at LMATC; distribution to the mirror data archives at GSFC, SAO and MSU; quick-look data production; maintenance of the data distribution system and basic IDL SolarSoft routines. Row 4 Science Data Analysis includes meta-data preparation such as the flare catalog and active region database; custom software and data processing such as browser enhancements; data analysis and research; production of DVDs for the solar science community (as opposed to the general public); documentation, presentation and publication of technical and scientific results; support for symposia and meetings. The E/PO activities are described elsewhere in the proposal. Administrative and management costs for the science team are allocated to the three rows in proportion to the direct costs.

All science team funding is provided via a prime contract to Lockheed Martin, managed by the PI at LMATC; the science teams at SAO and MSU receive subcontracts, as does L-3 Communications (which provides the science planner at the GSFC EOF). LMATC and L-3 provide all of the science team's mission service functions listed above. SAO and MSU contribute a significant share of the science planning and timelining effort; the remaining row 3 Science Center Functions are provided entirely by LMATC and L-3. All four institutions are involved in data analysis and E/PO. Both MSU and SAO receive limited support for senior scientists and employ students and recent college graduates as research assistants. In the past year, four graduate students at MSU have been supported by *TRACE* for their research and science planning efforts, and SAO has supported two post-docs. LMATC supports several senior and junior scientific staff members at very limited and moderate part-time levels, respectively; engineers and software specialists as needed; visiting graduate students and post-docs with travel and per-diem funds; and high school students in an E/PO program.

The in-guideline funding for the science team as obtained from the GSFC mission manager is $1,725 K for FY-2007 and $1,681 K for FY-2008. This has been allocated among the categories based on the past year actuals as follows: 80% to II.3 Science Center Functions (including the mission services functions listed above), and 20% to II.4 Science Data Analysis, after a small fixed allocation for E/PO. Nearly all of the funding goes for burdened labor costs at all four institutions. Materials costs are for additional hard drives for the archive, occasional replacement of obsolete computers, and hardware and software maintenance contracts on essential systems; these costs will be low in these years, both because hardware costs have come down and because multiple missions (and corporate funds) share support for the data archives at LMATC. Travel and publication costs are also covered by the contract. Lockheed Martin provides full support for PI Alan Title as well as additional E/PO, computer hardware, software, and maintenance labor costs from corporate funds.

Mission operations costs in the In-Guideline and Optimal Scenarios (II & V) consist of the following. Row 2.a Data Services are costs for the T-3 internet line for data mirroring between GSFC and LMATC. Row II.2.b Mission Services supports the *TRACE* FOT and DPS engineers as well as some GSFC burden and surtaxes, rendering invalid a comparison of these figures with their counterparts in the 2003 proposal. The FOT has become smaller in numbers and more efficient although the costs appear to have risen as NASA moves towards full cost accounting. Row II.2.c include some sustaining engineering activities, which used to be funded by the SSMO multi-mission account and are now to be charged to TRACE for 2006-2008. These result in direct hits on the science teams funding, $ 350 K in FY-2007 and $ 200 K in FY-2008; our Optimal Scenario budget increases are chosen to offset these hits back towards the FY-2006 level. The values in Section IV represent services provided on behalf of TRACE, but not charged directly to TRACE. Ground Network costs for data downlinks and command uplinks (6 per day) at Poker Flat, McMurdo, Merrit Island, and Wallops Island are captured in IV.2.a Space Communication Services. IV.2.b Mission Services are costs incurred by SSMO Project directly related to Project Management and sustaining engineering activities for which SSMO has a separate funding source at this time.

The budget estimates for the extended mission with SDO in FY-2009 and transition to Resident Archive in FY-2009 and FY-2010 were made as follows. GSFC provided costs for full operations in FY-2009 for all items except the science team. We used half of these and half of the FY-2008 science team budget to cover the cost of operations through April, 2009. Then the science team is funded at half of that level for an additional 12 months (the rest of FY-2009 and seven months into FY-2010) for the final calibration, data reprocessing, and Resident Archive creation.

The Optimal Scenario budget has increases for the science team of $ 250 K in FY-2007 and $ 200 K in FY-2008, to provide the optimal collaboration with Solar-B and STEREO during their prime mission phases.

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Figure 12: *The high resolution* TRACE *images capture the attention of young minds and scientists alike. This 20-foot full-disk mosaic image, for example, is part of the exhibits at the Chabot Space Science center in Oakland, CA.*

5 Education and public outreach

TRACE observations continue to hold the interest of the general public. It is hard to find a popular science article on the Sun that does not contain *TRACE* images, or a television special on the Sun that does not show *TRACE* image sequences. *TRACE* catches the public's attention particularly during special events, such as three solar eclipses, a Mercury transit, and a Venus transit during the past two years since the previous Senior Review proposal. On the day of the Venus transit, 8 June 2004, for example, a special website[11] alone logged over one million hits.

The spectacular *TRACE* images, movies, and discoveries thus contribute to the 3rd NASA "Mission" as formulated in the 2003 Strategy: "Inspire the next generation of explorers." The Strategy foresees this by inspiring and motivating students to pursue careers in science, technology, engineering, and mathematics, and by engaging the public in shaping and sharing the experience of exploration and discovery. *TRACE* images and movies are well suited for these goals, as demonstrated by our success in reaching out well beyond the circle of scientists.

Analyses of *TRACE* data led to three national press releases in 2005 alone: by McIntosh[12], on the source regions of the solar wind; by Nightingale[13] on rotating sunspots and X-class flares; and by Schrijver[14], on the forecasting of major flares.

Images or movies of particular interest are displayed on a special-purpose web site (cf. Fig. 13)[15]

[11] http://trace.lmsal.com/transits/venus_2004/

[12] http://www.nasa.gov/vision/universe/solarsystem/solar-_wind_speed.html

[13] http://www.nasa.gov/home/hqnews/2005/may/HQ_05132-_solar_fireworks.html

[14] http://www.nasa.gov/home/hqnews/2005/aug/HQ_05226-_Predicting_solar_flares.html

[15] http://trace.lmsal.com/POD/

that has been maintained since April 2000 (awarded the 2003 Select Astronomy Website Award by the Naperville Astronomical Association[16]). The *TRACE*-POD site has accumulated over one million hits over the past two years. The *TRACE* web server at Lockheed Martin logs a steady stream of, on average, 10,000 visitors (distinct IP numbers) per month. These visitors request 10,000 individual files per day, with a total volume of 1 GB per day. Intervals of particularly high solar activity spark additional interest: the *TRACE* web site logged over 200,000 hits in September 2005 during the 2-week interval with 34 X- and M-class flares from Active Region 10808.

TRACE images are distributed to a broad scientific audience and to the general public in printed form: in the past two years, we distributed six thousand posters, twelve thousand calendars, one thousand folding cubes, and 150 DVD/CDRoms. The 2004 calendar highlighted the Sun-as-a-star with emphasis on sunspot regions and their coronal activity. The 2005 calendar[17] focused on the period of high solar activity in October and November 2003, describing solar activity and the resulting space weather from the Sun to the Voyager orbits, as observed by the SSSC Great Observatory.

TRACE images find their way to museum exhibitions. These include a set of large prints that are now mounted on the walls of the Hayden planetarium in New York and a 20-foot full-disk composite that dominates the exhibit at the Chabot Space Science center in California (see Fig. 12). *TRACE* imagery is also shown in planetarium shows at Chabot, at the Cincinnati Observatory, and at the Fiske Planetarium of the University of Colorado. There were *TRACE* images in various display booths at interdisciplinary meetings including the American Meteorological Society, American Geophysical Union, and American Astronomical Society.

The *TRACE* E/PO budget, complemented by Lockheed Martin funding, is spent on the production of images and movies for the abovementioned purposes and on the ongoing high-school programs discussed below. No independent dedicated K–12 programs were developed in the past 2 years.

Over the past two years, we have provided images and explanatory texts for publications for both general and student use; these include a National Geographic special on the Sun (July 2004), Markus Achwanden's textbook on "Physics of the Solar Coronal", and a braille book entitled "Touch the Sun" (appr. 3000 copies). We have produced movie segments for HDTV broadcasts and NASA TV.

The "Expanding your horizons" workshop at Montana State University saw participation of 40 8th grade girls. This event gave them the chance to learn about solar physics questions and even decide on the pointing of *TRACE* for a day

5.1 Student involvement at LMATC

The *TRACE* project at LMATC participates in the Palo Alto Unified School District Work Experience Program, which brings high school students into the research lab to work part-time during the school year and full-time during the summer. Students work with a mentor in computing and data analysis, video and DVD movie production, web programming, resource tracking with spreadsheets, and sometimes even original research leading to publication. For example, during the past few years high school students Stuart Mayo, Charles Kang, and Jonathon Ullman have worked on *TRACE* calibration and *TRACE* website maintenance. In addition, high school students Jinna Lei, Steven Peng, and Shelly Manber have worked on designing, developing, and maintaining the active region database which is based on *TRACE* data[18]. These students also worked on production of movies showing correlations between *TRACE* and ground-based data. Chris Elmore, a Stanford undergraduate, worked on the initiation and accelleration phase of coronal mass ejections. Many graduates of this work experience program at LMATC (which is over 25 years old now), have entered careers in science or engineering. *TRACE* funds also supported visiting graduate students, including Astrid Fossum (Oslo) and Alfred de Wijn (Utrecht).

5.2 Student involvement at MSU

Since the last Senior Review, graduate students Jonathan Cirtain and Patricia Jibben have been the main

[16] http://www.stargazing.net/naa/sotw.htm

[17] See trace.lmsal.com/POD/TRACEpodarchive22.html

[18] http://zorak.lmsal.com/ar

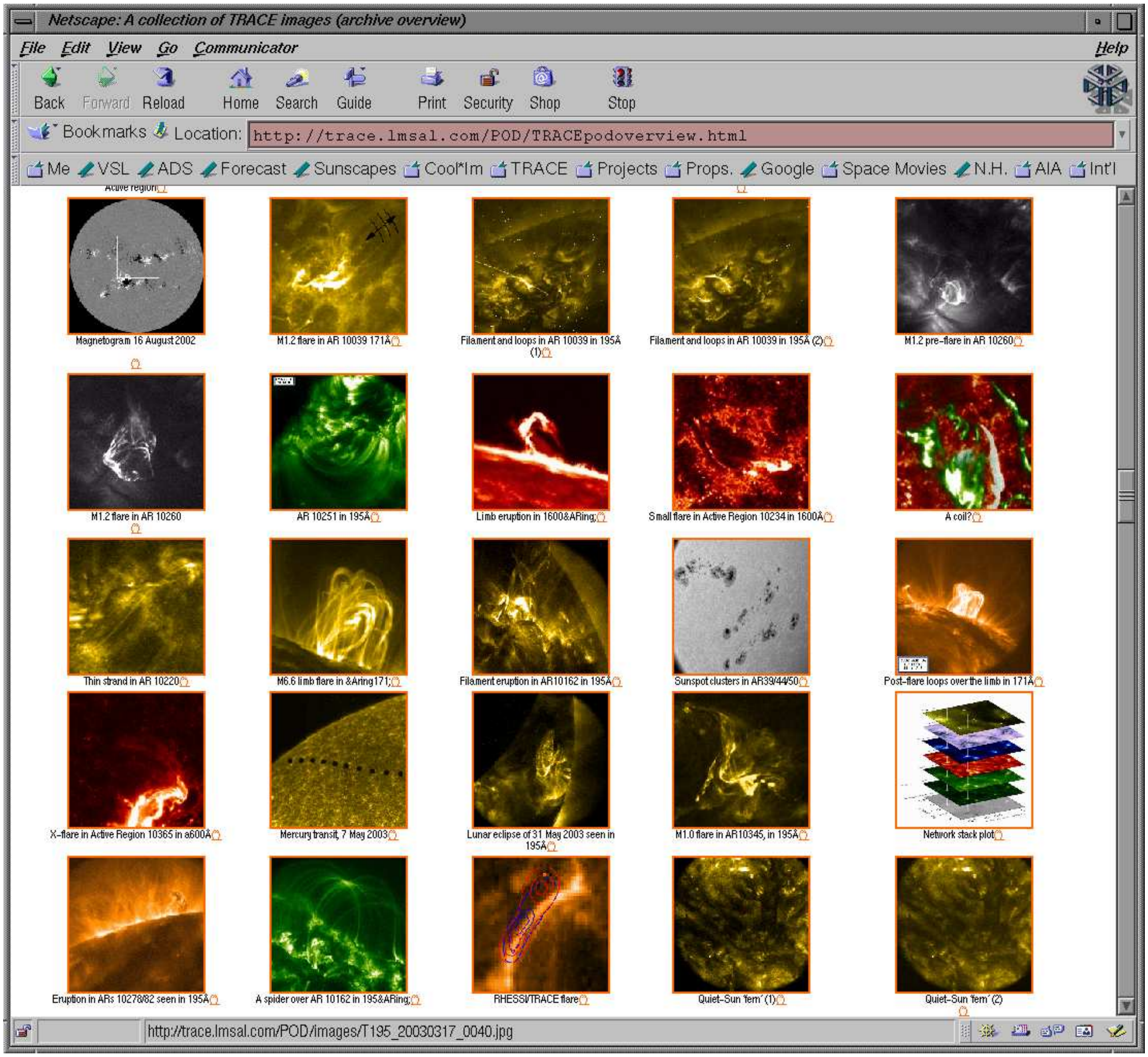

Figure 13: *Over 250 entries in the* TRACE *'picture of the day' archive describe events observed with* TRACE*, using over 360 images and 100 movies, as well as links to related web sites. These images are often used by the media around the world, and are frequently accessed by the general public; for example, the TRACEpod site saw over 443,000 hits in August 2005. This figure shows part of the summary page with thumbprints of each of the on-line images.*

MSU *TRACE* planners. Jonathan Cirtain had his PhD conferred in May 2005 with a thesis entitled "The Solar Extreme Ultra-Violet Corona: Resolved Loops and the Unresolved Active Region Corona". Patricia Jibben completed the requirements for a MSc in August 2005. Both have (co-)authored publications with *TRACE* data. Dr. Cirtain now is a research scientists at the SAO, while Patricia Jibben has received job offers from several solar physics research groups. In the fall of 2003 Meredith Wills-Davey, now at SWRI, received her PhD for a thesis on EIT and *TRACE* waves entitled "Propagating disturbances in the lower solar corona".

Currently, graduate students Sabrina Savage and Jason Scott have theses projects based on *TRACE* data. Jason spent the summer of 2005 at SAO updating the *TRACE* flare catalog.

Graduate student Trae Winter is working on a hybrid particle/fluid code for simulating flaring loops. His models produce simulated loop emission movies for RHESSI, *TRACE*, FASR, and Yohkoh-SXT and HXT. Trae won a prize for the best student paper at the 2005 New Orleans AGU/SPD for his work on ”Improving Flare Simulations by Combining Hydrodynamics Modeling with Stochastic Particle Transport”.

Undergraduates and summer students play a significant role in *TRACE*-related research at MSU. Jason Scott worked for three of his undergraduate years on the analysis of *TRACE*-SOHO data (graduating in May 2005 as the first in his Physics class). Summer student Jenna Rettenmayer became so enthused by the opportunity to do hands-on undergraduate research at MSU that she transferred to MSU. She is currently being trained as a *TRACE* planner. Andres Munoz from Colombia spent the summer of 2003 at MSU working on a research project in part studying flux emergence involving *TRACE* data. Local high school teacher Ivy Merriot has been supported for one year to complete an SXT/TRACE/H-α sigmoid catalog, after being supported for two years by a Murdock grant for collaborations between faculty (Prof. Martens in this case) and high school teachers.

MSU has started on a campus-wide major push to become one of the leading centers for Undergraduate Research in the country, and we intend to expand our contribution to that goal through our participation in *TRACE* and other (Solar-B/XRT, SDO/-AIA) projects.

5.3 Student involvement at SAO

The *TRACE* E/PO program at SAO involves research scientists working with students at various levels for extended periods of time. The students and interns work directly with senior SAO scientist on their research projects and are included in the group science meetings and discussions.

From 1998 to the present the SAO group have worked with 6 Harvard undergraduates and 6 summer high school interns. Three of the Harvard undergraduate have done their senior thesis projects using *TRACE* data. The group has also mentored REU (“Research Experence for Undergraduates”) students in 2001 and 2004.

SAO also involves graduate student visitors in the *TRACE* investigation. These included Paola Testa, from 2001 through 2003, who worked with Jeremey Drake and Ed DeLuca as a pre-doctoral fellow on stellar and solar coronal physics. She analyzed high resolution Chandra-HETG X-ray spectra of late-type stars at different evolutionary stages and activity levels; carried out a survey of coronal plasma characteristics (density, temperature, optical depth, coronal filling factors, etc.) highlighting trends with activity levels. She complemented that stellar work with analyses of SOHO/CDS EUV spectra and *TRACE* images of coronal loops. In the summer of 2005, SAO hosted MSU graduate student Jason Scott. Currently, Yingna Su is a predoctoral fellow from China working with Leon Golub and Aad van Ballegooijen on the relationship of *TRACE* EUV brightenings to particle acceleration in flares.

5.4 E/PO plans for FY 2007-2009

During the interval FY 2007 through 2009, the *TRACE* team plans to gradually increase its reliance on undergraduate and graduate students for its operations. The team will therefore train students in all aspects of the planning of science operations, as well as in the generation of the instrument instructions for daily operations. Summer students at high school and undergraduate level at LMATC, SAO, and MSU will learn to analyze *TRACE* data and assist in the scientific data analysis.

The *TRACE* team will continue to disseminate results on the primary website[19], by the distribution of posters and DVDs, by supporting and writing contributions for popular science journals, and by distributing calendars with *TRACE* images (the draft contents of the 2006 calendar, for example, is online[20]). Further details on the E/PO spending plan will be available at the time of the senior review.

[19] http://trace.lmsal.com/POD

[20] http://trace.lmsal.com/POD/calendar2006.html

Appendix A: Acronym definitions

AAS	American Astronomical Society
ACE	Advanced Composition Explorer
ACS	Attitude Control System
AGU	American Geophysical Union
AIA	Atmospheric Imaging Assembly
AR	Active Region
ATC	Advanced Technology Center
BBSO	Big Bear Solar Observatory
CCD	Charge Coupled Device
CDS	Coronal Diagnostic Spectrometer
CME	Coronal Mass Ejection
CoSEC	Collaborative Sun-Earth Connector
DOT	Dutch Open Telescope
DPS	Data Processing System
DVD	Digital Video Disk
EIS	Extreme-ultraviolet Imaging Spectrograph
EIT	Extreme-ultraviolet Imaging Telescope
E/PO	Education / Public Outreach
EUV	Extreme Ultraviolet
EUVI	Extreme UltraViolet Imager
FOT	Flight Operations Team
FOV	Field of View
FPP	Focal Plane Package
FTE	Full Time Equivalent
FTP	File Transfer Protocol
FY	Fiscal year
GB	Gigabyte
GI	Guest Investigator
GOES	Geostationary Operational Environmental Satellite
HMI	Helioseismic and Magnetic Imager
GSFC	Goddard Space Flight Center
IAU	International Astronomical Union
IDL	Interactive Data Language
IP	Internet Protocol
IT	Information Technology
IVM	Imaging Vector Magnetograph
JOP	Joint Observing Program
KPNO	Kitt Peak National Observatory
LASCO	Large-Angle and Spectrometric Coronagraph
LMATC	Lockheed Martin Advanced Techn. Center, part of LMSS
LMSAL	Lockheed Martin Solar and Astrophysics Laboratory, part of LMATC
LMSS	Lockheed Martin Space Systems Co.
LWS	Living With a Star
MDI	Michelson Doppler Imager
MHD	Magnetohydrodynamic
MLSO	Mauna Loa Solar Observatory
MOC	Mission Operations Center
MO&DA	Mission Operations and Data Analysis
MSU	Montana State University
NASA	National Aeronautics and Space Administration
NLFF	Non-linear Force-Free
NSO	National Solar Observatory
PI	Principal Investigator
POD	Picture of the Day
RHESSI	Ramaty High Energy Solar Spectroscopic Imager
RFA	Research Focus Area
RST	RHESSI/SOHO/TRACE
SAO	Smithsonian Astrophysical Observatory
SDAC	Solar Data Analysis Center
SDO	Solar Dynamics Observatory
SECCHI	Sun Earth Connection Coronal and Heliospheric Investigation
SMEX	Small Explorer
SOC	Science Operations Coordinator or Science Operations Center
SOHO	Solar and Heliospheric Observatory
SOLIS	Synoptic Optical Long-term Investigations of the Sun
SPO	Sacramento Peak Observatory
SR&T	Supporting Research and Technology
SSMO	Space Space Mission Operations
SST	Swedish Solar Telescope
STEREO	Solar Terrestrial Relations Observatory
SUMER	Solar Ultraviolet Measurements of Emitted Radiation
SXI	Solar X-ray Imager
SWRI	SouthWest Research Institute
TAG	*TRACE* Analysis Guide
THEMIS	Télescope Héliographique pour l'Étude du Magnétisme et des Instabilités Solaires
TB	Terabyte
TR	Transition Region
TRACE	Transition Region and Coronal Explorer
UV	Ultraviolet
WL	White Light
XRT	X-Ray Telescope

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