Transition-Region and Coronal Explorer (TRACE)

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Executive summary

Within the fleet of Sun-Earth Connections observatories currently operating, *TRACE* continues to offer the highest resolution imaging in space and time of the solar transition region and corona at temperatures up to a few million degrees; Solar-B (2006) and SDO (2008) will provide a comparable, but somewhat lower, resolution in future years. *TRACE* data enable solar physicists to probe the dynamics of the coronal field, to study flares and (erupting) filaments, to explore the plasma physics of the solar atmosphere, and to quantify the corona-heliosphere coupling (§ 1). Newly discovered waves in a variety of environments allow us to study quantitatively the physics of the solar outer atmosphere as interpretations and theory advance rapidly by mutual stimulation. The *TRACE* science goals remain closely aligned with the objectives and research focus areas of NASA/SEC and the LWS program (§ 1), and spark considerable interest in the solar-physics and astrophysical communities (§ 6).

As the Small Explorer *TRACE* celebrated its 5th anniversary in orbit on 2 April 2003, new discoveries continued to be made. These discoveries are presented in ~ 50 refereed papers per year with authors from around the globe (§ 3), and a comparable number of papers in conference proceedings. Graduate students in the US, Europe, and Japan contribute significant time to the analysis of *TRACE* data. The *TRACE* E/PO program (§ 13) is efficient at reaching the public through news media, television specials, the web, poster, and calendars.

TRACE, still in good health (§ 8) albeit with reduced detector sensitivity, continues to be a significant observatory for the Sun-Earth Connection (§ 3, 4, and 5) not only in its own right, but also as a partner in three out of every four SOHO Joint Observing Programs, as an indispensable source of context imaging for RHESSI's studies of flares, and as a source of upper-atmospheric information for ground-based studies of the photosphere and chromosphere. This important role is reflected in the continually increasing use of *TRACE* archival data, over 700 GB of which have been exported at a rate that doubles in volume every 1.4 yr and now exceeds the rate at which data enter (§ 2). Calibration of the CCD sensitivity changes has been incorporated into SolarSoft for use by the community.

Following the 2001 Senior Review, significant cost savings have been made in mission operations at GSFC with minimal added risk or loss of data (§ 9). The science team budgets have also been reduced to less than half of the prime mission levels, consistent with the extended mission paradigm. We have studied an alternative location for the control center and decided not to move from GSFC at this time, though this may be revisited if GSFC costs should change.

We request funding to (1) continue *TRACE* scientific operations, (2) stimulate world-wide *TRACE*-based research by joint observing, data management, research, and workshop organization, and (3) communicate results both to the scientific community and the general public. The funding guideline is the minimum for safe, scientifically productive operations and data archiving (§ 10 and 11). We request a modest increase (10%) for additional science support including meta-data, web site, and DVD production; display and calibration software enhancements; and a joint workshop with RHESSI and SOHO. Continued operation of *TRACE* will enhance the *TRACE*/RHESSI/SOHO archives not only with more opportunities for optimized joint observations, but also with observations of a new phase of the solar cycle in which the old butterfly wings converge, the wings of the new cycle begin to appear, and the polar caps strengthen following their polarity reversal.

Contents

1 Insights from *TRACE* Data

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

1. they are the only examples of fundamental magneto-hydrodynamic processes that occur in the universe that we can observe in detail in a truly astrophysical setting,
2. they are responsible for space weather and are therefore of direct societal significance.

Detailed observations of the processes in the solar outer atmosphere (such as the flare shown in Fig. 1) are essential to advancing our understanding of them because the required fidelity of numerical physical models remains beyond our reach. The nature of the solar outer atmosphere requires that the observations have the highest angular, temporal, and thermal resolution achievable. The *Transition Region and Coronal Explorer, TRACE*, was designed to provide these capabilities by combining $\sim 1''$ resolution with a frame periodicity as low as seconds, and narrow thermal passbands ($\lesssim$ 1 MK). *TRACE* continues to provide the highest spatio-temporal resolution for the quiescent solar transition region and corona, and is only exceeded by the spectral and temporal resolutions of RHESSI for high-energy phenomena related to flares. Until the launch of the Solar-B in 2006, and barring unforeseen circumstances, *TRACE* and RHESSI will remain the only instruments available to the community to provide such high-resolution observations that continue to spark exciting discoveries, such as those sketched in this Section.

The primary objective of the *TRACE*, as stated in the "Phase III & IV proposal" (August 1994) is "to explore both morphologically and quantitatively the connections between fine-scale magnetic fields and the associated plasma structures." This objective continues to be well aligned with the three Science Objectives of the NASA Sun-Earth Connection Theme as formulated in their 2002 Roadmap, as illustrated in Table 1.

In order to address these scientific objectives, the *TRACE* investigation focuses on the study of the 3-d field structure, its temporal evolution in response to photospheric flows, and the time-dependent fine structure and thermal topology of the corona and transition region.

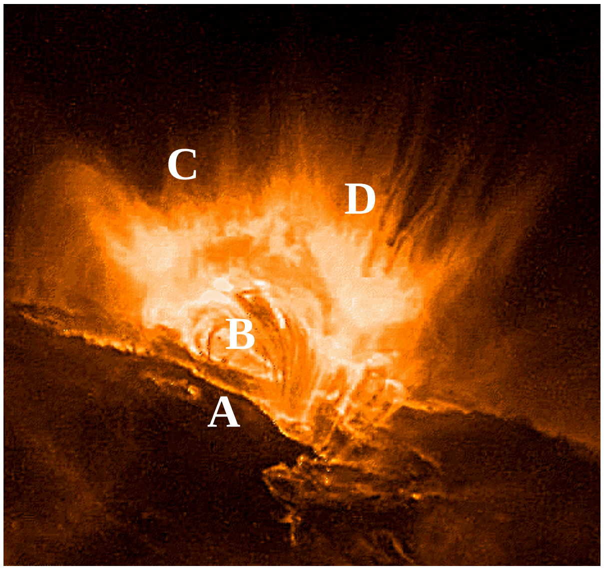

Figure 1: TRACE*'s high spatio-temporal resolution allows the detailed study of flare-related processes. This image of an X1.5 flare on 2002/04/21 illustrates some of richness of observed phenomena: A: flare ribbons that map particle impacts, B: cooling loops, including some with dark coronal rain, C: fuzzy, high emission from what is likely hot (10-20 MK) plasma seen in the 195 Å passband, and D: an unusual pattern of downward-moving eddy-like intrusions, possibly retracting reconnected loops (either empty or filled with cool plasma) or matter falling back from the mass ejection. For a movie, see http://vestige.lmsal.com/TRACE/POD/.*

TRACE has been addressing these problems since its launch on 2 April 1998 by obtaining sequences of coaligned images (over 11 million to date, half of them since the last Senior Review) of the photosphere, transition region, and corona (see Table 2 for the wavelengths observed), with an angular resolution of 1.25 arcsec FWHM (Golub et al., 1999), and uninterrupted viewing of a field of view spanning $8' \times 8'$ for over eight months of each year. The instrument characteristics have been described in detail by Handy et al. (1999).

In this Senior-Review proposal we focus, as requested, on discoveries from the past two years that

Table 1: TRACE *within the primary Sun-Earth Connection science objectives and research focus areas. The last column identifies how* TRACE *contributes in a primary (P) or supporting (S) role.*

SEC science objective	SEC research focus area	Role of *TRACE*
• Understand the changing flow of energy and matter throughout the Sun, heliosphere, & planetary environments	• Understand the transport of energy and matter within the Sun, the solar atmosphere, and into the solar wind	• P: Observe the propagation of waves through the transition region, the dynamics of the coronal magnetic field, the evolution of source regions of the solar wind, flares and initial phases of coronal mass ejections
	• Determine the evolution of the heliosphere and its interaction with the galaxy	• S: Observe the detailed evolution of the coronal field geometry to guide models of the corona-heliosphere interface
	• Understand the response of magnetospheres and atmospheres to external and internal drivers	• S: Observe the initial dynamics of the drivers of geospace activity in, e.g., filament destabilization and in flares involved in CMEs and particle storms
• Explore the fundamental physical processes of plasma systems in the solar system	• Discover how magnetic fields are created and how charged particles are accelerated	• S: Observe the detailed, fast dynamics involved in flares as observed by, e.g., RHESSI.
	• Understand coupling across multiple scale lengths and its generality in plasma systems	• P: Observe the coupling across multiple scale lengths within the corona as well as from the TR to the corona, in particular with full-disk SOHO obs.
• Define the origins and societal impacts of variability in the Sun-Earth connection	• Develop the capability to predict solar activity and the evolution of solar disturbances as they propagate in the heliosphere and affect the Earth.	• P: Observations aid modeling of solar impulsive events, and investigate the lower boundary conditions to heliospheric perturbations.
	• Develop the capability to specify and predict changes to the Earth's radiation environment, ionosphere, and upper atmosphere	• S: Observe the coronal and transition-region context and responses to flares as observed, e.g., by RHESSI, VLA, etc.
	• Understand the role of solar variability in driving global change in the Earth's atmosphere and in controlling long-term space climate	• P: Understand energy dissipation in the solar outer atmosphere to aid in model development and validation of UV, EUV, and X-ray solar irradiance

are either based solely on *TRACE* observations or are based on multiple data sets in which *TRACE* data played a significant role. Although given less emphasis here, findings reported prior to 2001 continue to be investigated today, ever deepening our understanding of coronal physics. For example, among the big surprises produced by the *TRACE* science investigation prior to 2001 was the general lack of braids and twists in the coronal field (except around filaments), even though *TRACE* observes with a resolution close to the scale of the granulation that drives its dynamics. Moreover, *TRACE* found that magnetic connections form between distant active regions within hours of flux emergence. Based on these and other observations, reconnection in the quiescent corona has been found to be much faster and more common than assumed before *TRACE*.

Furthermore, the prevailing view of the solar corona prior to *TRACE* was that it was a magnetically-dominated environment, (1) comprising mainly slowly

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

Central wavelength	Ion	Region of solar atmosphere	log(T)	T range (FW at 2%)	Characteristic exposure time (s)		
					Quiet Sun	AR	Flare
2500Å	Cont.	Photosphere	3.7	3.6-3.8	0.003	0.003	0.003
1700Å	Cont.	$T_{\rm min}$/Chrom.	3.8	3.6-4.0	5	3	1-3
1600Å	CI,FeII,cont,CIV	$T_{\rm min}$/Chrom.	3.8	3.6-5.4	1	1	0.01-0.1
1550Å	CIV	Trans. region	5.1	4.8-5.4	15	10	1-5
1216Å	H Ly α	Chromosphere	4.2	4.0-4.5	3-30[1]	3-30[1]	1-2[1]
284Å	Fe XV	Corona	6.3	6.0-6.7	60	5-30[2]	2-20
195Å	Fe XII (XXIV[3])	Corona	6.1 (7[3])	5.0-6.4	30	5-30[2]	1-10
171Å	Fe IX/X	Corona	5.9	5.3-6.3	30	5-30[2]	1-10

1 The two values are for on-disk and off-limb observations, respectively. Off-limb exposure times are longer, because there is no significant continuum contribution there.
2 The lower value is for 2×2 binned imagery.
3 Fe XXIV line, and sometimes a high-temperature thermal continuum, visible during flares.

evolving loop atmospheres that (2) were heated rather uniformly and persistently, (3) within a narrow temperature range, (4) in which rapid changes occurred only by field emergence, flares, and filament eruptions. *TRACE* has shattered each aspect of that traditional view of the quiescent corona as we summarize below.

One discovery that has resulted in an entirely new, rapidly-expanding branch of solar physics, is the phenomenon of loop oscillations; interestingly, transverse field oscillations and longitudinal plasma oscillations were discovered within months of each other based on *TRACE* and SOHO/EIT data.

A number of the most far-reaching of the earlier discoveries based on *TRACE* data are outlined in Table 3; where appropriate, key references from within the last two years were added to this list that first appeared in the 2001 Senior Review proposal. A brief overview of some of the new discoveries made during the last 2 years is given in Table 4; we discuss some of these findings in more detail below:

Atmospheric seismology

TRACE and SOHO made a major breakthrough in the study of atmospheric activity by providing observations of oscillatory perturbations, including EIT (coronal Moreton) waves, compressible waves in plumes and loop fans, global kink-mode oscillations induced by eruptive events, and longitudinal oscillations within loops. The rapidly developing field of atmospheric seismology provides new ways of diagnosing and understanding the physics of the Sun's chromospheric and coronal magnetic field and the plasma in it. This new field has been and will be the focus of various (sessions at) international meetings, some of which are listed at the end of §§ 4 and 6.

Because of its high spatio-temporal resolution, *TRACE* is uniquely suited to observe the propagation of compressible (intensity) oscillations as well as transverse loop oscillations. In the past two years, over 30 publications based (in part) on *TRACE* observations have discussed various wave phenomena newly observed in the solar outer atmosphere.

The first example that we discuss here is that of the transverse loop oscillations (Fig. 2). Discovered in 1998, these oscillations remained elusive at first, but a careful search through the *TRACE* data base has now uncovered over two dozen active regions within which at least one loop is observed to oscillate (see Table 5 for these data on the web). The oscillations are excited by filament destabilizations or flares (in 6% of the 255 flares inspected, ranging from about C3 to X2), even though there is no clear

Table 3: Selected discoveries from the 2001 Senior Review proposal based in large part on *TRACE* observations; many of these have seen subsequent developments, reflected by sample references.

Finding	Select reference(s)
• Loops of significantly different temperatures exist side by side, probably because heating is variable and sensitive to the details of the coronal field.	Schrijver et al. (1999)
• Many coronal loops are incompatible with the traditional quasi-steady, uniformly-heated loop (Rosner-Tucker-Vaiana model). Dynamical evolution, flows, and plasma MHD effects have been proposed as explanations.	Aschwanden et al. (2001); Reeves and Warren (2002); Winebarger et al. (2002, 2003); Warren et al. (2002); Spadaro et al. (2003); Bellan (2003)
• Loop cross sections lie near the instrumental resolution, without significant expansion with height, even for those loops that are significantly wider than the instrumental resolution.	Watko and Klimchuk (2000), Klimchuk (2000)
• Relatively cool 1-2 MK loops tend to arch over hotter 3-5 MK loops within active regions, implying a hot core and a cooler shell.	Schrijver et al. (1999)
• Coronal heating occurs predominantly low in coronal loops, with a scale height of 10-20 Mm, in agreement with recent numerical MHD modeling	Aschwanden et al. (2000, 2001), Gudiksen and Nordlund (2002)
• Coronal heating in active region coronae frequently drops by more than an order of magnitude for up to an hour or more, leading to coronal rain and bright loop-top sources.	Schrijver (2001)
• Twists and braids in the corona rarely exceed one half turn, even on the scale of the granulation that should drive such braiding. Long-range reconnections between active region field occur within hours of emergence. Both findings suggest unexpectedly efficient reconnection.	Schrijver et al. (1999)
• The downward conducted energy from the corona seen in the transition-region moss is not spatially correlated with chromospheric emission on small length scales, perhaps reflecting distinct heating mechanisms, or strong sensitivity to local conditions.	De Pontieu et al. (1999, 2003)
• Transverse coronal loop oscillations, discovered essentially simultaneously by *TRACE* and SOHO/EIT, opened the field of coronal seismology. Their damping is unexpectedly rapid; apparently, we do not understand the coronal environment, the dissipative coupling to the lower, denser chromosphere, or the means to amplify small surface effects in the corona.	Nakariakov et al. (1999), De Pontieu et al. (2001), Aschwanden et al. (2002), Schrijver et al. (2002), Goossens et al. (2002), Ofman and Aschwanden (2002)
• Hot plasma above post-flare EUV arcades appears diffuse because of its multi-T nature rather than the source itself being diffuse.	Warren (2000)
• Cool material in filaments is extremely dynamic, commonly accelerated and decelerated, exhibiting counter-streaming on nearby field lines.	Schrijver et al. (1999), Kucera et al. (2003)
• The energy spectrum of small-scale brightenings was extended with *TRACE* to 10^{24} ergs, a factor 10 below earlier *SOHO/EIT* results. It remains uncertain whether the extrapolated distribution of these small brightenings contains enough energy to explain quiescent coronal heating.	Aschwanden (2000), Parnell and Jupp (2000), Aschwanden et al. (2000), Aschwanden and Charbonneau (2002)
• Canceling flux most likely retracts into the solar interior.	Harvey et al. (1999)
• Fast flows (up to several hundred km/s) and wave-like phenomena occur commonly over magnetic plages and in association with spots and filaments.	Ireland et al. (1999), De Moortel et al. (2000), Shine (2000)
• CMEs are often associated with significant amounts of material that falls back to the surface. Many filament eruptions are confined eruptions, with material falling back down after being thrown upward to some 100 Mm.	

Table 4: A selection of recent discoveries (2001-2002) about the physics of the Sun's atmosphere that are based in large part on *TRACE* observations.

Finding	Select reference(s)
• The chromospheric magnetic canopy appears to be lower than expected. Its presence affects acoustic wave propagation through mode conversion, causing "acoustic shadows" around flux concentrations in the upper photospheric layers.	McIntosh et al. (2001), Judge et al. (2001), Krijger et al. (2001)
• Evidence for slow magneto-acoustic waves in the corona over sunspots and strong flux concentrations in the network requires rethinking of wave propagation through the chromosphere-corona interface.	Berghmans and Clette (1999), De Moortel et al. (2000), King et al. (2003)
• The apparent rotation of some sunspots was discovered to be associated with the twisting of the coronal field configuration, suggesting hysteresis in the current-system and connectivity development.	Nightingale et al. (2002), Brown et al. (2002)
• Study of simulated coronal field over mixed-polarity quiet Sun suggests that coronal heating does not preferentially occur near magnetic null points.	Schrijver and Title (2002); cf. Longcope et al., 2003
• Magnetic null points (and the associated spine and fan field lines) above the photosphere have been observed, and are likely involved in flares and CMEs.	Aulanier et al. (2000)
• Direct observations confirm that active regions, and sometimes the sunspots within them, are directly connected to the heliosphere.	Schrijver and DeRosa (2003)
• Structure and evolution of EUV and soft X-ray loops around sunspots are consistent with spatio-temporal Poynting flux predicted by sunspot models	Hurlburt et al. (2002)
• Transverse loop oscillations are observed in 6% of flares and major eruptive events.	Aschwanden et al. (2002), Schrijver et al. (2002)
• Evidence of non-linear (if not shock) waves observed in the transition region above magnetic plage.	De Pontieu et al. (2003)
• Filling factors for coronal loops likely lie between 0.1 and 1, on average ~ 0.3.	Fletcher and De Pontieu (1999), Aschwanden et al. (2003)
• TRACE EUV and RHESSI hard X-ray endpoints of loops are significantly offset.	under study, e.g. Fig. 6
• Differences in initial conditions may explain why post-flare loops are more fuzzy in the 2 MK 284Å channel than in the 1 MK 171 Å channel	Patsourakis et al. (2002)

dependence of oscillation amplitude on flare magnitude. The loop oscillations are not a resonance that builds up: oscillations in loops that are excited along their entire length by, e.g., a wave that comes in perpendicular to the loop, are likely to be near the fundamental resonance mode because of that excitation profile. In contrast, asymmetrically excited oscillations clearly show propagating waves that are damped too quickly to build up a resonance. Why certain loops are much more likely to oscillate at observable amplitudes remains a puzzle, although it appears that all oscillating loops lie near magnetic separatrices for the large-scale field.

These oscillations damp remarkably, and unexpectedly, quickly. The mechanism for that damping remains unidentified, with models including extremely high coronal viscosity or resistivity (perhaps because of resonant absorption), efficient "radiation" of the oscillatory energy owing to gradients in the curved field, or unexpectedly strong leakage of the waves into the chromosphere and transition region (e.g., Nakariakov et al., 1999; Roberts, 2000; De Pontieu et al., 2001). Each of these options requires physical processes that were deemed negligi-

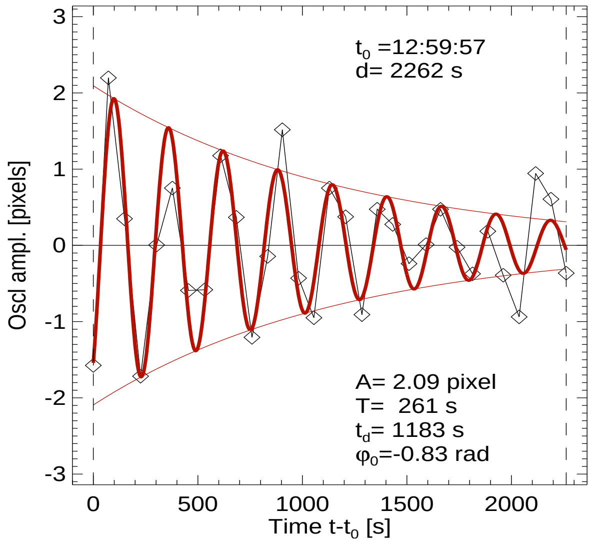

Figure 2: *An example of transverse loop oscillations (from Aschwanden et al., 2002), showing transverse displacement vs. time (diamonds) and a model approximation.*

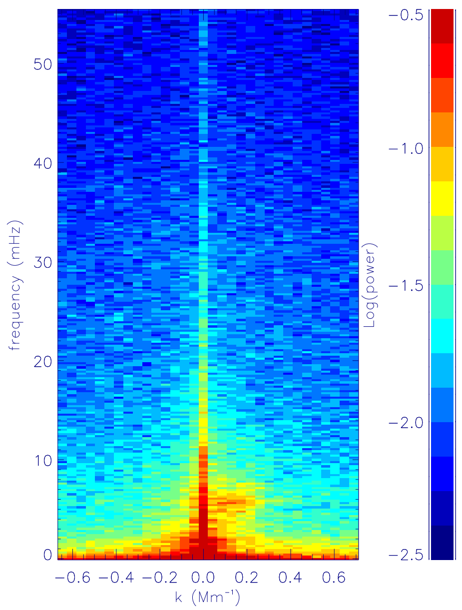

Figure 3: *A first phase diagram, displaying logarithmic power in a* $1/P$ *vs.* $1/\lambda$ *diagram, of apparent magneto-acoustic slow mode oscillations propagating through loops emanating from a large sunspot, seen in the* TRACE *195 Å channel.*

ble prior to the observations of damped loop oscillations: the Reynolds numbers of the coronal plasma may be anomalously low (by a factor of a billion or more), the chromosphere/transition-region interface may be geometrically extended over thousands of kilometers, or resonant absorption may be very efficient if plasma loops have "vague" and gradual transitions to the surrounding medium rather than crisp edges.

Another oscillatory phenomenon is what appear to be slow magneto-acoustic waves in the corona, that were discovered in both TRACE and SOHO/EIT observations. This was a surprise because numerical modeling had suggested that such waves could not reach the corona; if they can indeed, the debate on how much they contribute to coronal heating will be reopened.

Thus far, the literature has focused on periodicity studies in spectra or images, often in wavelet space. The first, still preliminary, k–ω diagram of compressible waves propagating in loops rooted in a sunspot is shown in Fig. 3. There is a strong peak corresponding to the 3-min. period, but there is no sign of either significant wave reflection or downward propagation of waves excited at the conjugate footpoint (i.e., there is only weak power at negative k). Nor is there significant power at frequencies significantly higher than the dominant 3-min. period up to a Nyquist frequency of 55 mHz; the lack of power at such high frequencies suggests that coronal sausage modes (e.g., Edwin and Roberts, 1983) are, at best, only weakly present.

The top of the transition region over active regions, as seen in the 171 Å "moss," also shows oscillatory modulation. The power resides mostly in the 5-min. band. The intensity profiles (see an example in Fig. 4) can be strongly asymmetric, however, suggesting nonlinear wave evolution.

As a final example of atmospheric seismology, we discuss a finding based on observations in the *TRACE* UV channels, which offers a view of oscillations in the atmosphere within the first few hundred kilometers above the photosphere. Such imaging data directly confirms the existence of significant "acoustic shadows" (first seen spectroscopically in SOHO/SUMER data) around magnetic concentrations immediately above the photosphere as seen in the UV continuum around 1600 Å. These have been suggested to be a consequence of mode

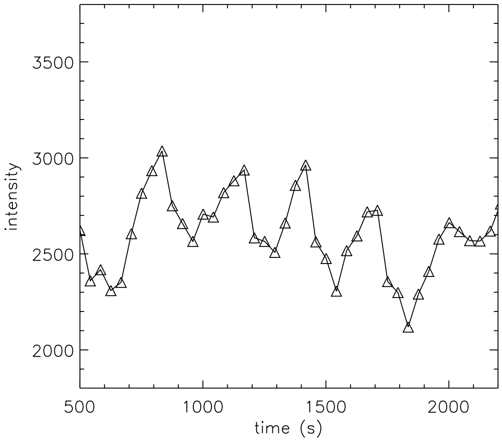

Figure 4: *Waves in the active region transition region, as observed in the 171 Å passband of* TRACE*, i.e. in the so-called moss. The panel shows a segment of the wave intensity profile; note the relatively steep sides of the curve, suggesting the presence of nonlinear processes. Figure provided by B. De Pontieu, from work in progress.*

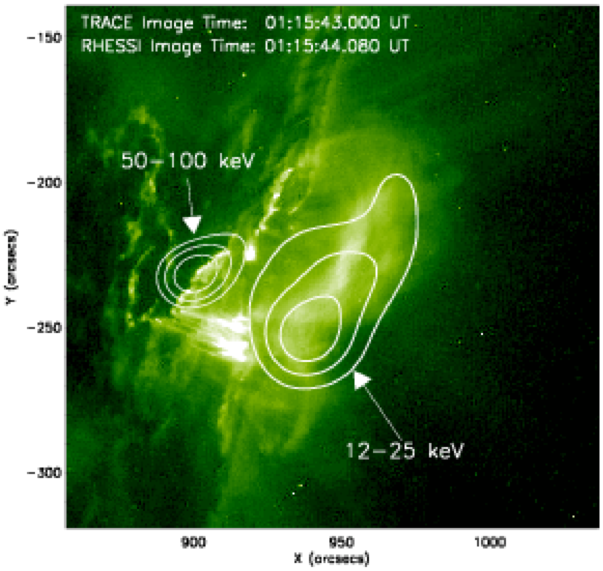

Figure 5: TRACE *195 Å and RHESSI 12-25 keV and 50-100 keV images during an X-class flare on 21 April 2002.*

conversions from compressible to transverse waves in the atmospheric domain where the plasma β transitions unity, i.e. around the magnetic canopy. If that is the correct interpretation, this happens much lower than anticipated. Is the magnetic canopy lower than we thought, or is there some as yet unrecognized interaction of a weak field with the canopy capable of modifying wave propagation?

Flares and high-energy phenomena

The interpretation of the magnetic topology during flares (an example is shown in Fig. 5) depends crucially on high-quality context observations in the EUV, provided by *TRACE* and – at lower resolution – SOHO/EIT, as well as the availability of ground- and space-based magnetograms. Almost every possible interpretation of flare phenomena requires a spatial model of the magnetic topology which can be inferred from *TRACE* pre-flare, flare, and post-flare data.

One particularly well studied example of the field geometry involved in a major flare is the “Bastille day flare” (14 July 1998). A detailed comparison of the observed coronal loop geometry with force-free fields demonstrated the importance of a coronal null point and the associated spine and fan field lines (Aulanier et al., 2000). The activity seen at the field sites connected directly to that null point started well before the flare itself, demonstrating that the activity there is not merely a consequence of the flare process but that the flare process may have started there. Observations such as these are important in the study of, e.g., the “breakout” model of coronal mass ejections, in which reconnection at a coronal null opens field that was previously constrained below a separatrix dome ((Antiochos et al., 1999)).

Flare studies have been dramatically stimulated by the launch of the *Ramaty High Energy Solar Spectroscopic Imager,* RHESSI, (Lin et al., 2002). In its first year of observing (since 5 February 2002) it has observed 7500 solar flares during its first year, ranging from a large GOES-class X4.8 flare with γ-ray line emission, down to B-class “microflares.”

For instance, the first γ-ray line image of the 2.223 MeV neutron capture line was imaged by RHESSI during a flare on 23 July 2002 (Hurford et al., 2003; Krucker et al., 2003). An unexpected offset of $20''$ was measured with respect to the hard X-ray sources that usually occur at footpoints of flare loops. Without the high-cadence context images of the flare loop arcade, such as provided by *TRACE*, a meaningful physical interpretation of the mysterious γ-ray line source would be virtually impossible.

One of the foremost problems in flare physics is the localization and mapping of the fragmented energy release region associated with bursty magnetic reconnection, which can now be probed from hard X-ray kernels to the chromospheric flare ribbons. The magnetic connectivity between these extremes can only be traced accurately on *TRACE* images. Moreover, *TRACE* UV images reveal the filamentary structure of flare ribbons with excellent resolution; these ribbons are highly correlated with the hard X-ray ribbons (Fletcher and Hudson, 2001) that can now be imaged with RHESSI with unprecedented spatial and energy resolution. It is of interest to note that the UV ribbons are often seen to exhibit brightenings before the onset of the hard X-ray emission (already seen in comparisons of *TRACE* and BATSE data; Warren and Warshall, 2001). The analysis of the imaging data suggests that UV brightenings prior to the hard X-ray even and the later energy deposition from precipitating electrons often occur on different field lines, with important consequences for flare-triggering and field-evolution studies.

One new discovery of RHESSI is the existence of microflares with non-thermal electron signatures down to 3 keV (Krucker et al., 2002). *TRACE* can resolve the associated small loops as they cool through the EUV passband, allowing an estimate of their thermal energy content, thus providing insight in both the magnetic topology and the energetics.

One detailed example of a comparison of sites of high-energy emission with the *TRACE* field morphology is shown in Fig 6, which shows a very small flare that was observed jointly by TRACE (195Å) and RHESSI on 06 May 2002. This flare was not large in spatial extent or in total energy (not even reaching C-level on the GOES scale), but it shows many aspects seen in much larger events. The flare initially brightened in RHESSI images at what appeared to be two footpoints separated by $25''$. A few minutes later, we see a post-flare loop brightening in the TRACE 195 Å passband. If we compare the post-flare loop with the earlier RHESSI data, we see an interesting misalignment. Blue contours in Fig 6 show 3-8 keV soft X-rays and red contours show 8-15 keV X-rays. The RHESSI "footpoints" in the 8-15 keV energy range do not line up with the *TRACE* 195 Å loop endpoints. The uncertainty in the relative pointing for this event, estimated to be 3–$5''$, may account for some of the misalignment, but the scale of the two images is quite precise, so there is no way to make both RHESSI bright points match the *TRACE* footpoints. Perhaps RHESSI in fact shows us hot plasma above the *TRACE* loop rather than (near) chromospheric footpoints?

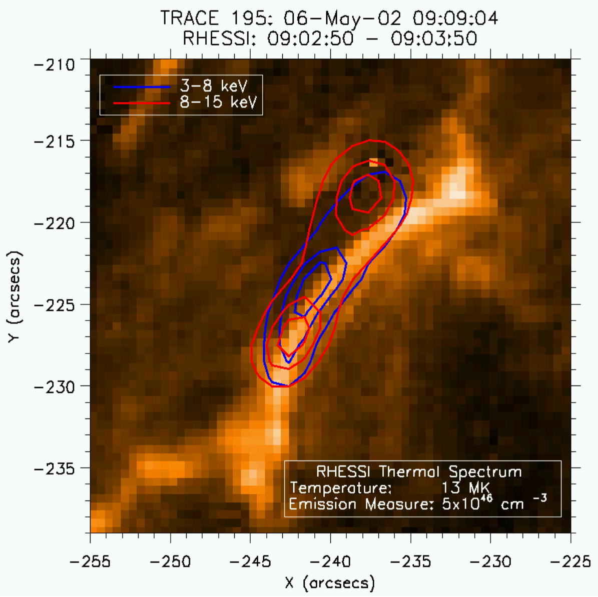

Figure 6: *A small (sub-C) flare: RHESSI contours (blue: 3–8 keV; red: 8–15 keV) are shown on a* TRACE *195 Å image taken 5 min. later when the post-flare loops become visible. By Tom Metcalf.*

On the related topic of cooling post-flare loops, Patsourakis et al. (2002) point out that the 284 Å images are "fuzzier" than the 171 Å images. They interpret this as a consequence of loops cooling from slightly different temperatures and densities, resulting in different cooling times: the cooling proceeds more slowly for warmer loops, causing them to be more space-filling, with an associated fuzzier appearance.

High velocities and twists

Over the past year, RHESSI coordination led the *TRACE* team to push the instrument cadence to its limits. Particularly during the past six months, *TRACE* has often operated in the UV passband at a cadence of 1.5 s, or in the EUV passbands at 171 Å and 195 Å at 5–10 s (often by summing 2×2 pixels to achieve an acceptable S/N ratio). As a result, we discovered that even outside flares, displacement velocities in the 1600 Å passband frequently reach up to 500 km/s. These motions occur mostly in highly inclined, low loops where the emission is presumably dominated by the C IV doublet. The associated signatures in a spectrograph would be weak (plasma crosses the slit very quickly), and at rather lower velocities (owing to the inclination). This may explain why such values have not been reported from spectrograph observations. A study of these phenomena, and the magnetic environment within which they occur, is in progress.

Such high cadence movies in the EUV passbands have revealed what appears to be twisting of erupting loops. That was already known for destabilizing filaments (and, on the largest scales, observed spectroscopically with SOHO; e.g., Pike and Mason, 2002), but this is now seen in erupting fibrils no longer than a few thousand kilometers, often associated with emerging ephemeral regions. Observational and theoretical studies on this continue.

Corona-heliosphere coupling

Furthering our understanding of space weather requires us to better know the lower boundary condition of the heliosphere. Recent studies revealed that active regions can be directly connected to the heliosphere (Fig. 7). At times of cycle maximum they contribute as much as 30–50% to the interplanetary magnetic field, whereas at cycle minimum that fraction is generally smaller than 10%. This active region open field is surrounded by bright loops that can be imaged in the *TRACE* EUV passbands as they evolve into and out of the open-field domain, in contrast to the faint and featureless loop structures in and around quiet-Sun coronal holes. This opens up the possibility of observing much of the transition from closed to open (and back?). Such data can be used to study the potential impact of current systems and Lorenz forces within the large-scale corona, which act to distort the large-scale field and thus change the mapping into the heliosphere.

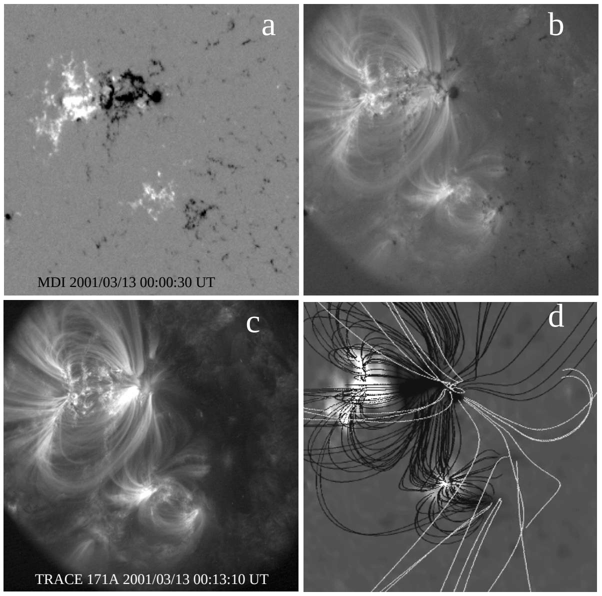

Figure 7: *The corona-heliosphere interface can be studied with* TRACE *images.* a *a SOHO/MDI magnetogram;* b *the corresponding* TRACE *171 Å image blended with a white-light image to identify the location of spots relative to the coronal loops;* c *the* TRACE *171 Å image;* d *a potential-field extrapolation showing open (white) and closed (black) field lines. From Schrijver and DeRosa (2003).*

Properties of coronal heating

Studies of the stratification of the 1–1.5 MK plasma in long coronal loops indicate that most loops, even those that are apparently quiescent, are not compatible with the classical quasi-static loop models (e.g.,Aschwanden et al., 2001; Winebarger et al., 2003) as developed by Rosner et al. (1978) (RTV). For a minority fraction of the loops the emission scale height is compatible with a quasi-steady state, but the temperature profile is found to be essentially flat (a finding that sparked an intense and continuing controversy about the relative merits of thermal diagnostics in high-resolution narrow-band images versus lower-resolution spectroscopic data; Schmelz et al., 2001; Martens et al., 2002; Aschwanden, 2002). For these loops, it has been argued that the bulk of the coronal heating occurs low in the loops, rather than uniformly, as assumed by RTV. A low heating scale height of order 10–20 Mm is compatible with recent MHD modeling (Gudiksen and Nordlund, 2002) in which the current density (and with it the heating rate) scales with the energy density in the magnetic field, which decreases rapidly with height as the field fans out above active regions.

Gudiksen and Nordlund show the heating to be intermittent in space and time, spanning several orders of magnitude at a given height. This intermittent nature leads to transsonic flows along loops, with many loops not being in hydrostatic equilibrium. These flows, expected from the numerical modeling, may be involved in another mystery: for most of the *TRACE* loops studied by Aschwanden et al. (2001), not only is the temperature profile too flat, but the emission scale height is significantly too large, up to 4 times larger than expected given the plasma temperature. Detailed modeling of dynamic loops (e.g., Reeves and Warren, 2002; Winebarger et al., 2003; Spadaro et al., 2003) suggests that the cooling phases associated with intermittent heating can indeed cause the instantaneous stratification to differ substantially from that of a steady state.

Another possible explanation for the high emission scale height of loops comes from the plasma-physics (tokamak) community. This could at the same time explain the nearly constant cross section of coronal loops. Bellan (2003) proposes that any loop expanding with height that carries a current (possibly involved in the heating of that loop), introduces $J \times B$ forces that lift plasma up into the loop, thus effectively counteracting gravity and raising the emission scale height. This upflow carries a toroidal current that would act to reduce the loop expansion, thus contributing to the apparently constant cross section of such loops.

Even as the rapidly increasing fidelity of MHD simulations (e.g., Gudiksen and Nordlund, 2002) offers support for Parker's concept of microflare heating, careful observational analysis suggests the opposite. For example, Aschwanden and Charbonneau (2002) have assessed in detail the biases that are introduced by the observational tools available. Careful correction for, for example, the narrow thermal ranges over which the smallest flares are currently observed results in a spectral index well below the critical value of 2. If these findings prove correct, then a straightforward extrapolation of the observable part of the (micro-)flare spectrum falls short of the total energy needed to heat the corona.

The intermittency of coronal heating not only leads to a modified emission scale height, but in extreme cases to catastrophic cooling, when "coronal rain" is seen within the field Schrijver, 2001). Such events require that the heating is essentially shut down over the entire loop volume coherently for hours. This happens for loops on a time scale of no more than a few days, depending on the environment. On shorter time scales, we perhaps need to conclude that the heating is intermittent on such high spatio-temporal frequencies that most of the observed loops are filled with plasma most of the time. Not only did Fletcher and De Pontieu (1999), for example, infer a filling factor of 0.1 based on spectral and imaging data of the high transition region ("moss"), but recently Aschwanden et al. (2003) used observations of cooling loops to argue that the volume filling factor for loop plasma should lie above ~ 0.3 to be compatible with the observed cooling time scales.

What about coronal heating in the quiet Sun? One particular topic of study focused on the potential role of topological separators. At these locations, coronal currents were deemed to be particularly intense, possibly leading to substantial coronal heating (e.g., Longcope and Cowley, 1996; Longcope et al., 2003). Contrary to this suggestion, however, *TRACE* observations show no evidence supporting such a significant role of separators: there are simply far too few visible loops or partial-loop brightenings with endpoints over locations where null points are expected (Schrijver and Title, 2002). Hence, the role of the "magnetic carpet" in the heating of the corona, as compared to waves and granulation forcing, needs to be re-examined.

2 Data Archiving and Access

Investigations based on *TRACE* data are a mixture of studies requesting tailored observations (see § 3) and studies based on archival data. The *TRACE* project has had a completely open data policy from the very first day of observations: *there are no restrictions on the use of* TRACE *data*. As soon as the spacecraft telemetry has been reformatted and archived, the data are accessible - normally well within

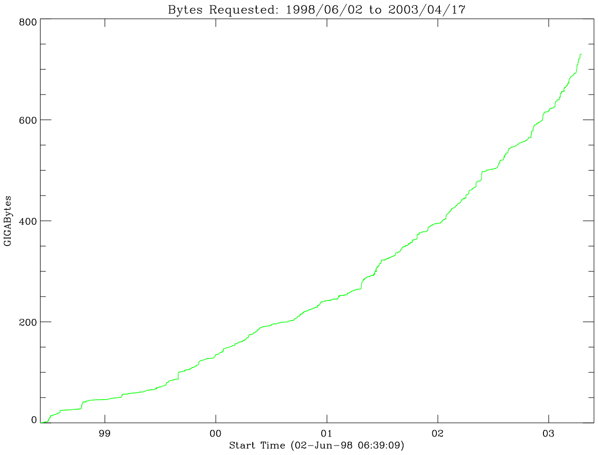

Figure 8: *Cumulative data volume (GB) transferred from* TRACE*'s primary data archive at Lockheed Martin since the start of normal operations. The rate of transfer continues to increase slowly, averaging* ∼ *600,MB/day over the most recent year shown above. In early 2003, the daily data volume being exported from the archive through user requests started to exceed the volume at which TRACE obtains data.*

12 hours of observing. In order to allow faster access to the large amounts of data, the archive files are mirrored to Goddard Space Flight Center, and further transferred electronically or by tape to mirror archives at Rutherford-Appleton Labs in the U.K., the Kiepenheuer Institute in Germany, ISAS in Japan, and Meudon in France.

The primary *TRACE* archive at Lockheed Martin is frequently accessed via the internet; a total of $\sim 0.7\times 10^{12}$ bytes in 740,000 images has been transferred (cf. Fig. 8). The average rate of data requested has continued to grow, equivalent to doubling every 1.4 years over the past three years (the archive site at GSFC shows similar trends at approximately 1/4 the Lockheed Martin level). This rapid increase in the requested data volume has caused the rate at which data is exported from the archive to exceed that at which *TRACE* obtains it starting in early 2003. This continuing increase in part reflects the joint studies now underway with the RHESSI science team.

TRACE analysis software is available on the web, as part of the widely used and openly available SolarSoft 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). Apart from the TAG, the *TRACE* team maintains web pages with interesting images, observed flare events, loop oscillation events, etc. (Table 5).

3 Collaborations

The *TRACE* project closely coordinates with other observatories, both in space and on the ground. Coordinations with SOHO and RHESSI are given particular emphasis, and *TRACE* observes all Major Flare Alerts. For example, of the 21 Joint Observing Programs run by SOHO in 2002, 16 (76%) involved *TRACE*. This fraction is the same as that found for 2000, when 23 of the 30 JOPs required *TRACE*. Note that 17 of the 21 JOPs run in 2002 were not yet formulated in 2000: *TRACE* remains an important complementary instrument to SOHO.

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 EIT bakeouts.

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 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 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

Table 5: *Some web resources for the* TRACE *investigation*

TRACE home page	http://vestige.lmsal.com/TRACE/
TRACE Analysis Guide	http://www.lmsal.com/ bentley/guides/tag/tag_top.html
TRACE Publication list	http://vestige.lmsal.com/TRACE/Science/ScientificResults/tracepubs.html
TRACE data centers	US (West) http://vestige.lmsal.com/TRACE/DataCenter US (East) http://penumbra.nascom.nasa.gov/TRACE/Data/trace_cat.html Germany: http://trace.kis.uni-freiburg.de/ U.K.: http://trace.solararchive.rl.ac.uk/trace/home.html
TRACE flare catalog (no. of flares: X: 37, M: 297, C: 291):	http://hea-www.harvard.edu/SSXG/kathy/flares/flares.html
TRACE "picture of the day" image & movie collection):	http://vestige.lmsal.com/TRACE/POD/TRACEpod.html
TRACE loop oscillation data and movies	http://vestige.lmsal.com/TRACE/POD/looposcillations
TRACE Educational CD-ROM (web version)	http://vestige.lmsal.com/TRACE/Science/ScientificResults/trace_cdrom/
SUNSCAPES exhibition images	http://vestige.lmsal.com/TRACE/POD/NAS2002.html
Active region data base (under development)	http://blackadder.lmsal.com/ar/

Pic du Midi (France), SST (Swedish at La Palma), DOT (Dutch at La Palma), Huairou (China), Modra (Slovakia), Bialkov (Argentina), and Ondrejov (Czech Rebublic). We also coordinate with radio observatories, including VLA (U.S.A.), Ooty (India), Nagoya (Japan), and EISCAT (Norway). Through JOP 136 (the Max Millenium RHESSI coordination), we further participate in a world-wide flare program that involves 40 ground-based observatories.

Special efforts to coordinate are made whenever unique observing opportunities occur. Following the Senior Review in 2001, these included rocket flights (*MXUVI*, *MSSTA-III*, *VAULT,* and other calibration rockets), the *Cassini* conjunction with the Sun, the Japanese Balloon-borne Hard X-ray Spectrometer, and eclipse observations (21 June 2001; 4 December 2002). We are currently planning for disk passages of Mercury (7 May 2003) and Venus (8 June 2004).

4 *TRACE* Scientific Effectiveness

Solar physicists have embraced *TRACE* as a key observatory to further their field. The efficient implementation of a freely accessible data archive, and flexible, responsive planning by the team operating the science instrument, has resulted in broad community interest in and dependence upon *TRACE* data. As a result, there are now (1 April 2003) 370 papers or books published in the scientific literature, 237 of which in refereed journals, that are based entirely or in part on *TRACE* data. That is nearly double the number listed in the Senior-Review proposal of two years ago (148 publications as of 1 May 2001) showing the continuing interest in and relevance of TRACE observations. Fig. 9 shows the rate of publications per year, differentiating between refereed and other publications.

A total of 441 authors contributed to these publications, from 133 institutions in 28 countries (up from 242 in March of 2000). This is to be contrasted to the membership of 570 of the AAS Solar Physics

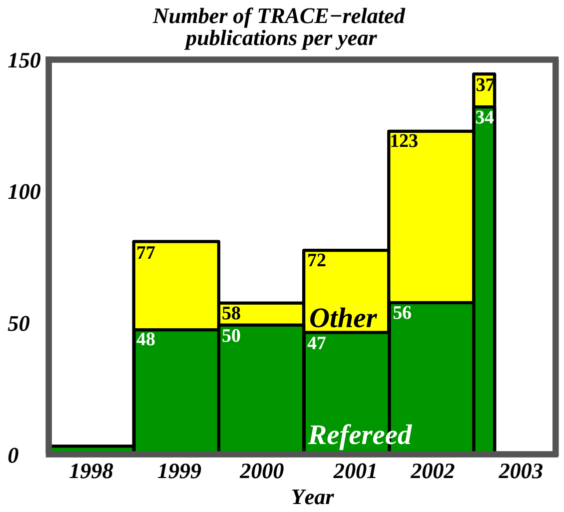

Figure 9: *Number of research publications per year (up to 1 April 2003) based directly on* TRACE *data or on findings derived from it. The shorter (green) bars reflect the numbers in refereed journals (Astrophysical Journal, Astronomy and Astrophysics, Publ. of the Astron. Society of Japan, Physics of Plasmas, Science, and Solar Physics). Publications limited to an abstract (as in AGU and AAS meeting booklets) were excluded. Numbers for 2003 were scaled to reflect that only 3 months had passed at the final count. For the full listing, see: http://vestige.lmsal.com/TRACE/Science/Scientific-Results/tracepubs.html.*

Division in 2000.

The *TRACE* team not only contributes to quantitative scientific studies of solar activity, but also makes material available to the scientific community for general viewing outside the channels of refereed publications. For example, a substantial set of movies was included on a special DVD as well as additional material on the CD-ROM included in the 200th issue of the journal Solar Physics; this wide-spread distribution ensures that all active solar researchers have at least seen, if not had direct experience with, the dynamics of the solar corona that is so dramatically emphasized by *TRACE* data. We are currently working on a $\sim$15-DVD set with examples of various phenomena, ranging from a set of full-disk passages of active regions to flares, and from long-term sunspot evolution to filament destabilations; if funding is available, these will likely be completed in early 2004.

TRACE data are presented not only in the refereed literature, but also at workshops. Among those with particularly substantial *TRACE* input we mention four held last year: Yohkoh-10, held in Hawaii; Euroconference/IAU Colloquium 188: ”Magnetic Coupling of the Solar Atmosphere,” held in Santorini, Greece; a NATO Advanced Research Workshop entitled “Turbulence, Waves, and Instabilities in the Solar Plasma,” held in Budapest, Hungary; and a topical MEDOC Workshop on “Coronal Loops,” held in Paris, France. Another meeting focusing on “Waves in the solar corona” is to be held in Greenbelt in May 2003.

5 The Role of *TRACE* in the Long-term Vitality of Solar Physics

One of the main challenges in solar physics in the present decade is to develop a comprehensive understanding of, and numerical model for, the evolution of the Sun’s magnetic field, including its formation in the overshoot layer, rise through the convective envelope, emergence onto the surface, evolution within the corona, and transport through the heliosphere. Such a comprehensive understanding and numerical model is a necessary prerequisite for a physics-based predictive capability of space weather.

Advancing our quantitative understanding of solar activity requires coordinated multi-wavelength observations to study the evolution and eruption of magnetic fields in and above the photosphere in full detail. *TRACE* offers angular and temporal resolutions in the EUV that exceed other current instruments (*SOHO/EIT*) by a factor of almost 30 in number of pixels per area and in cadence, making it an extremely valuable asset. *TRACE* currently provides an EUV microscopic view of the upper transition region and cooler parts of the corona, and will remain the only mission to do so for the next few years until Solar-B and SDO have been launched. In an ongoing collaboration with SOHO (magnetograms, coronagraph images, UV and EUV spectroscopy, EUV full disk context) and RHESSI (high resolution soft and hard X-rays, X-ray spectroscopy), as well as with constantly improving ground based observatories (e.g., Themis, SST, and some day ATST), *TRACE* will continue to provide a crucial part of "the full picture" of solar magnetic activity in the visible layers of the Sun, because of its high cadence and resolution. As a result of requests from the RHESSI team *TRACE* is now frequently operated at high cadence for extended time periods on flaring regions, sometimes sacrificing angular resolution or field of view for speed.

TRACE continues to provide these crucial capabilities as the solar cycle moves from its maximum to the upcoming minimum. In this phase, we can observe transequatorial coronal connections, the connections with the new solar cycle expected to start soon at high latitudes, and the formation and evolution of the new polar caps following the polarity reversal. The interactions between these three phenomena are of significant interest, particularly in studying the role of helicity and of flux transport in the solar atmosphere.

Until the start of observations by Solar-B (in 2006), *TRACE* will remain the highest resolution solar telescope in orbit, and even after that *TRACE* will continue to provide the highest-resolution EUV window on the Sun. Once Solar-B becomes operational, it will provide extremely valuable information on the lower boundary conditions to the solar atmosphere and the structure of the chromosphere and transition region. Joint studies will be defined to dramatically enhance the scientific return of both Solar-B and *TRACE*.

The STEREO mission (2005) focuses on the "solar origins and development of coronal mass ejections," the "propagation of ejections and disturbances from Sun to Earth," the "mechanisms of solar energetic particle acceleration," and the "3-D structure and dynamics of corona and heliosphere." The high resolution of *TRACE* in both space and time will provide crucial information on the early stages of coronal mass ejections (both for the coronal field and any filament configurations that are involved), and the topological evolution of magnetic fields involved in flares. The scientific effectiveness of the STEREO mission will be substantially enhanced by (planned) coordination with *TRACE*.

Focus areas for the TRACE *investigation*

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

6 Proposed Science Program

The funding that the *TRACE* science investigation has received during the past two years has been lean, but it has been used effectively to stimulate research in a broad segment of the worldwide solar physics community. This mode of operations is expected to continue in the coming years, subject to the decision to continue to operate *TRACE*. We plan to continue to stimulate research, publish in both the refereed and general literature, and (help) conduct workshops dedicated to *TRACE*-related science. As most of the scientific investigation is performed through separate SR&T funding and international collaboration, we cannot direct the outcome. However, we identify ongoing developments and shifts in research focus in the community and plan to stimulate these through, e.g., workshops, and to optimize the use of *TRACE* resources through a continued flexible response to requests for special observing runs or collaborations.

Continued operation of *TRACE* is crucial to (a) the study of the dynamic solar magnetic field that drives space weather; (b) the development of new models or validation of tentatively proposed models for some of the most interesting discoveries made with *TRACE* that at present are based on small sets of events or even a single event; and (c) the interpretation of results from new and future missions, including *RHESSI*, *STEREO*, and *Solar-B*. The most important categories of research include:

Filaments and CMEs: Close collaboration with *SOHO* (*MDI*, *EIT*, *CDS*, and *SUMER*) will continue in the study of filaments in order to understand their formation (including sigmoid structures within active regions), eruption, and demise utilizing the high temporal and angular resolution of *TRACE*. In high-cadence observations, special emphasis will be given to the study of what appear to be twisting motions seen in large filaments and small fibrils alike; these provide information on the development of currents within the erupting system.

Flare physics and rapid reconnection: A primary focus in the next years will continue to be coordination with RHESSI and SOHO on flare studies. Focus areas include (1) understanding the relationships between the footpoint hard X-ray emission, the UV flare ribbons, and the structure of the photospheric magnetic field, and (2) understanding the properties of the hot thermal flare plasma (12-25 MK), which *TRACE* observes through continuum radiation in the EUV passbands and Fe XXIV in the 195 Å channel, and its relationship to both footpoint and coronal hard X-ray sources. *TRACE* data can, moreover, be used to study white-light and UV data for weak flares to see how important non-thermal particle acceleration is in these flares.

Combining observations from the two missions will allow us to study the relationship between the footpoint hard X-ray emission and the flare ribbons. *TRACE* UV observations show the flare ribbons to be complex structures with many compact bright points within them, whereas previous, low-resolution hard X-ray images suggested much simpler conjugate footpoint brightenings. Thus, the relationship between the precipitating energetic electrons and the global structure of the flare ribbon is not well understood. Furthermore, by including magnetograph observations we will be able to study the relationship between energy deposition into the chromosphere and the structure of the photospheric magnetic field. The rate of magnetic reconnection and clues to the connectivity of the field lines can be inferred from the ribbons' spatio-temporal fine structure.

Although the activity of the Sun will continue to decline in the coming years, *RHESSI* has demonstrated that it is sensitive not only to large flares, but also to the much more frequent smaller flares (such as the small flare shown in Fig. 6 that did not even register as a C-class event on the GOES X-ray scale). We plan to continue coordination with the worldwide Max Millenium program whenever a major flare alert is called, or whenever scheduling with other Joint Observing Programs allows.

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

Atmospheric seismology: As summarized in § 1, the analysis of wave phenomena is proving to be an extremely fruitful means to learn about the physics of the solar outer atmosphere. *TRACE* plans to continue to observe (in both primary and secondary roles) wave phenemena, including EIT (coronal Moreton) waves, slow magneto-acoustic waves, and kink modes.

A recent finding (by De Pontieu, in progress) that conjugate footpoints of low-lying coronal loops frequently oscillate in phase requires high-frequency observations of plage regions. Such observations can elucidate the details of wave propagation from end to end in loops, and wave damping on the way. We also plan to continue the hunt for high-frequency sausage modes (not yet detected in the preliminary k–ω diagrams such as that in Fig. 3).

The *TRACE* team is stimulating theoretical studies with, e.g., Drs. Erdelyi, Nakariakov, and Roberts in the U.K. to further our understanding of these wave phenomena. We have also collaborated closely with the organizers of a future workshop on atmospheric seismology (SOHO 13, see below) to bring this interesting topic to the attention of a wide audience.

Loop physics: The fact that there appear to be no uniformly heated, quasi-static loops requires fundamental changes in loop modeling. Guidance to the development of these models (likely to involve flows, variable heating, and sub-resolution structuring) will be derived from continued loop analyses. Joint observing with *SOHO/SUMER* and *CDS* will be given priority to study thermal and flow properties of the plasma in coronal loops.

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

Our studies of the field geometry are now extending their reach to the corona-heliosphere coupling (see § 1) by studying how bright active region coronal loops couple into and away from the heliosphere. This will be of particular interest in the coming years as the active region contribution becomes comparable to the polar-cap component.

Another interesting aspect that can be studied in particular in the coming years is the coronal coupling between active regions, both across the equator between regions on the two converging branches of the present activity cycle, and the interaction between active regions of the current and next activity cycles. In combination with (vector) magnetograms, this will provide insight into the Sun's helicity budget: how do regions on different branches of the dynamo patterns interact; is there a measurable difference depending on their helicity?

Coronal response to photospheric driving: Coordinated continuous observations with *TRACE* and *SOHO/MDI* allow the analysis of the coronal response to photospheric evolution. *TRACE* has a unique data set of over a dozen disk passages of active regions extending over more than 10 days, many coordinated with *SOHO/MDI*. The analysis of this data, and further examples, will advance our understanding of the coronal magnetic field.

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

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

To facilitate all of the above, new observations are needed. To stimulate their analysis and interpretation, we are already strongly involved in the organization of two workshops:

- "SOHO-13: Waves, oscillations and small scale transient events in the solar atmosphere: A joint view of SOHO and TRACE," to be held on Mallorca in the fall of 2003 (see: http://soho13.uib.es/; Title and Schrijver are both members of the SOC).
- "SOHO-14", with special emphasis on high-energy processes in the solar atmosphere, based on RHESSI, *TRACE*, and SOHO. This meeting, to be co-hosted by Lin, Schrijver, and Fleck, will likely be organized for the fall of 2004, in northern California (provided adequate funding can be found).

To facilitate efficient data analysis we will work to include the *SOHO/MDI* magnetograms in *TRACE* analysis programs, in particular to provide easy access from the BROWSER package written in the analysis language ANA, while having a substantial subset of *MDI* magetograms available on-line in parallel to the *TRACE* archive. We have recently installed a SolarSoft/IDL tool for the computation of potential field lines using the global potential-field source-surface model in combination with a full-sphere surface-field model based on MDI data; we plan to make this tool accessible via the web under separate funding.

How much of the above science can actually be successfully addressed will, of course, depend on the magnitude of the funding that will be available in the coming years. This is discussed in §§ 10 and 11.

7 Overview of Mission Operations and Data Analysis

TRACE was launched into a near-perfect orbit on 2 April 1998. Within two days all subsystems of both the spacecraft and instrument were turned on and functioning nominally. 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 preplanned 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 season 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 35 minutes long). This pattern of modest yet still productive observing during the eclipse season has been followed ever since. For example, in the winter of 2002 two months were devoted exclusively to high cadence UV observations of the Max Millenium target region.

Aside from the pleasant surprise of eclipse season observing, the pre-flight plans for both science operations and data handling were closely followed in the first two years of 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 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 for sending commands, which 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 several missions.

Every week, one of the *TRACE* scientists is designated as planner. General priorities for each week are decided in a telecon the previous Thursday, using a calendar of proposed observations similar to the *SOHO* calendar. 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 identical programs are run for weeks at a time.

A significant change in our operational approach was made in 2000 when we switched to predominantly remote science planning. In the first observing season (1998), we had maintained an operations team at the Experiment Operations Facility (EOF) at GSFC of three scientists, a data technician, and a computer systems administrator. Often an additional scientist was present on travel from LMSAL, SAO, or MSU. In 1999 and 2000, the connectivity and software tools were improved so we now routinely conduct operations from the home institutions. 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 and one part-time computer system administrator. Still, we have never missed a deadline for providing the science timeline to the FOT for uplinking.

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 a workstation in the EOF provided by the science team; this is the official delivery of data by NASA to the science team. A NASA technician maintains the DPS and tracks down missing data files from the ground station.

Once the data is delivered, it is sent by ftp to LMSAL in Palo Alto for cataloging, reformatting and archiving. Web-based summaries of the data appear within a few hours of receipt, and within 12 hours the archived data is usually available for the entire science community online from the LMSAL data center. 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 LMSAL and SDAC facilities for immediate access. All data is available to anyone via a web interface with capabilities for searching the catalog. This 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 gamma ray flare. The planner, our local operator, and the FOT then work together to ensure that *TRACE* is observing the proper target region.

8 Observatory and Ground System Status

The health of the *TRACE* Observatory has not changed significantly since the last Senior Review; it is excellent, and we are confident that *TRACE* can continue to collect outstanding solar data well beyond the period covered by this Senior Review. Orbit predictions show an altitude that decreases very little until the middle of 2008; the min/max altitudes presently being 580/610 km, compared with 600/660 km at the start of the mission. The original dawn-dusk orbit resulted in an eclipse season of 97 days each winter, and the eclipse season last winter was only 98 days. Not until 2009 does the orbit begin to experience two eclipse seasons per year before going into a continual eclipse “season” a couple of years later. Neither the spacecraft nor the instrument (see Figure 10) contain any consumables that would lead to a predictable end of mission life. There are, however, some signs of aging and these are discussed below.

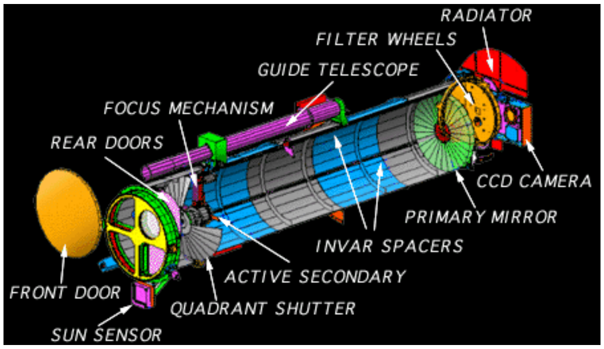

Figure 10: *Cutaway figure of the TRACE instrument*

Since launch, the spacecraft has gone into a safe-hold condition four times, in 1999, 2000, and twice in the Fall of 2002. The first occurred during a proton storm and is attributed to a single event upset in the spacecraft computer. Causes for the second and third events are not fully understood; but both occurred when commands were being sent to a second SMEX spacecraft in the vicinity of *TRACE*. The last safe-hold occurred just after *TRACE* exited the shadow of the solar eclipse on 4 December 2002. During the eclipse, the spacecraft attitude drifted so that the sun was out of range of the digital sun sensor. The ACS switched to the coarse sun sensor, which indicated a pointing error greater than 10 degrees. Then the failure detection and handling part of the ACS software correctly triggered the safe-hold. This episode was studied carefully by the FOT and flight software engineer, who concluded that the coarse sun sensor gave an inaccurate reading because it saw both the earth’s bright limb and the partially eclipsed solar disk. They recommended technical changes in the approach to avoid this problem, which had not occurred in 8 previous eclipses, in the future.

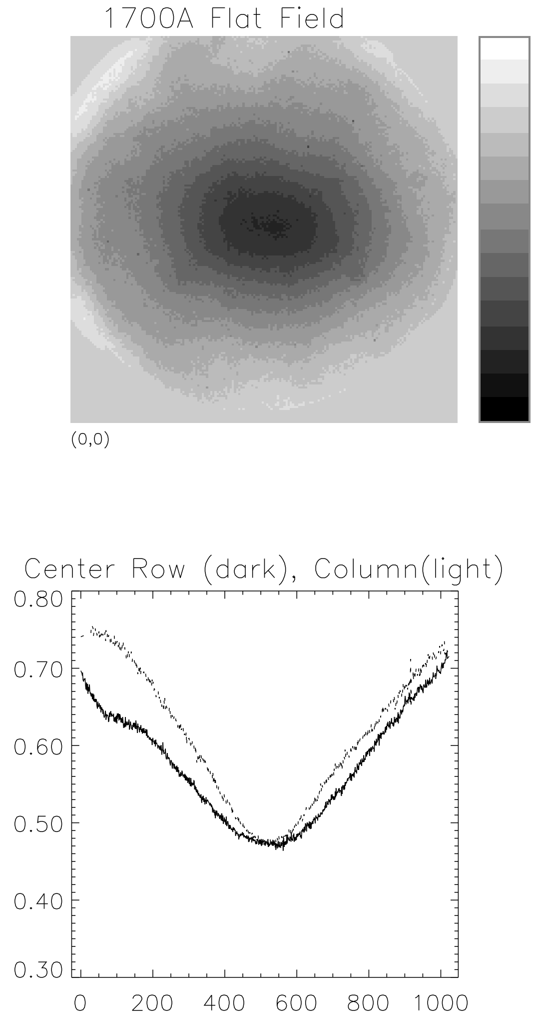

Figure 11: *1700 Å flat fields for 1 May 2002, in percent relative to the initial sensitivity. Flat fields for other wavelengths are qualitatively similar.*

In all of the safe-hold events, 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 2002 events coming on Friday afternoon before a holiday weekend and the other during a blizzard which shut down GSFC. With only four such occurrences in over five years there is no meaningful prediction of how often such events may occur in the future, other than very infrequently.

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 battery still shows considerable margin during eclipse season, so there is no foreseeable need to power down the instrument then. The anomalous behaviour of one reaction wheel mentioned in the last Senior Review proposal is no longer occurring.

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. Prelaunch experiments at the Stanford Synchrotron Radiation Laboratory provided a prediction of degradation versus dosage and indicated that the degradation in sensitivity would level off at about 30% of the original value. Experience on orbit has shown that the rate of sensitivity loss is less than predicted, perhaps because of the temporal acceleration of the ground tests. Most observations can use longer exposure times to compensate without real loss of temporal resolution, since cadence is usually limited by onboard 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.

Since the last review, we have succeeded in calibrating 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 has been a complicated procedure, involving four types of calibration data: flat fields derived from the Kuhn-Lin algorithm in 1700 Å, the lowest contrast of the UV wavelengths; synoptic disk center images in all UV wavelengths, in which quiet disk center is used as a “standard candle;” EUV “dosimeter” images, low resolution records of total EUV flux on the CCD throughout the mission; and image sets in which the same solar feature is placed on different parts of the CCD by repointing in small steps over a short time interval. Figure 11 shows a 1700 Å flat field image, that demonstrates the center to edge sensitivity variation. Figure 12 shows the time history of the inferred sensitivity in 171 Å at a uniform grid of points on the CCD. The degradation at the center of the CCD, where the brightest part of the

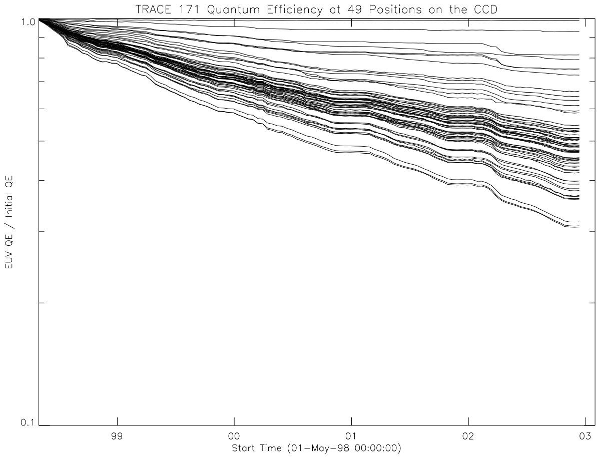

Figure 12: *Quantum efficiency in 171 Å vs. time on a uniform 7x7 grid of positions on the TRACE CCD, normalized to the initial value*

solar target is usually placed, is now down to about 30% of the original. Near the edges of the CCD, the sensitivity is still around 80% of the initial value. These data suggest that the sensitivity may show a steady exponential decay rather than stop at a nonzero level. Even so, the e-folding time over most of the CCD is more than 5 years, so very productive observing can continue well beyond the period of this review. 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 (expected).

In terms of mechanisms, *TRACE* contains two filterwheels, a focal plane shutter, a quadrant selector mechanism, a pair of rotating pointing wedges, and a focus mechanism. Although the nearly 12 million images which have been taken by *TRACE* in the last five years is an impressive number, it pales in comparison to the 70 million images that have been taken by MDI; and the focal plane shutter, filterwheels, and rotating wedges are basically copies of MDI units. The focus mechanism, which has made about 15 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 focus, which is hardly noticeable on such high contrast images.

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. From time to time, it misses its destination by more than one step. Sometimes it recovers on its own, but other times it loses track of its position with the result that useless images are taken until a reset sequence is run by commands from the FOT or the timeline. We do not fully understand why this occurs but are convinced that the unit is not mechanically "breaking down;" rather its control system "gets confused." The problem is quite intermittent. Typically we limit the time periods of heavy usage of the quadrant selector to weekdays before the last telemetry pass of the day, so the FOT can send the reset sequence if necessary. On the other hand, during some JOPs and campaigns we use the quadrant selector intensively and run for days without data loss.

Since the last proposal, we have investigated causes and solutions for this anomalous behaviour, so far with limited success. A diagnostic mode with high rate sampling of the motor current was loaded onboard. These data look very similar to that from preflight testing and from a brassboard mechanism, lending confidence that the mechanism has not changed significantly but rather the controller is flawed. We have a *TRACE* simulator at LMSAL consisting of brassboard mechanisms, flight electronics, computer and image processor. The anomalous behaviour of the quadrant selector also occurs occasionally in the simulator, and some software fixes to the control algorithm have been tried without success; the key control features are in firmware which cannot be changed. We have recently begun testing a combination of new instrument and spacecraft software, with which the instrument alerts the spacecraft if it detects the quadrant selector in an invalid position; the spacecraft then pauses observing and executes the reset procedure. This can potentially limit the lost observing time after an anomaly to less than a minute, rather than hours at present. If successful, we can return to essentially unlimited usage of the mechanism; if not, we will continue to consider possible solutions while following the present operational guidelines to limit its use.

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, and EOF and LMSAL computer systems have received considerable attention to plug security loopholes. We have submitted a *TRACE* Information Technology (IT) Security plan, which received partial approval by the GSFC experts; the process of receiving full approval proceeds at a deliberate pace. Probably the largest remaining security loophole in the TRACE ground system is the use of ftp in automated mirroring of data and software directories between GSFC, LMSAL, SAO and MSU. We have tried without success to replace ftp with secure sftp in mirroring. Consequently, we plan to replace our existing mirroring software with more secure and robust mirroring software based upon GridFTP and other components of the Globus Grid toolkit.

In summary, the *TRACE* observatory and ground system show only modest signs of wear, indicating that their useful lifetime will extend well past the launches of STEREO, Solar-B, and SDO, resulting in new and extraordinarily productive collaborative observations.

9 Response to the 2001 Senior Review

The 2001 Senior Review gave the TRACE mission an excellent rating for its science and strongly recommended continued operations for the next two to four years. Dr. Withbroe concurred with these findings; the following comes from his letter to the PI reporting the results of the review.

“We congratulate you and your colleagues on having maintained an excellent science program and promoting the excitement of solar science to the general community. However in view of the overall budget situation for the SEC MO&DA program that we are facing as we approach the period of minimum solar activity, the Senior Review panel recommended that TRACE decrease the pure science FTE load and, if necessary, reduce science planning expenditures. We, in general, endorse this recommendation, and have used it in formulating the programmatic directions given below. The FY-02 funding allocation has a modest increase over that recommended by the Senior Review in recognition of the contributions of TRACE to public outreach and its importance to the HESSI mission.”

“A. You should plan on funding (“new obligation authority”) at the level of $3,700 K in FY-02.”

“B. FY-03 funding will be $2,700 K. To help limit MO costs, you should examine the feasibility of alternate arrangements for conducting mission operations functions. One suggestion would be to move the operational control center for TRACE to Bowie State University as was successfully done with the SAMPEX satellite.”

This budget for FY-02 was reduced below the ”Minimal Scenario” request of $4,061 K in the Senior Review proposal, a cut of 9%; the FY-03 funding is an additional reduction by 27%. Painful though this has been, the TRACE team has adjusted to these lower budgets in a manner consistent with the mission extension paradigm outlined in the Senior Review Instructions. The loss in data collection capability has been very small, but support by the *TRACE* project for scientifically-motivated data analysis and research has decreased quite dramatically.

First, funding was phased out for the two university co-investigators who were not involved in science operations – Stanford and Chicago. This reduced the “pure science FTE load,” as requested by the Sr. Review Panel and the Withbroe letter, by removing partial support for four post-docs. Thus, it also decreased our ability to bring new scientists into the discipline of Solar (and Solar-Terrestrial) Physics, which is very unfortunate. Next, funding for the three remaining core team institutions was reduced by approximately 30% at SAO and MSU and by 25% at LMSAL; the latter reflecting the greater role in operations, engineering support and data archiving at LMSAL. This has reduced the research support considerably, and several team members formerly supported primarily by *TRACE* funds have written SRT and LWS proposals to replace the losses (for example, Schrijver, De Pontieu, Aschwanden, Golub, Warren, Winebarger). We have continued operating the data archive and improving the instrument calibration, so the community has seen no changes in the availability and quality of TRACE data.

Next, we discussed the Mission Services tasks and costs with the GSFC personnel responsible for them, mainly R. Mahmot, P. Crouse, and M. Madden. Based on these discussions, the allocation for Mission Services was revised from $1148 K to $848 K in FY-02 and $574 K in FY-03. These reductions resulted from a review of all the mission operations being conducted by GSFC and the subsequent creation of revised Project Service-Level Agreements with SOMO for these missions.

The services provided to the TRACE mission under the new agreement have been basically unchanged in FY-02 and FY-03 from those provided in FY-01. The only significant exception has been the level of effort expended to maximize data capture, consistent with the extended mission guidelines, resulting in a minor increase in data losses. The cost reductions were also accomplished through consolidating the three mission service elements (flight operations, flight dynamics, and level-zero processing) into a single CSOC facility, namely SMEX MOC. This consolidation, leveraged across the SMEX missions managed by GSFC, resulted in reductions of direct operations staff, support staff, and management. FOT members also spend part of their time supporting integration and test for other non-SMEX projects at GSFC. The risks identified as a result of this effort are only incremental increases over those already accepted under the five day, single shift staffing operations concept.

Finally, we have looked at alternate arrangements for conducting mission operations. Shortly after receiving the results of the review, we evaluated the SMEX operations at Bowie State and concluded they did not represent a feasible, cost-effective alternative for *TRACE*. With the dramatic reductions in mission operations costs at GSFC in FY-02 and FY-03, we did not look at additional options until late 2002. At that time it became apparent that *TRACE* might be the only mission operating from the SMEX MOC at the end of 2003, and therefore the costs attributed to *TRACE* might rise with no other missions to share them.

By this time, RHESSI was launched and operating smoothly, and the RHESSI science team was extremely interested in *TRACE* data and in ensuring that *TRACE* would continue observing through their mission. At the invitation of RHESSI PI Bob Lin, we visited the MOC at the UC Berkeley Space Sciences Lab, which operates RHESSI, FAST, and now CHIPSat. The UCB operators were trained at GSFC, using software (ITOS) and procedures similar to those used at the SMEX MOC, and are certified by NASA for satellite operations. After detailed discussions, it was apparent that the UCB MOC would be capable of operating *TRACE* in a safe and effective manner. A proposal with their technical approach to *TRACE* operations and budget estimates for transition costs and operations in 2004 and 2005 was prepared by UCB project manager Manfred Bester in late February, 2003.

Using the UCB proposal and the cost estimates for GSFC operations prepared for this Senior Review, we have made a detailed cost comparison. Assuming a transition period of the first 6 months of FY-04, we included costs for the UCB proposal, GSFC operations during the transition, continuing low-level engineering and SW maintenance support from GSFC, slightly increased LMSAL operations and administrative costs, LMSAL savings from closing the EOF later in FY-04, and some contingency reserve for the changeover. The conclusion is that in the first year (FY-04) the total operations costs for the UCB option would be more than those for leaving operations at GSFC by $400-450 K; the biggest single component is support for both facilities during the transition. Subsequent annual savings would $100-150 K, so the break-even period would be 3-4 years. In view of the transition costs, risks involved in the move (probably small), and modest future savings, we have decided not to shift operations to UCB at this time. We will closely monitor the funding requirements and performance of the GSFC SMEX MOC in the coming year and reconsider this in the future if necessary. In any case, we expect our close scientific collaboration with RHESSI will continue.

10 In-Guideline and Requested Scenarios

The in-guideline level of funding for the science team is the absolute minimum level 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. After the 2001 Senior Review, we 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 FOT and science team is now more than a factor of two below the primary mission level. The guidelines for the "mission extension paradigm" described in the call for this proposal are just being met at present. The data archiving is highly automated and running in a cost-effective steady state. No additional funding cuts can be accomodated without jeopardizing a safe and productive extended mission.

The present effort is just consistent with the "mission extension paradigm" for science, as stated in the call for proposals. The first two aspects of the paradigm, "bare-bones" mission and science operations and data handling, have been described in previous sections. The next aspect, "minimal science data analysis" to maintain understanding of the instrument performance, is being accomplished, literally; and knowledge of the instrument calibration is gradually being transferred 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 SEC missions," is being carried out very effectively. The collaborations and coordinated observing campaigns cited earlier in the proposal demonstrate this. These latter activities are labor intensive and require trained *TRACE* science planners for operations. Finally, as we have explained, most research with *TRACE* data is being supported by funds other than the *TRACE* project, and several core team members have sought such funds to continue their personal research.

Consequently, our requested budget scenario (we hesitate to call it optimal) asks for a modest increase in funding to support activities that only the core team can perform but which have the effect of bringing *TRACE* data to a larger number of solar scientists and increasing their effectiveness in analyzing it. Recognizing the funding constraints which always affect MO&DA programs, we are proposing only a 10% increase in funding. Since the mission operations are already at a satisfactory level, all of this increase will go into science. This scenario will benefit the community at large by supporting development of new software tools and meta-data and by increasing collaboration with other missions. Some specific tasks in the near-term are listed below.

We will increase our collaboration with RHESSI, both in joint observations and science data analysis. We will take an active role in organizing "SOHO-14," a joint *RHESSI*/*SOHO*/*TRACE* workshop in 2004 and publishing its proceedings, following the model of the 1999 Monterey Workshop. The set of DVD's of *TRACE* movies grouped by phenomena (flares, filament eruptions, loop oscillations, emerging flux, etc.) will be completed in time for the meeting. Copies of this set will be made and distributed to the major solar research groups in the world. After the first production run, we will explore new editions with enhancements, for example, multiple coaligned data sets including magnetograms and potential field extrapolations.

The web resources to facilitate access to *TRACE* data such as the flare catalog, active region database and loop oscillation site will be updated and enhanced. *TRACE* team members have access to other little-known databases which are under development or are a fallout from the operations monitoring software. A significant goal is to make Yohkoh, EIT, and MDI images (including magnetograms) corresponding to selected *TRACE* data more easily available from the web site. We will increase public access to these resources both through improvements in the existing website and through integration and coordination with the distributed data services infrastructure being developed with NASA funding by the Virtual Solar Observatory (Gurman 2002) and Collaborative Sun-Earth Connector (Bose et al 2002) projects.

The *TRACE* BROWSER software (distributed as part of SolarSoft) is used by all of the core team as the primary tool for inspection of *TRACE* images and movies. It is far more effective than any IDL software we have seen for making large digital movies and viewing them interactively. We will continue to upgrade BROWSER so it can import time series of MDI magnetograms and rapidly coalign them in space and time with *TRACE* movies. The *TRACE* IDL software (also available via SolarSoft) is used by most of the community for reading and calibrating *TRACE* image data. The mission-long CCD calibration of the instrument will soon be conveniently available to all users. Changes in the relative pointings of the different *TRACE* wavelengths, and thermally-induced pointing drifts are areas which still need substantial improvement. These effects are especially important for coalignment with RHESSI.

Our long-term requested scenario is for *TRACE* to continue observing the Sun with high cadence and resolution in all its temperature regimes, until *TRACE* is rendered unnecessary by SDO in 2007 or 2008. Starting in 2005, we will work with the *STEREO* science team so that *TRACE* can be a third viewing point early in the *STEREO* mission when the spacecraft are best positioned to resolve low coronal structures and loops in 3-dimensions. And we look forward to joint observing programs with Solar-B, where *TRACE* will serve as a coronal microscope for that mission starting in 2006, as it continues to do so for *SOHO*.

11 Budget Summary

The budget summary in the required spreadsheet format is appended to this proposal. We have added some rows to the spreadsheet (as in the *SOHO* Senior Review proposal) to distinguish more clearly the budgets for the science team and for the mission operations team at GSFC. The science team funding is shown in rows 2.b Mission Services (Science Team), 3. Science Center Functions, and 4. Science Data Analysis & E/PO. All other entries were provided by the *TRACE* mission operations manager at GSFC. They represent direct funding to GSFC for *TRACE* mission operations, funding to other branches of NASA for data services, charges attributed to *TRACE* in multi-mission funding pools, and some much more nebulous attempts to bring full cost accounting to GSFC. 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 2.b Mission Services (Science Team) functions are command generation and telemetry monitoring for the instrument; health and performance monitoring of the instrument and the ground system at the EOF; and flight SW maintenance and engineering consultation for the instrument and the simulator at LMSAL. Row 3. Science Center Functions include science planning and timeline generation; instrument and observation performance analysis; science data calibration; master data archiving at LMSAL; distribution to to the mirror data archives, SAO and MSU; quick-look data production; maintenance of the data distribution system and basic IDL SolarSoft routines. Row 4. Science Data Analysis & E/PO includes meta-data preparation such as the flare catalog and active region database; custom SW and data processing such as browser enhancements; data analysis and research; documentation, presentation and publication of technical and scientific results; support for symposia and meetings; and E/PO. 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 the PI at LMSAL; the science teams at SAO and MSU receive subcontracts, as does L-3 Communications (which provides the part-time science planner and systems administrator at the GSFC EOF). LMSAL (assisted by L-3 Communications) provides all of the 2.b Mission Service functions. SAO and MSU contribute a significant share of the science planning and timelining effort; the remaining row 3. Science Center Functions are provided by LMSAL. 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; two Ph.D. students at MSU are fully supported. LMSAL supports several senior and junior scientific staff at very limited and moderate part-time levels, respectively; engineers and SW specialists as needed; visiting graduate students and postdocs with travel and per-diem funds; and high school students in an E/PO program. Materials costs are for additional hard drives for the archive, occasional replacement of obsolete computers, and hardware and SW maintenance contracts on essential systems. Lockheed Martin provides full support for the PI as well as additional E/PO, computer hardware, software, and maintenance labor costs from corporate funds.

The in-guideline funding for the science team as obtained from the GSFC mission manager is constant at $1,991 K for the entire period (until rounded up in FY-07). This has been allocated among the categories based on the past year estimated actuals as follows: 15% to I.2.b Mission Services, 55% to I.3 Science Center Functions, and 30% to I.4 Science Data Analysis & E/PO. The Requested Scenario adds an additional $75 K to II.3 Science Center Functions and $150 K to II.4 Science Data Analysis & E/PO. As described above, these will support additional software and calibration development for community use, meta-data development to facilitate access to the *TRACE* data, the “SOHO-14” Symposium (including publication of proceedings), and DVD production. We also include a 3% inflation correction each year in the request. This very modest increase (10%) in funding beyond the level guideline will greatly increase the scientific returns from *TRACE* data obtained by the entire community, not just the core science teams, and will help to ensure the safe and productive operation of the observatory until the SDO era begins.

Mission operations costs in the In-Guideline and Requested Scenarios (I & II) consist of the following. Row 2.a Data Services are costs for T-1 lines enabling data mirroring between GSFC and LMSAL. Row 2.b Mission Services (GSFC Ops Team) supports the *TRACE* FOT and DPS engineers rather directly. Row II.2.c in FY-04 represents contingency for transition costs at the end of the CSOC contract. Data downlinks at Poker Flat and Wallops Island and some voice and data transmission costs are captured in III.2.a In-Kind NASA Data Services. III.2.b Mission Services (GSFC Ops Team) represents the fraction attributed to *TRACE* of hardware infrastructure, maintenance, and engineering support in a multi-mission pool at GSFC. III.2.c and III.2.d are mysterious personnel and miscellaneous administrative costs attributed to *TRACE* in an early attempt at full cost accounting for GSFC. We believe that none of these In-Kind costs in section III actually come from the SEC MODA budgets, and therefore it would not be possible to recover them by moving operations away from GSFC at this time.

It is difficult for us to predict the future of mission operations at GSFC, given the decreasing number of missions served, the transition to full-cost accounting, and the end of CSOC. *TRACE* has always received excellent service from the GSFC MOC, and the costs have decreased significantly since the prime mission years. We hope that this state of affairs will continue; however, if it does not, we will revisit the option of moving mission operations to the capable facility at UC Berkeley or to other alternatives which may appear.

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Figure 13: *Left: A collection of images showing the science of the Sun-Earth connection, with particular emphasis on TRACE, is now shown at NASA headquarters (above), and at the National Academy, the Swedish Academy of Sciences, and Cambridge University. Right: A paper model of the TRACE satellite (in full color in a more recent verion) is available on the web (see Table 5).*

13 Education and Public Outreach

The spectacular *TRACE* images, movies, and discoveries have found their way to many people around the world. These 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. A partial listing of *TRACE* in the media resides at http://vestige.lmsal.com/TRACE/Science/Scientific-Results.

The relatively small *TRACE* team continues to work with high-school and undergraduate students, as well as attract graduate students at, e.g., the Smithsonian Astrophysical Observatory (Boyd, Seaton) and at Montana State University (Cirtain, McMullen, Scott, and Wills-Davey), within the U.S. Graduate students at at least the Universities of Oslo, Stockholm, St. Andrews, Tokyo, and Utrecht also dedicate substantial time to the analysis of *TRACE* data.

The *TRACE* project at LMSAL 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. Many graduates of this program at LMSAL (which is over 25 years old now, dating from OSO-8) have entered careers in science or engineering.

During the past two years, the period reviewed in this proposal, *TRACE* images are found in textbooks, popular science journals (including Science, Scientific American, Popular Science, Sky and Telescope, Astronomy, American Scientist, Nature, and National Geographic), newspapers (including the Boston Globe) and news magazines (a two-page spread in the year-2000 overview of LIFE Magazine; The Economist; Space Illustrated; Science News Magazine, Aviation Week & Space Technology). *TRACE* images, and the science of the Sun in general, were given attention in two cover stories of Sky and Telescope in early 2001, with a readership of over 200,000. *TRACE* will also appear in "Best Ever Astronomy," a series of science books aimed at children of ages 8 and up (to be published by Kingfisher in 2003).

Images of the 1999 Mercury transit were used

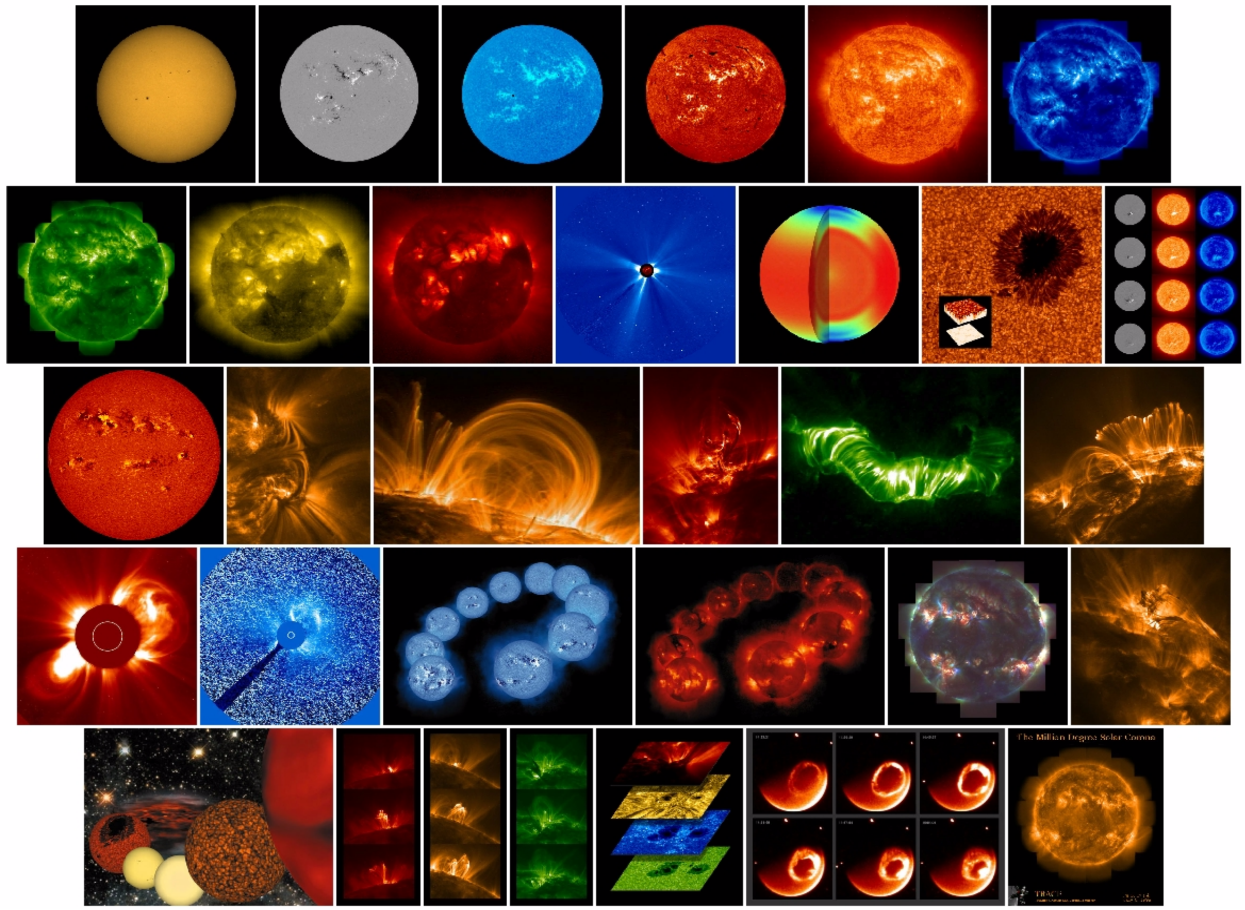

Figure 14: *A collage of images that were part of the "Sunscapes" exhibit at the National Academy of Sciences during 2002. Many of the images are based on observations by* TRACE*, and demonstrate that importance of that mission to solar-terrestrial science and the Living With a Star program.*

for a pamphlet at the Carnegie Institute of Washington. Even an advertising agency in Turkey used some *TRACE* imagery. The Italian print of the Space Odyssey had a TRACE image on the cover. Images appeared in the German magazine "Sterne und Weltraum." The Institute for Plasma Physics of the Max-Planck Society in Garching/Germany, JPL, the Denver Museum of Natural Science,all used *TRACE* images.

Special efforts produced a very high-quality image set for public viewing, covering the entire Sun-Earth connection with emphasis on the *TRACE* images of the solar corona. A set of 32 images (Fig. 14) was shown in the National Academy building (19 Feb. - Aug. 15, 2002; see the images at http://vestige.lmsal.com/TRACE/POD/NAS2002.html). This set now decorates various Academy buildings. Copies of this set are currently being shown in the lobby of NASA headquarters (Fig. 13), at the Royal Swedish Academy of Sciences, and in the Applied Mathematics building of the University of Cambridge.

In the last two years, we have distributed 7,500 copies of a poster on Coronal Loops. Half of these were distributed directly to schools (including the Challenger Centers), museums and small science centers (such as Chabot); another 1000 were distributed through NASA educational resource centers and brokers, including Goddard and Ames); and the rest was distributed at AAS and AGU meetings, or in response to request from around the world. We also produced calendars for two consecutive years: 1000 yearly calendars were produced for 2002, and 2000

Figure 15: *Sky and Telescope (Feb. and Mar. 2001 issues) featured papers discussing the "Science of the Sun." These papers, winning the 2001 Popular Writing Award of the AAS Solar Physics Division, included* TRACE *discoveries and images.*

monthly calendars were produced for 2003. These found their way to many solar-physics and astrophysical colleagues, and to schools near the primary partner institutions of *TRACE*. We have also distributed several hundred DVD's with *TRACE* movie collections.

TRACE movies were provided to the National Film Board of Canada for a special on the Sun, as well as for an episode of the series "Zone Science." They feature prominently on a commercial DVD entitled "The Universe;" that program is currently being formatted to be aired on PBS stations, starting with KCSM in the Bay Area. *TRACE* movie sequences were also featured in "Total Eclipse," a production of the Exploratorium and the NASA Sun-Earth Connection education forum.

The *TRACE* E/PO budget, complemented by Lockheed Martin funding, is spent entirely on the production of images and movies for the abovementioned purposes; no independent dedicated K–12 programs were developed in the past 2 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 (see also Fig. 8).

Some of the most interesting images and movies are posted regularly on these *TRACE* web pages (at http://vestige.lmsal.com/TRACE/POD), where they are often found both by our scientific colleagues and by the media in general.

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Appendix A

Acronym Definitions

AAS	American Astronomical Society
ACS	Attitude Control System
AGU	American Geophysical Union
AR	Active Region
ATC	Advanced Technology Center
ATST	The Advanced Technology Solar Telescope
BATSE	Burst And Transient Source Experiment
BBSO	Big Bear Solar Observatory
CCD	Charge Coupled Device
CDS	Coronal Diagnostic Spectrometer
CHIPSat	Cosmic Hot Interstellar Plasma Spectrometer
CME	Coronal Mass Ejection
CSOC	Consolidated Service and Operations Contract
DOT	Dutch Open Telescope
DPS	Data Processing System
DVD	Digital Video Disk
EISCAT	European Incoherent Scatter (radar facility)
EIT	Extreme ultraviolet Imaging Telescope
E/PO	Education / Public Outreach
EUV	Extreme Ultraviolet
FAST	Fast Auroral Snapshot Explorer
FOT	Flight Operations Team
FTE	Full Time Equivalent
FTP	File Transfer Protocol
FWHM	Full Width at Half Maximum
FY	Fiscal year
GB	Gigabyte
GOES	Geostationary Operational Environmental Satellite
GSFC	Goddard Space Flight Center
IAU	International Astronomical Union
IDL	Interactive Data Language
ISAS	Institute for Space and Astronautical Sciences
IP	Internet Protocol
IT	Information Technology
ITOS	Integration, Test and Operations Software
JOP	Joint Observing Program
JPL	Jet Propulsion Laboratory
KPNO	Kitt Peak National Observatory
LMSAL	Lockheed Martin Solar and Astrophysics Laboratory
LMSS	Lockheed Martin Space Systems
LWS	Living With a Star
MDI	Michelson Doppler Imager
MEDOC	Multi-Experiment Data Operation Centre
MHD	Magnetohydrodynamic
MOC	Mission Operations Center
MO&DA	Mission Operations and Data Analysis
MSSTA	Multi-Spectral Solar Telescope Array
MSU	Montana State University
MXUVI	Multiple XUV Imager
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Orgaization
NSO	National Solar Observatory
PI	Principal Investigator
POD	Picture of the Day
RHESSI	Ramaty High Energy Solar Spectroscopic Imager
RTV	Rosner, Tucker, Vaiana (Loop Models)
SAO	Smithsonian Astrophysical Observatory
SDAC	Solar Data Analysis Center
SDO	Solar Dynamics Observatory
SEC	Sun-Earth Connection
SHARPP	Solar Heliospheric Activiy Research and Prediction Program
SMEX	Small Explorer
SOC	Science Operations Coordinator or Science Operations Center
SOHO	Solar and Heliospheric Observatory
SOMO	Space Operations Management Office
SPO	Sacramento Peak Observatory
SR&T	Supporting Research and Technology
SST	Swedish Solar Telescope
STEREO	Solar Terrestrial Relations Observatory
SUMER	Solar Ultraviolet Measurements of Emitted Radiation
TAG	TRACE Analysis Guide
THEMIS	Télescope Héliographique pour l'Étude du Magnétisme et des Instabilités Solaires
TR	Transition Region
TRACE	Transition Region and Coronal Explorer
UCB	University of California at Berkeley
UV	Ultraviolet
VAULT	Very high Angular resolution ULtraviolet Telescope
VLA	Very Large Array
WL	White Light