Ground-Based Solar Physics in the Era of Space Astronomy

A White Paper Submitted to the 2012 Heliophysics Decadal Survey

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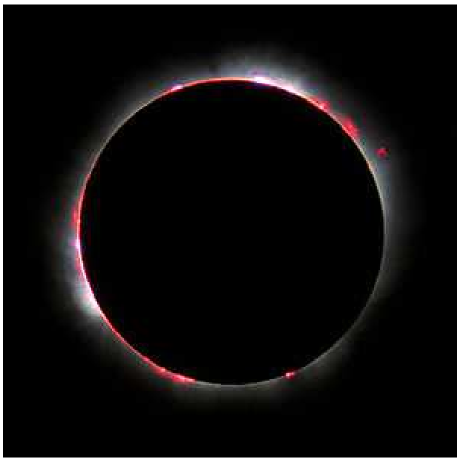
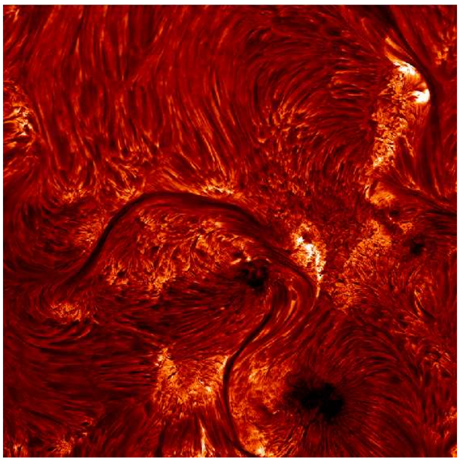
(on behalf of the 2009 AURA Solar Decadal Committee)

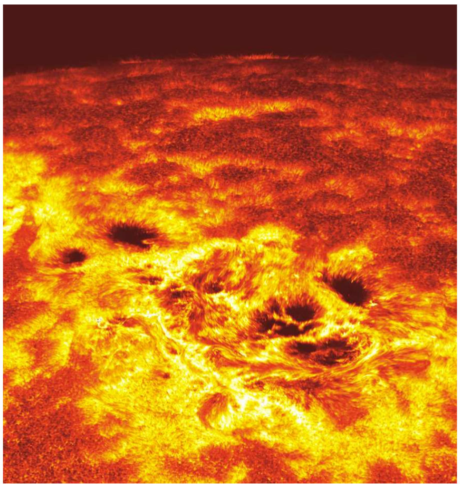
Chromosphere-Corona at eclipse



Hα filtergram



Photospheric spots & bright points



Same area in chromospheric Ca^{+}

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SUMMARY. *A report, previously commissioned by AURA to support advocacy efforts in advance of the Astro2010 Decadal Survey, reached a series of conclusions concerning the future of ground-based solar physics that are relevant to the counterpart Heliophysics Survey. The main findings: (1) The Advanced Technology Solar Telescope (ATST) will continue U.S. leadership in large aperture, high-resolution ground-based solar observations, and will be a unique and powerful complement to space-borne solar instruments; (2) Full-Sun measurements by existing synoptic facilities, and new initiatives such as the Coronal Solar Magnetism Observatory (COSMO) and the Frequency Agile Solar Radiotelescope (FASR), will balance the narrow field of view captured by ATST, and are essential for the study of transient phenomena; (3) Sustaining, and further developing, synoptic observations is vital as well to helioseismology, solar cycle studies, and Space Weather prediction; (4) Support of advanced instrumentation and seeing compensation techniques for the ATST, and other solar telescopes, is necessary to keep ground-based solar physics at the cutting edge; and (5) Effective planning for ground-based facilities requires consideration of the synergies achieved by coordination with space-based observatories. Additional findings — more broadly relevant to solar physics as a whole — involved workforce and training issues, and the support of theory and modeling. A final recommendation considered the possible transfer of the National Solar Observatory and its facilities from NSF's Math & Physical Sciences directorate to Geosciences, urging that full consideration be given to ensuring that key intellectual and material links of solar to broader astrophysics are not broken. We also take this opportunity to advocate the solar-stellar connection, especially its role in understanding aspects of our star that are difficult to capture with contemporary measurements, such as the post-T-Tauri stage, relevant to the evolution of primitive planetary atmospheres, and the far distant future of the Sun, and what it might hold for the ultimate fate of the solar system.*

Background

In 2009, a report[1] concerning the future of ground-based solar physics was commissioned by the Association of Universities for Research in Astronomy (AURA), which manages the National Solar Observatory on behalf of the National Science Foundation. The report considered the standing of ground-based solar in an era when funding for heliosciences by NASA greatly eclipses that by the NSF for solar facilities on the ground and competitive grants. The report was written before construction of NSO's premier new ground-based facility — the 4m Advanced Technology Solar Telescope — had been approved by the National Science Board, and MREFC funding for the initial phases had been secured. The intent of the report was to inform AURA's efforts to advocate the value of ground-based solar physics, especially at the NSO and particularly the ATST, to the NRC's Astronomy & Astrophysics Decadal Survey. The report never was formally submitted as a white paper to Astro2010, however, and much of its impetus evaporated when the ATST construction was approved, shortly before the deliberations of the Astro2010 panels began, and the ATST then was removed from reconsideration (and possible re-ranking).

At the same time, the findings and recommendations of the report are pertinent to the new 2012 Heliophysics Decadal Survey. It is our intent here to provide a synopsis of those

[1] See: http://www.aura-astronomy.org/news/Future of Ground Based Solar Physics.pdf

results, on behalf of the original AURA committee.

We also take the opportunity to discuss the role of the "solar-stellar connection" in the heliosciences context. It is a multidisciplinary effort to, on the one hand, provide a conduit of solar knowledge to the broader astrophysical community; and on the other, passing stellar lore back to solar physics to address aspects of the Sun — especially historical and futuristic — that are not easily accessible with contemporary measurements.

Solar Physics: Support, Demographics, and Facility Usage

Before delving into the specific recommendations of the AURA report, it is worth mentioning some of the background information that was woven through that narrative (and in other solar-related Astro2010 white papers), as a backdrop for those recommendations.

Solar physics plays a unique role in astronomy. It is the only field in classical astronomy that can claim significant societal relevance, extending from the obvious direct influence of the solar luminosity on planetary habitability, to the more subtle impacts of Space Weather on human civilization and commerce. Solar physics also is unique in contemporary stellar astronomy in having a next-door view of its (albeit singular) subject, even to the extent of directly capturing particulate matter in the extreme outer limits of the solar atmosphere (i.e., the coronal wind). The uniqueness of solar physics extends to its (divided) support at the Federal level, to the demographics of its adherents, and to the facilities upon which it relies.

Unlike classical astronomy, which is funded almost exclusively by NASA Astrophysics and the AST division of NSF's Math & Physical Sciences directorate, most solar grant support and that for the High Altitude Observatory comes out of the AGS division in a separate directorate, Geosciences. At the same time, facility support — the National Solar Observatory and its two current observing sites — comes almost exclusively from the AST division, but few solar-related competitive grants are awarded from that source. Similarly, NASA supports solar physics almost entirely through its Heliophysics division, the focus of the present Decadal survey. Solar facilities governed by NSF's AST division are assessed separately in the decadal survey covering NASA's Astronomy portfolio. Furthermore, NSF AST conducted a "Senior Review" of facilities several years ago, which was applied to NSO together with the classical dark-side observatories, but independently of the part of solar physics funded through the AGS division.

Most self-identified solar physicists are located at federally-funded research centers such as NSO, HAO, the Naval Research Lab, NASA Goddard and Marshall Space Flight Centers, and in for-profit organizations such as the Lockheed-Martin Palo Alto Research Labs and the Southwest Research Institute. In contrast to other areas of astronomy, there are relatively few solar physicists on the faculties of major research universities. On the one hand, the concentration of solar astronomers in a few large organizations achieves an important intellectual critical mass that would be lacking in a typical Astronomy department hosting one or a few solar faculty. On the other hand, the diffuseness of solar presence in traditional research universities limits access to students, and makes the training of the next generation of solar astronomers problematic and a cause for concern. Strong REU programs at the national solar centers can allay the concerns somewhat, but does not change the fact that solar training at the top research universities has been neglected. The U.S. situation differs from that in Europe, for example, where solar research groups typically have strong ties with university departments, and consequently many of the top solar researchers in the U.S. today have had their graduate training elsewhere.

Another unique aspect of solar physics is its ability to make occasional use of ground-based facilities designed primarily for night-time astronomy. Examples include the Very Large Array, which operates in the centimetric radio band sensitive to flare processes, and the James Clerk Maxwell Telescope (draped by a teflon sheet to protect the dish from direct solar heating) to image the Sun at sub-mm wavelengths. It is rarer for the exchange to go in reverse, although the historical night-time program at NSO's McMath-Pierce should be acknowledged. The Atacama Large Millimeter Array (ALMA), currently under construction in Chile, promises to be a powerful tool for solar astronomy when it is commissioned later this decade; as will the recently completed Expanded VLA. The awkwardness here is that while these ground-based night-time facilities are potentially quite valuable to solar astronomers, the reviews of the existing facilities (and proposals for new facilities and instruments) historically have been conducted in a forum where solar interests are only lightly represented, if at all (as in the recent Astro2010 Decadal Survey). To be fair, the flagship facility for ground-based solar — the 4m Advanced Technology Solar Telescope (ATST) — was the outcome of the 2000 Astronomy decadal review, so it cannot be said that solar has fared badly in the past. Nevertheless, it is important in the future that a mechanism exists to allow solar interests to be represented in discussions of night-time facilities and instruments that might have unique applications for day-time astronomy.

A major theme of this white paper is the role of ground-based observations in the era of space astronomy, wherein literally billions of dollars have been invested in a series of increasingly sophisticated orbiting solar observatories that have revolutionized our view of the Sun over the past four decades. These sums dwarf the $300M to be spent on NSO's flagship ATST, the major expenditure on solar-related ground-based experiments in the foreseeable future. When we can obtain uninterrupted sequences of $0.''1$ resolution narrow band images from *Hinode,* for example, or high quality vector magnetograms and helioseismic measurements 24/7 from HMI on the Solar Dynamics Observatory, is there even any need for ground-based observations in the future? The AURA committee concluded, "Of course there is the need!" Here are a few of the more compelling reasons:

(1) High-precision spectropolarimetry of the smallest-scale — dominantly magnetic — features in the solar atmosphere requires a large-aperture telescope to collect sufficient photon flux to ensure accurate measurements of the Stokes parameters at many positions across the line profile in a time short enough that the scene has not changed significantly due to plasma motions. For many reasons, principally cost, the aperture of the largest ground-based telescope always will exceed that of the largest orbiting telescope, solar or otherwise.

(2) Ground-based facilities can be easily maintained, repaired and upgraded; whereas most space observatories (with the conspicuous exception of *Hubble*) are subject to unrecoverable failures that can limit their useful lifetimes. Because solar space experiments tend to be of a one-off nature, there usually are no backup facilities to replace a lost unique capability. Further, the long lead times for design, approval, development and fabrication of space ex-

periments, and the restriction to flight-qualified hardware, limits the amount of advanced technology that can be incorporated. And once the experiment has reached orbit, upgrading is not an option. Ground-based experiments, on the other hand, can be supplied with state-of-the-art technology to respond agilely to new opportunities. For example, the venerable GONG helioseismic network could be retrofitted to observe multiple spectral features, to provide a sharper view of the solar interior beyond that achieved by a single-channel instrument (like HMI).

(3) While space observatories provide unique access to parts of the electromagnetic spectrum invisible to ground-based experiments — gamma and X-rays, and the ultraviolet — there are other key parts of the spectrum for which orbiting platforms have little, or no, advantage. For example, the thermal IR — rich in molecular diagnostics — requires a large aperture telescope to achieve diffraction limited performance, and, as mentioned earlier, we are unlikely to see such an instrument in orbit anytime soon. The sub-mm to metric radio bands are valuable diagnostics of thermal structure in the chromosphere and of nonthermal particle acceleration in flares, but again the large antenna arrays required to collect the radiation, and interferometrically image the Sun, are impractical for space deployment. In fact, there would be little advantage of the space environment in the first place, except perhaps for the very short sub-mm range, since the atmosphere is relatively transparent throughout the radio band and seeing is not an issue. A final example is the observation of solar neutrinos, whose detectors require shielding from cosmic rays by a kilometer or so of solid rock: an experiment clearly ill-suited for Earth orbit.

(4) Space weather encompasses a wide range of time scales, especially decadal, and longer, variations associated with magnetic cycles. The study of such long-term phenomena requires a consistent base of synoptic observations. The collection of synoptic data is rarely accomplished from space, however, due to undependable access, high cost, and NASA's choice to focus on novel science. In contrast, ground-based facilities have produced such invaluable data sets as the 400-year record of sunspot numbers, 8 decades of solar images from Mount Wilson, and the long-term magnetogram series from NSO's Kitt Peak facility. NSO is in the process of consolidating its major synoptic components — GONG and SOLIS — into a single coherent program with the intent to maintain a long-term magnetic — and full-disk imaging — context for future solar research.

We hope that these few examples clearly demonstrate that ground-based observations of the Sun are not merely an adjunct to the space-based counterparts, but rather a full partner in the broad enterprise of solar physics.

Specific Recommendations for Ground-Based Solar Physics

(1) Advanced Technology Solar Telescope

At the time of writing the AURA report, NSF construction funding for ATST was not yet approved, and there was concern within the community that its premier ground-based project would be reevaluated in the Astro2010 Survey, and possibly re-ranked to the detriment of its funding prospects. Thankfully, the re-consideration did not occur, but in preparation for that possibility, the AURA committee placed ATST at the top of its recommendations. In an era when 1.5m solar telescopes are beginning to replace historical 50–70cm aperture instruments, the leap to 4m, while technically challenging, promises to maintain, if not restore, U.S. leadership in ground-based solar physics. Many non-solar astronomers misinterpret the need for ATST, imagining that it is the raw diffraction-limited resolution that is important. Rather, it is the light gathering power of the large aperture that will be essential to support the spectropolarimetry of the smallest scale magnetic features that are at the heart of many contemporary solar puzzles. When one divides the incoming light in a spatial pixel into a half dozen or more polarization states, and over a dozen or so frequencies in the line profile, at a cadence fast enough to avoid velocity smearing by surface flows, one quickly runs out of photons; hence the need for large aperture. Nevertheless, the 4m, all-reflecting design of ATST will be a welcome innovation for thermal-IR solar astronomers, who currently are struggling to achieve even $1''$ resolution with the largest existing solar telescopes.

Hand in hand with the construction of ATST, the AURA committee recommended strong (financial) support by NSF for consolidation of NSO into a single headquarters site, and for the full-up operations of ATST together with the existing synoptic program.

(2) Full-Sun Measurements

The new mantra is to treat the Sun as a physical system that contains a hierarchical series of fundamental scale lengths that should be accessed simultaneously to build a coherent picture of the underlying physical processes. ATST will be the premier solar facility for peering into the crucial fine scale details of surface structure, but its observations on the upper end will be limited only to the sizes of active regions. Synoptic instruments like SOLIS and GONG on the ground, and SDO in space, will play key roles in building the broader spatial context for interpreting ATST's measurements, but there is additional complementarity that could be contributed by novel new mid-scale initiatives such as the Coronal Solar Magnetism Observatory (COSMO) and the Frequency Agile Solar Radiotelescope (FASR). One aspect of FASR that should be emphasized is that it, unlike the EVLA or ALMA, is exclusively a solar instrument, so it can provide the radio context without the scheduling vagaries of the dark-side facilities.

(3) Synoptic Solar Astronomy

Synoptic measurements are at the core of elucidating many types of astronomical phenomena — eclipsing binaries, pulsars, flare stars, stellar cycles, AGN reverberation mapping, and so forth — and such time-domain studies are no less important to solar physics. In fact, solar synoptic measurements are a key to Space Weather assessment and prediction, as mentioned earlier, and thus have an operational role beyond the mainly curiosity-driven nature of other parts of astronomy, and indeed much of solar physics itself. Synoptic observing is a mainstay of helioseismology, and its offshoots like far-side imaging; as well as long-term solar cycle studies. Just as the full-Sun view provides a key context for the more narrowly focused stare of large aperture solar telescopes, so too does the long-term synoptic gaze provide the crucial context for shorter-term phenomena. Thus, in the era of 'giant' solar telescopes, we must not lose sight of the value of the synoptic backdrop.

(4) Instrumentation and Technology

To keep ground-based solar physics at the cutting edge, and to complement space-borne assets, it is not simply enough to build a large aperture solar telescope like ATST, but it is equally important to provide that facility with first-class instrumentation to exploit the large collecting area, and with other technologies to mitigate the main drawback of a ground facility: atmospheric seeing. Furthermore, beyond the complement of first-light experiments, there must be provision for advanced instrument development; to build on the initial experiences, exploit the latest technologies (especially in cameras), and perhaps shift emphasis based on new discoveries. At the outset, ATST will be equipped with Adaptive Optics to deliver crisp imaging, although only over relatively small fields. The development of Multi-Conjugate Adaptive Optics promises to provide stable corrections over much larger fields, but it will be challenging to implement. If MCAO can be demonstrated, it will pave the way for wide-field simultaneous spectral imaging, using for example massive fiber bundle arrays or advanced reflecting image slicers. These types of spatial multiplexing techniques will move solar astronomy beyond the age of the scanned slit, into a brave new world.

(5) Synergy of Coordinated Ground and Space Measurements

Ever since the first solar satellites were launched into orbit, there has been a strong desire to coordinate their observations with those from the ground, again because the context matters. Some types of coordination happen naturally, as with synoptic facilities that simply carry out their canned programs and provide their data products in well characterized, non-proprietary ways. Other types of coordination require considerable effort: to align the space and ground instruments to the same solar target at the same moment, and coordinate the joint analysis of the resulting perhaps not so compatible data sets. Given that the synergy between ground and space observations is firmly established, and will be even more essential in the future, the AURA committee urged special consideration for the planners of new ground facilities to explicitly accommodate joint scheduling with space observatories.

(6) Transfer of Facility Support to Geosciences

A final recommendation considered the then hypothetical, but now imminent, transfer of the National Solar Observatory and its facilities from NSF's Math & Physical Sciences directorate (AST division) to the Geosciences directorate (AGS division), urging that full consideration be given to ensuring that key intellectual and material links of solar to broader astrophysics are not broken. With all of the nation's solar assets supported by AGS, there will be little direct influence on the night-time facilities wholly residing in AST. Under this arrangement, it will be necessary to exercise more diligence to identify and exploit the possible synergies that might be achieved using such facilities during the daytime (as mentioned earlier for EVLA and ALMA). For example, without solar advocacy in AST, there would be the danger that potential solar uses of astronomical facilities might be precluded by inadvertent design decisions, or cost tradeoffs. This is a two-way street, in fact, because one also loses advocacy from the night-time community concerning possible uses of, say, the unique capabilities of ATST for stellar or exosolar planet research ("night-time solar physics" according to one pundit). The concentration of solar into Geosciences also raises flags with the practitioners of the solar-stellar connection, who already are virtually homeless in terms of advocacy in NSF, let alone NASA. More on that, next.

The Solar Stellar Connection

We also take this opportunity to mention the solar-stellar connection, a cross-disciplinary field where the same synergies between ground- and space-based observations exist. The solar-stellar connection is especially valuable for exploring aspects of our star that are difficult to characterize with contemporary measurements, such as the operation of magnetic cycles over evolutionary timescales; or the coronal activity of the Sun at a very young age, of relevance to the survival of primitive planetary atmospheres; or the far distant future of the Sun, when it bloats into a red giant, frying — if not also swallowing — the inner planets of the solar system in the process. In fact, even the near term evolution of our star's luminosity will guarantee the nonhabitability of our home world in a mere billion years or so, regardless of humanity's efforts to tame our contemporary bout of global warming.

From humble beginnings in the early 1970's, with exploratory high-resolution measurements of the Ca II 395nm lines in nearby bright stars, and tentative access to the key ultraviolet wavelengths with *Copernicus,* the study of stars as suns in their own right has blossomed into a mature field, fueled in large part by remarkable instrumental advances. These include *HST, FUSE, Chandra, XMM–Newton,* and now *Kepler,* to mention a few recent examples in space. Similar progress has occurred on the ground in high-resolution spectroscopy, photometry, and spectropolarimetry at optical telescopes; radio imaging at the VLA; and soon the bright promise of mm/sub-mm astronomy with ALMA, again to mention just a few examples. Solar physics has witnessed equally impressive strides with recent missions such as *SoHO, TRACE, Hinode,* and now *SDO,* in space; together with steady advances in ground-based solar imaging and spectropolarimetry, especially with the development of modern adaptive optics systems.

With all these excellent discovery tools at hand, one would imagine that the solar-stellar connection community would be making progress by leaps and bounds. This has been true to some extent, but a major hindrance has been lack of a funding home for this multidisciplinary field. Unlikely purely solar astronomy (seeking grants through AGS programs, or NASA Heliophysics), or its purely stellar counterpart (proposing to the AST AAG program, for example, or NASA ADP), solar-stellar researchers unfortunately seem to be regarded somewhat as orphans by both sides. The major sources of support, in fact, have come almost accidentally through NASA Guest Investigator programs (e.g., *IUE, HST, FUSE, Chandra,* and so forth) rather than via a well-defined, long-term funding opportunity (like NASA's Living with a Star targeted research). Those of us in the solar-stellar community of course desire a higher profile for our science, and additional opportunities to support our work (as well as to hire postdocs and train grad students). The situation of solar-stellar is not unlike that of other multidisciplinary efforts whose advocacy falls between the cracks of traditional fields. It would be self-serving, if not also shameless, of us to propose a specific targeted effort to support solar-stellar research within NASA and/or NSF, but we do wish to raise the awareness of the heliosciences community that an important opportunity to exploit solar-stellar insight for both disciplines could be languishing for lack of direct support.