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HIGH-RESOLUTION SOLAR PHYSICS

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Abstract. I review current developments in solar physics with emphasis on high-resolution observations in the visible part of the spectrum. Formerly, high-resolution observing was primarily a matter of seeing quality. Nowadays, post-detection image restoration through speckle and/or phase-diverse reconstruction and pre-detection wavefront restoration through adaptive optics are revamping optical solar physics from ground-based observatories. These new techniques enable much better angular resolution than the seeing limit and have initiated an impressive wave of new large-aperture solar-telescope projects. At the same time, small-aperture telescopes are finally making it to space.

I first summarize the corresponding solar physics science questions, emphasizing the magnetic coupling between the photosphere and the outer solar atmosphere as a principal issue for the coming years.

High-resolution solar physics presents a host of exciting research tasks, challenges, and opportunities the coming years. The context is threefold: astrophysical MHD, plasma physics, and Sun-Earth connections. The field is expanding and offers excellent career perspectives for bright students with a good physics education.

1 Introduction

Solar physics, including optical solar physics addressing the photosphere and low chromosphere, is currently in an upswing. This revival comes not only through space weather funding from NASA but also from the general computer revolution. On the observational side, fast computing now permits higher resolution from groundbased telescopes than the Fried parameter (see below) through wavefront correction and image restoration. Long-duration image sequences collected from space observatories can now be analyzed as dynamical large-volume movies rather than snapshots, even small groups at relatively poor institutes such as university departments using regular PC's. On the theoretical side, detailed numerical simulations provide insight in solar processes and phenomena at the level of complexity at which they occur, bridging the large gap between cartoon model simplicity and actual reality.

In the past, the fine structure of the solar atmosphere has given solar physics a bad name ("dermatology of detail") but presently, computer advances are giving us the means to both observe fine structure properly using appropriate diagnostics and to model fine structure numerically with appropriate physics tools. Solar fine structure so becomes a treasure trove of observable and understandable astrophysical processes, instead of blemishes as unwelcome to our non-solar colleagues as sunspots were to Catholic authorities in Galileo's time. Solar magnetism is a key actor in most of these processes.

In this brief review I concentrate on optical observing, hence on low-atmosphere (photosphere and chromosphere) science and groundbased techniques. More detail is found in recent topical conference volumes such as the Sacramento Peak Workshops (*e.g.,* Rimmele et al. 1999, Sigwarth 2001) and the presentation files[1] from the recent "Beyond Solar-B" workshop (refereed to as "Huntsville" below).

I pay particular attention to the Dutch Open Telescope (DOT) on La Palma, not only because I am its project scientist but also because it sets an example of how relatively small instrumentation projects can fill a valuable science niche at the forefront of research. The same holds for the neighboring Swedish solar telescope, presently being transformed from SVST to NSST.

[1] Huntsville, April 2001, http://science.nasa.gov/ssl/pad/solar/Beyond_Solar-B.htm

2 High-resolution science

For brevity, let me present solar physics issues requiring high-resolution observing in the form of questions, roughly following a comparable list in Keller's Huntsville presentation[2]. They are obviously dictated by presently ongoing research. New questions will crop up, while old ones are likely to remain with us for longer time. The purpose of writing down a snapshot question list now and here at Udaipur is simply to illustrate that there is lots to do in high-resolution optical solar physics.

Non-magnetic. Can we use granules as tracers of persistent surface motions to understand the mesogranular and supergranular flow patterns and provide decisive constraints to numerical simulations trying to model these? What is the role of granular collapse as provider of "seismic events" in pistoning the five-minute p-mode oscillation and as a source of chromospheric three-minute and high-frequency oscillations? Do the acoustic shocks that constitute the internetwork "grains" contribute high-frequency heating to the quiet chromosphere or is the internetwork chromosphere predominantly cool out to $h \approx 1000$ km as indicated by shock simulations and by the darkness of the strongest CO lines? What is the role of the atmospheric gravity waves that seem to pervade the upper photosphere without receiving much attention so far?

Quiet-sun magnetism. What is the "true" flux spectrum of solar magnetic fields? Are there intrinsically weak fields? What contribution results from near-surface convective turbulence? Can we diagnose such fields down to the Hanle regime? What do they do, and what do they not do? Does the observed hierarchy of discrete strong-field elements extend to cross-sections as slender as micro-structure MISMA threads? Does convective collapse actually produce strong-field fluxtubes the way it is supposed to do, and if so, how often, where, when? What is the role of ephemeral regions in field emergence and what is their contribution to network (re-)generation? How does network disappear? Does fluxtube shaking indeed cause wave heating of the magnetic and nonmagnetic chromosphere? Does fluxtube twisting cause relaxation and/or reconnection heating? What is the actual structure and role of magnetic canopies? What are the nature, cause, and effects of spicules?

Active-sun magnetism. How do sunspots work, how do they appear and assemble, why and how do they disappear? What is the nature and role of umbral dots and umbral flashes? What is the exact penumbral topology; how do penumbral and moat flows arise and work? How do active regions emerge, assemble, evolve and disappear? When, where, why and how do filaments form, become and stay stable, regenerate, erupt or vanish? When, where, et cetera for flares and CME's? When, where, et cetera for blinkers, X-ray bright points, ultraviolet jets, explosive events? Et cetera, et cetera…

Magnetic connection. This high-resolution question list is far from exhaustive. It simply illustrates that the part of the solar atmosphere sampled by optical radiation contains a host of fine-structure elements, phenomena and processes that provide a great many research issues of widely varying nature, requiring a large scala of expertise. The "grand solar physics questions" such as the nature of the dynamo, of the activity cycle, of coronal heating, and of solar wind generation are still open. They undoubtedly require solution of many of the above more focused questions. I don't deem any one particular question much more "important" than any other. However, it is often good policy to promise solutions to "grand" questions in proposals, so let me describe what seems a key question for the coming years: the magnetic connection between photosphere and corona. How do the surface fields couple to, constrain, and energize coronal fields? Most questions above have a magnetic connection, but what I mean here by "connection" is the transition from low to high atmosphere in terms of magnetic topology and magnetically controlled dynamics and energetics.

[2]Although I usually make it a point to provide extensive reference lists, I refrain from doing so here. References are nowadays so easily obtained from ADS (`http://adsabs.harvard.edu/abstract_service.html`) that it would be a waste of page-limited review space to add them here. Entering the listed topics in the ADS search engine produces near-complete and up-to-date bibliographies. Another example of the computer revolution, and an enormous boon to astronomers! Similarly, it is becoming less useful to supply URL's for every project mentioned in a review like this since "googling" (`http://www.google.com`) will quickly deliver the pertinent website.

Tubes and loops. At photospheric levels the basic building block of solar magnetism is the "magnetic fluxtube", a concept originating from Zwaan and now an astrophysical paradigm pertinent also to accretion disks and other faraway objects. At coronal levels, the basic building block is the "coronal loop", a phenomenon diagnosed from Skylab data and now spectacularly imaged in TRACE 171 Å movies. The actual connection between photospheric tubes and coronal loops remains enigmatic. It is striking and somewhat disconcerting that one can cleanly divide magnetophysics specialists in solar MHD and plasma physics between fluxtube types and coronal loop types. Clearly, these specializations must come together in questioning and answering how actual loops and tubes come together, *i.e.,* how photospheric fields connect to coronal fields.

Transition domain. The fluxtube paradigm prescribes field expansion into magnetic canopies that spread field homogeneously throughout the atmosphere already in the upper chromosphere. Coronal loops delineate slender field configurations at specific temperature that become visible through density contrasts. In between, observations in H-alpha reveal a plethora of low-lying finely-scaled structures with rapid large-amplitude dynamical changes. In EUV lines the so-called "moss" detected with TRACE indicates similar small-scale large-amplitude dynamical structuring. This transition regime is largely sol incognito. It is *not* what plane-parallel modelers call "the transition region". The latter does exist as a thin, highly crinkled interface between hot (over 10^5 K) and cool (less than 10^4 K) structures, but it certainly does not exist as a near-circular shell on top of a an equally improbable laterally nearly homogeneous chromosphere. Of course the temperature does shoot up from photosphere to corona, but this domain is also a radiation transition from thick to thin, a plasma-beta transition from larger-than-unity to smaller-than-unity, a dynamics transition from nicely linear waves to shocks and high-speed flows. Overall, a transition from near-radiative and hydrostatic equilibrium to severely "non-E conditions" (Thomas 1983). Principally, the domain in which magnetic concentrations and dynamic flows compete with photon losses as primary atmospheric structuring agent. Since neither the magnetic concentrations nor the flows obey plane-parallel shell geometry whereas both vary rapidly over small scales, this domain is intrinsically fine-structured and time-dependent, and difficult to chart.

H-alpha revival. A key diagnostic of the transition layer is provided by H-alpha. H-alpha studies appear less frequently in the current literature then in the 1960's and 1970's, with the Dunn Solar Telescope at Sacramento Peak having turned to ASP spectropolarimetry, Kiepenheuer's Capri refractor and Gaizauskas' Ottawa telescope closed down, and most solar physicists shying away from H-alpha fine structure since it poses such an enormous challenge to interpretation and modeling. H-alpha is a nasty beast of a line, much harder to interpret than a clean resonance line as Ca II K. It most awkwardly mixes NLTE excitation/ionization sensitivity and Doppler sensitivity in its apparent brightness structure. Nevertheless, it seems that the time is ripe to "pull a Zirin" in the Big Bear tradition that is also followed here at Udaipur, and to concentrate on H-alpha diagnostics — on the condition that this is done at really high angular resolution, in the form of large-field long-duration digital movies, with full profile sampling, and accompanied by sophisticated line-formation modeling as well as simultaneous lower-and-higher (visible and ultraviolet) and diagnostic (magnetogram and Dopplergram) data collection.

3 High-resolution techniques

Three telescopes. The three telescopes sketched in Fig. 1 illustrate different solar telescope principles. THEMIS, the national French-Italian solar physics facility, is a large undertaking resembling the never-realized LEST plans. Its 90-cm aperture makes it presently the largest solar telescope aiming at high angular resolution. It is particularly suited to precision polarimetry thanks to low instrumental polarization, and is equipped with a Fabry-Perot filter magnetograph (Italian, to be replaced with a faster version) and a large double-pass spectrograph for multi-line spectropolarimetry and two-dimensional MSDP spectrometry. The optical scheme is complex, having tens of reflections before the photons finally reach the CCD cameras in spectrograph mode, and is non-versatile in the sense that there is no optical laboratory or bench allowing one to feed the solar image into experimental instrumentation setups. The angular resolution remains coarser than nominal, half an arcsec at best.

The Dutch Open Telescope (DOT, center of Fig. 1, photographs in Fig. 2, diameter 45 cm) has taken over the role of providing solar images at nearly 0.2 arcsec resolution from the former Swedish Vacuum Solar Telescope (SVST, at right in Fig. 1, aperture 48 cm) from whose building it is operated. These

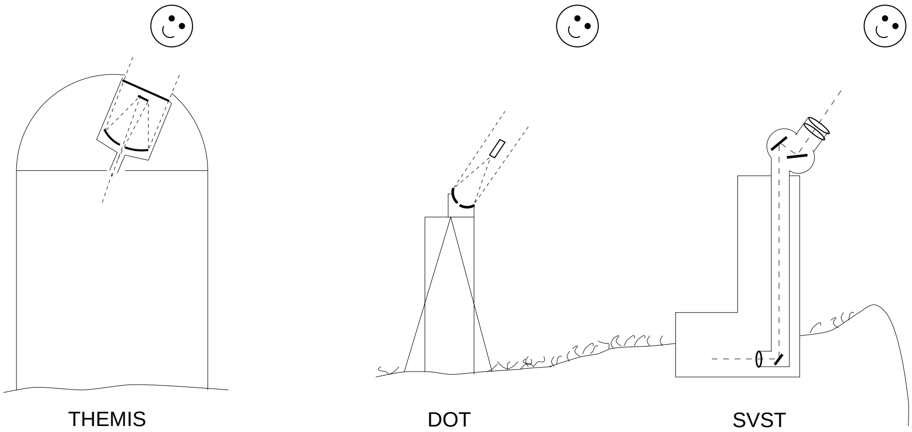

Figure 1: Three Canary-Island solar telescopes: THEMIS (Tenerife), DOT (La Palma), SVST (La Palma). The first two came on line during the past two years; the SVST saw its last light in 2000 to make place for the NSST. THEMIS is a 90-cm reflector with exceedingly complex secondary optics including a filter magnetograph and a double-pass spectrograph. It was intended as vacuum telescope but remains helium-filled so far. Its strength lies in quantitative polarimetry. The other two telescopes represent the limit of optical simplicity rather than complexity, respectively in reflection and in refraction. The DOT is basically an open wind-swept parabolic mirror, feeding multi-channel re-focusing optics that is presently being mounted in the telescope top besides the incoming beam. Its strength lies in tomographic long-sequence large-field high-resolution imaging (more below). The late SVST was a revolutionary 48-cm vacuum refractor. Its alt-azimuth turret followed the design of the Sacramento Peak tower turret, but with the important difference that the vacuum window was replaced by a doublet objective lens taking its proper shape under one atmospheric pressure differential between outside and inside. It fed a tip-tilt stabilized image to an optics laboratory where multi-wavelength filtergraphs including Lockheed's tunable SOUP filter were easily set up on a large optical table, or to a small high-resolution spectrograph. The SVST has been particularly productive in filter imaging in the hands of the Lockheed-Martin group (*e.g.,* Berger, T. @ ADS). Its successor, the NSST (New Swedish Solar Telescope) will have twice larger aperture (96 cm), a singlet lens instead of a doublet as objective, a Schupmann corrector to gain achromaticity, and adaptive-optics wavefront correction.

"small" telescopes are effectively not small because even at La Palma the Fried parameter r_0 describing atmospheric quality in terms of equivalent telescope aperture exceeds 10 cm only occasionally. The same holds at Big Bear (Goode et al. 2000).

DOT principle. The DOT was built by my colleague R.H. Hammerschlag and his coworkers at the instigation of the late C. Zwaan (1928–1999). Zwaan involved Hammerschlag in JOSO's site testing campaigns in the 1970's which led to the establishment of the Canary Island volcanoes as preferred solar-telescope site. They came to appreciate the benign influence of the strong trade winds which, blowing upslope over the Caldera rim of the Observatorio del Roque de los Muchachos, confines the turbulent convection from solar ground heating to a boundary layer of only 10 m thickness. Above this thin layer the trade wind is often laminar, resulting in excellent local seeing conditions that may last all day. (In addition, the upper-atmosphere jet streams which cause high-altitude shear layers defining the night-time seeing limit come only rarely as far south as the Canary Islands.) Zwaan and Hammerschlag worked out the concept of an open telescope mounted on an equally open 15 m high tower which would minimize local disturbance of the trade wind and permit the latter to flush the telescope and primary mirror from solar-induced internal telescope seeing. Its realization by Hammerschlag in the subsequent decades took much innovative engineering in order to match the open concept with sufficient mechanical rigidity to withstand strong and highly variable wind loads The result is portrayed in Fig. 2. A sample image is shown in Fig. 3. The DOT has shown that the principle of a wind-flushed open telescope indeed works.

Image restoration. Much better image quality than the nominal r_0 seeing quality was obtained at the SVST through phase-diverse image registration (*e.g.,* Löfdahl et al. 1998) and is now reached at the DOT through speckle burst registration (Sütterlin et al. 2001a). Both techniques produce image quality close to the theoretical diffraction limit already when the seeing is only reasonable ($r_0 > 6$ cm) at the cost of elaborate off-line image reconstruction. The latter starts with tessellating the observed field in isoplanatic subfields which are reconstructed independently and then rejoined. The total field of view

Figure 2: The Dutch Open Telescope (DOT) on La Palma. Left: telescope with 45 cm primary mirror and 15-m high support tower, both open to the strong trade winds that come in from the right (North). The inversion layer (ocean clouds) is well below the volcano rim (2400 m) during the summer. The clamshell bad-weather canopy is folded away but is needed in winter when the weather can be a killer combination of heavy fogs, ice deposition, and storms. The white box contains a water tank for prime-focus cooling. The pipe transports control commands and digital images from/to the control room in the nearby Swedish telescope building. Right: parallactic telescope mount. The heavy construction and the extraordinary stiff gears avoid image shake from wind buffeting. The on-axis tube at the top contains a water-cooled tilted mirror which reflects the primary solar image away except for a 1.6 mm hole transmitting the 2 arcmin field of view to the focusing mechanism and re-imaging optics. The primary beam continues to the G-band filter and CCD camera. Four more cameras are being mounted along the telescope top besides the incoming beam. They are fed by beamsplitters and dichroic mirrors plus multi-wavelength re-imaging optics (continuum, Ca II K, H-alpha, Ba II 4554). The continuum channel became operational during the USO jubilee meeting and serves to separate granules and G-band bright points. The Ca II K channel will image the low chromosphere and permit exact co-alignment with TRACE sequences including near-ultraviolet imaging. The rationale to add H-alpha is given above; the DOT will use the tunable Zeiss filter formerly at Gaizauskas' ORSO. The Ba II 4554 Å line is a very promising Doppler diagnostic (Sütterlin et al. 2001b). More detail and photographs at `http://dot.astro.uu.nl`.

is therefore limited by the camera chip (or the field stop or the optics quality) but not by the image restoration technique. A drawback of phase-diverse and speckle reconstruction is the large amount of subsequent processing. The actual restoration per isoplanatic patch is split between patches (nearly 1000 with the present DOT cameras) and so parallellizes well in a Beowulf cluster approach (Denker et al. 2001). The initial frame alignment is less easily parallellized and gains considerable processing speed from hardware tip-tilt or higher-order active optics correction.

Wavefront correction. The alternative to post-detection reconstruction is to employ adaptive optics to correct the incoming wavefront in real time. Progress in adaptive optics technology presently revamps groundbased solar physics just as it revolutionizes groundbased nighttime astronomy — with the im-

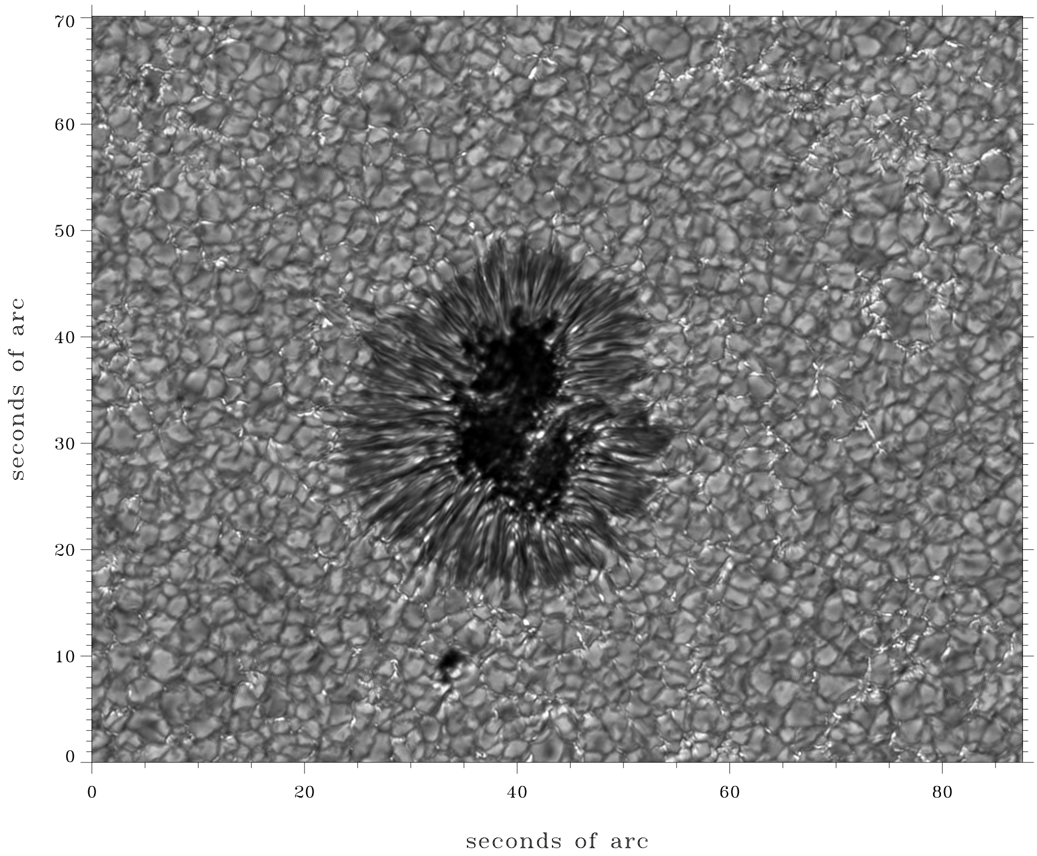

Figure 3: G-band image of sunspot AR 9407 taken with the DOT on April 1, 2001 by P. Sütterlin using the first camera of the multi-channel imaging system. It will consist of five Hitachi KP-F100 cameras (1296×1030 px, 10 bits) that always run in synchronous speckle mode. Each camera takes 100–200 frame bursts at up to 11 frames/s and stores these via its own fiber link on its own PC with 70 Gb disk space in the Swedish telescope building. The tiny white specks in intergranular lanes mark kilo-Gauss flux concentrations. They only become visible at better than 0.5 arcsec resolution (Title & Berger 1996). They have higher contrast in the G band than in continuum passbands because the many CH lines that contribute darkness to the G band dissociate in magnetic elements (Rutten et al. 2001). The penumbral fine structure in this image is analyzed in Sütterlin (2001). The full one-hour movie sequence is available at `http://dot.astro.uu.nl`. The DOT has an open data policy; FITS files can be requested from `P.Suetterlin@astro.uu.nl`.

portant difference that the sun is a very extended object with granulation and other small structure (magnetic elements in plage and sunspots) serving as wavefront encoder rather than natural or artificial point stars. The encoder contrast is low but covers the whole field of view.

How do speckle reconstruction and adaptive optics compare? Speckle reconstruction divides the image plane into subfields smaller than the isoplanatic patch and restores each by describing a seeing-sampling sequence of perturbed images ("speckle burst") with a model of atmospheric turbulence. Each patch sees the whole pupil; larger aperture averages the wavefront corrugation wider so that the speckle S/N in the image plane goes down. Better seeing is therefore required to obtain full speckle restoration at larger telescopes.

Adaptive optics instead divides the pupil plane into subapertures (ideally smaller than r_0) and corrects the wavefront for each. The correction quality is likely to be somewhat less (fewer Zernike coefficients) than for good-seeing speckle restoration. Since the spread function tails are corrected well only at very high system order, wavefront correction works best for bright structures in a dark field (such as network flux concentrations in polarized light). In addition, only the on-axis isoplanatic patch of just a few arcsec is corrected optimally. The smallness of the optimally-restored field of view is a major drawback. Adaptive-optics system multiplication for other directions would be impractical; a better option is multiconjugate adaptive optics in which tomography of the seeing layers increases the isoplanatic patch (*e.g.,* Beckers 1989, 2000).

Adaptive optics projects. Adaptive optics makes it feasible and desirable to build meter-class and larger solar telescopes, presently leading to a new wave of solar telescope building. An excellent review of ongoing solar telescope projects (including those mentioned here by acronym only) is found in Tarbell's Huntsville presentation. The NSST successor to the SVST will be a 96-cm vacuum refractor operational already in 2002. The venerable German Gregory Coudé Telescope (GCT) at Tenerife will be retrofit with an open 1.5-m Gregorian feed telescope into GREGOR by about 2005. The US National Solar Observatory leads the Advanced Technology Solar Telescope (ATST) enterprise, aiming at an open 4 m aperture reflector by about 2010 at a superior site to be identified through comprehensive site testing. All three telescopes will utilize adaptive optics (as will, hopefully, THEMIS do at some stage).

Aperture and resolution. Note that if the aperture exceeds 1 m considerably, the attainable angular resolution does not keep pace. Aperture increase does not change the photon flux per diffraction-limited resolution element whereas the permitted integration time (set by the solar scene change speed, *e.g.,* the sound speed) diminishes with increasing resolution. The number of photons available for detection goes down with increasing aperture! This point is quantified in graphs in Keller's Huntsville presentation.

The need for much larger aperture like the ATST's envisaged 4 m comes from the requirement to feed sufficient photon flux into spectrometers, full-Stokes spectropolarimeters and tunable Fabry-Perot interferometers whose narrow bandpasses decimate the photon take spectrally and whose application often requires very high S/N (as in polarimetry where images or spectra using only a small fraction of the light are subtracted and photometric precision is the name of the game). In these photon-starved applications optimal wavefront correction means restoring as many Zernike coefficients as the system order can reliably handle at a given angular resolution, say 0.1 arcsec.

Thus, small solar telescopes may exploit a high-resolution niche by full-field imaging and subsequent reconstruction at 0.2 arcsec resolution, whereas wavefront restoration should enable larger solar telescopes to achieve about 0.1 arcsec resolution over small fields in quantitative narrowband diagnostics such as Stokes spectropolarimetry. If cost is no concern large telescopes can of course also fill the small-telescope full-field niche by combining wavefront correction and speckle reconstruction, but since money is a concern large-telescope projects require goals not attainable by small telescopes. Large telescopes must be driven by polarimetry.

Above the atmosphere. Obviously, if money were no concern both small and large optical solar telescopes are much better off in space where the seeing is optics-limited, weather is perfect apart from particle storms, nights are rare (in polar orbits as TRACE's) or absent (in L1 orbits as SOHO's), and where co-pointing with EUV and X-ray instruments is relatively easy. Since money is a concern, only small telescopes make it to space while 1 m telescopes so far do not climb beyond high-altitude balloons (Flare Genesis, Sunrise proposal). The 50 cm diameter Solar-B telescope, slated for launch into polar orbit in 2005, may be seen as the SVST or DOT in space combined with a spectropolarimeter emulating the HAO/NSO ASP currently at the Sacramento Peak Dunn telescope. The niche which Solar-B will leave for small telescopes on the ground is to team up, for example in observing the other end of coronal loops at the same time or in employing diagnostics not implemented in Solar-B to the same field of view, and to try out newer technology and more daring tricks than permitted in space. Reversedly, the niches which ATST leaves open for future solar telescopes in space are non-optical wavelengths and locations well away from earth, but not quantitative polarimetry if money counts.

4 Conclusion

Various developments come presently together to constitute a major solar physics rejuvenation.

Optical solar physics is moving into the domain of meter-class resolution thanks to adaptive optics and image restoration. The Dutch Open Telescope presently uses large-volume speckle processing to provide multi-wavelength image sequences consistently reaching 0.2 arcsec over 1–2 arcmin fields. SOLAR-B will hopefully do even better from space during the second half of this decade. The NSST, GREGOR and ATST will successively bring down the angular resolution limit in quantitative and sensitive polarimetry from 1 arcsec to 0.1 arcsec and even better.

Large-volume solar imaging from space in visible, ultraviolet and X-ray wavelengths has come of age with SOHO and TRACE, and will be pursued at much larger telemetry bandwidth by SDO. The combination of high-resolution and intricate-diagnostic observation from the ground and durable short-wavelength observation from space, both in large volume and covering extended durations, integrates solar atmosphere research across the thin/thick and plasma-beta boundaries, from the deep photosphere to the million-degree corona.

Solar physics as a whole is moving into an era of understanding because observational resolution and coverage and numerical simulation capability and sophistication converge to being commensurate with the complexity of the astrophysics problems posed by solar magnetic fields. The lesson that solar physics will bring to general astrophysics the coming years (after initiating radiative transfer theory, spectral line formation, convection modeling, the cool-star activity connection, and asteroseismology over the past century) concerns the physics of magnetic fields in astrophysical context. Only relatively few astronomers are presently familiar with the basic MHD and plasma physics equations, whereas the specialists in magnetophysics have only started to understand the rich physics that nature distills out of these equations. The solar atmosphere offers a principal theater where this physics is put on display, representing a key "laboratory" for terrestrial researchers. Obviously, solar magnetism also sets the processes that govern space weather in our terrestrial environment.

The solar physics and space weather emphasis on magnetophysics defines our field to be a potential breeding ground for magnetophysicists. It takes sharp minds to become thoroughly familiar with MHD and plasma physics as needed for solar-process interpretation, be it analytical or through numerical simulation. A challenge to gifted students who like intellectual adventure. Lots to do!

Indian solar physics possesses both the width and the depth to take an active part in this revival. In particular, Udaipur Solar Observatory is well positioned to share in the optical resolution revolution by building a high-resolution facility with emphasis on magnetic field and H-alpha diagnostics.

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