ESA Colloquium on Targets for Space-based Interferometry, Beaulieu, 13-16 Octiber 1992, ESA SP-354, p. 317-317.

HIGH RESOLUTION SOLAR PHYSICS

Robert J. Rutten

Sterrekundig Instituut Utrecht

ABSTRACT

Solar physics is a prime example of the quest for high spatial resolution as the coming space frontier of astrophysics. The proximity of the Sun brings the enormous advantage that modest baselines suffice to fulfill an important goal: *to resolve basic plasma processes at their characteristic scales.* At such resolution, the solar atmosphere represents a plasma physics laboratory of broad interest. Concerted observations combining high spatial and temporal resolution with narrow-band diagnostics in the ultraviolet and the visible will deliver detailed insights in plasma processes that are ubiquitous in the cosmos, but resolvable only for the Sun. Space interferometry is the obvious way to fulfill this promise.

Keywords: Sun, interferometry, space research, astrophysics, plasma physics.

1. INTRODUCTION

High spatial resolution represents the future in all of astrophysics. It will also revolutionize solar physics, and re-integrate this field back into general astrophysics. I elaborate on these prospects in this article. It gives a broad outline of the reasons why solar physics is a prime candidate for space interferometry.

The case for solar space interferometry is very strong. Much new science is in grasp of relatively small interferometers, with baseline lengths of a few meters only. By no means can this paper do justice to their potential; all I can do here is to give an overall flavour of the sort of research which solar space interferometry will bring, with appropriate references. A more extensive overview is given in the science assessment sections of the SIMURIS Study Report by Coradini *et al.* (1991) [1] and in the dozen brief reviews in the first part of the SIMURIS workshop proceedings that recently appeared in the ESA–SP series [2].

"High resolution" means different things (cf. Title *et al.* [3]). It may stand for:

(i)—the best that is presently reachable,

(ii)—the best that mankind may ultimately achieve,

(iii)—the fundamental limit imposed by the physics of the object itself.

In this meeting, we have been instructed by ESA to descend from the realm of green "science fiction" dreams towards realizable missions, scaled to the size of a Blue Mission or, at most, a Cornerstone. This descent from SIST and LIST-like free-for-all *Gedankeninstrumentes*[1] to budget reality drastically cuts the list of feasible science objectives for optical space interferometry. In astronomy, the list is practically limited to astrometry and searches for exoplanets; in astrophysics, to the Sun and the largest stars on our sky. The reason for this severe curtailment is obvious: most astrophysical objects in the cosmos are still unresolved on the milli-arcsec scale; micro-arcsec or better resolution is required to observe their surface detail. That requires exceedingly long baselines. Yet much higher resolution would be needed to identify the physical processes which cause the surface detail, since most astrophysical objects have limits of type *(iii)* that are beyond limit *(ii)* even in the grandest dreams of lunar-based interferometry.

The situation is radically different for the Sun because our nearest star supplies limits of type *(iii) which are resolvable.* They lie between limits *(i)* and *(ii)*. A good illustration at low resolution is given by the solar granulation. The solar surface is covered by about a million granules at any moment; each of these is larger than the largest stars on the sky. Solar granules measure about one square arcsec and have been resolved since Herschel's time. Recently, three-dimensional time-dependent numerical simulations of turbulent convection have given fairly complete understanding of the hydrodynamical processes from which solar granules originate (Refs. [5] – [6]), while subsequent numerical simulations for other stars predict the nature of the granules on their surface [7]. Obviously, direct observation of such stellar granules requires an out-of-reach increase in spatial resolution, but indirect methods based on spectral line shifts and asymmetries ([8] – [12]) show excellent correspondence between predictions and observations. In this example, solar type *(iii)* resolution inspires and constrains theories of turbulent convection that are more widely applicable. Space interferometry will bring a host of similar astrophysics insights, with a shift of emphasis from radiation hydrodynamics to plasma physics. "High resolution" is the key word, covering all that is needed to observe astrophysical objects in sufficient detail to permit full understanding of their structure and role.

The current and future frontiers of solar physics lie at the small scales set by the strong magnetic fields in the solar atmosphere. They pervade the photosphere and dominate the outer atmosphere (chromosphere, transition region and corona) with processes and structures that together constitute the prime target of solar astrophysics. Their scales are well below the comfortable arcsec size of granules, and the physics will be more complicated than the pure hydrodynamics of turbulent convection. Interferometric resolution and informative plasma diagnostics are required. However, many of the corresponding type *(iii)* limits lie well within limit *(ii)* in the ultraviolet, and not far beyond the ground-based capabilities of type *(i)* in the visible: *solar process scales are resolvable.* This is the

[1] Zirin [4] defines a *Gedankeninstrument* as: virtual instruments that are non-existent or improbable devices, normally proposed to government agencies or panels of theoreticians.

Three Astrophysics Revolutions

1. SPECTRAL RESOLUTION
   - *technique:* X-ray — UV — vis — IR — radio
   - *nature:* inventory of phenomena
   - *Sun:* photons galore

2. NUMERICAL RESOLUTION
   - *technique:* 3D time-dependent interpretation
   - *nature:* experimentation through simulation
   - *Sun:* detailed constraints galore

3. SPATIAL RESOLUTION
   - *technique:* space interferometry
   - *nature:* structure & process identification
   - *Sun:* structures & processes galore

Fig. 1. Three resolution revolutions in astrophysics. Astronomy became astrophysics with spectral resolution, first in the visible and then at longer and shorter wavelengths. Now, we are in the midst of a computer revolution permitting detailed, realistic interpretation rather than idealized scenario modeling. Space interferometry will bring a third revolution by showing what is actually going on. In each revolution, the proximity of the Sun gives solar physics a leading role.

major reason why solar space interferometry represents a realistic, worthwhile and exciting venture.

For full insight into what solar space interferometry will bring, one may delve into nearly every topic of modern solar physics. (The major exception is helioseismology because it requires high Fourier resolution rather than high spatial resolution.) The following references are good starting points for deeper study. Priest's [13] monograph on magnetohydrodynamics supplies physics background while the textbooks of Stix [14] and Foukal [15] are good introductions to general solar physics at the student level. The Crieff proceedings [16] which have just appeared contain authorative and up-to-date graduate-level overviews across much of solar astrophysics, including instrumentation.

2. PERSPECTIVE

Broadly speaking, we may discern three revolutions in astrophysics. They are characterized by spectral, numerical and spatial resolution, respectively. The first one is now at its close. This was the opening up of the electromagnetic spectrum and of its rich array of astrophysical diagnostics. New windows of the electromagnetic spectrum were invariably opened first for the Sun, partaking of its largesse in supplying photons to small experimental telescopes in any wavelength band, whether ground or space based. This was a time of inventory taking, of looking at the universe with newly opened eyes, mapping the sky in all wavelength bands and discovering lots of unexpected objects and phenomena. Of course, this era is still continuing; by and large, however, our eyes are now wide open across most of the electromagnetic spectrum.

The second resolution revolution is one of interpretational detail. The next step after inventorising is to make out what things are made of. A physicist may do this by taking his object apart accelerator-wise; the astrophysicist has to be contented by model building. This is the domain of a current revolution of enormous impact, provided by computers that supply sufficient numerical resolution. Thanks to their progression, we now have the capability of realistic numerical experimentation. No longer is one required to mimic a stellar atmosphere by a "plane-parallel" simplification, to judge spectral line diagnostics from a "two-level atom", to use "turbulence" rather than detailed hydrodynamics, to circumvent the complexities of MHD and plasma physics by semi-analytical methods. With numerical simulations astrophysics turns from an observational into an experimental science, reaching the inherent complexity of actual astrophysical objects and phenomena. Time-dependent non-linear processes become modelable through simulations across a wide range of astrophysical disciplines. Hard physics replaces scenario-type speculation.

The third revolution brings observational detail commensurate with this new interpretational detail. High spatial resolution, high time resolution, large sensitivity, precise digital CCD imaging, digital spectrometry at large spectral purity are, in tandem with the computer revolution (which of course also supplies fast data processing and vast data storage) the domains of current and future observational progress.

In principle, the quest for more spatial resolution has been with us since Galileo. At present, however, it evolves to being the major frontier of our science *because* the other two revolutions are maturing. The spectral windows are open; sophisticated numerical modeling is at hand. The issue now is: *how does it all work?* This is where solar physics is bound to be re-integrated back into general astrophysics.

In the past, solar physics was "the mother of astrophysics". Understanding the formation of the spectral

Two Solar Regimes

PHOTOSPHERE	UPPER ATMOSPHERE
• radiation	• MHD
• hydrodynamics	• plasma physics
• doesn't feel higher layers	• subject to photosphere
• characteristic scales: – photon mean free path – pressure scale height 10 – 100 km	• characteristic scales: – Alfvén resonance – current dissipation 0.1 – 10 km
• thick	• thin
• success stories	• lots to do
• visible	• ultraviolet & X-ray
• ground	• space

Fig. 2. The photosphere (left) and the outer atmosphere (right) present physical regimes that differ strongly from each other in many respects.

lines from the solar photosphere lay at the root of the general transition from astronomy into astrophysics during the first half of this century.

Later, solar physics became somewhat isolated. The main reason is that it matured earlier in the second revolution. Indeed, the solar detail is so overwhelming that many astrophysicists were put off by the spicules, granules, fibrils, mottles, grains and all the other entities seen in solar "dermatology", bewildering and a source of embarassment for any astronomer who prefers to model his object with blemish-free plane-parallel, annular or spherical geometry. Solar physics became isolated when its emphasis shifted from plane-parallel spectrum synthesis to solar blemishes, *i.e.,* to MHD modeling of the small-scale solar structures and time-dependent processes.

The underlying cause for the huge variety in structures and phenomena seen on the Sun is the solar magnetic field. To quote Robert B. Leighton: "without its magnetic field, the Sun would be as boring as the night-time astronomers think it is". Magnetic fields and the attendent MHD and plasma processes are not restricted to the Sun, however. Plasmas account for 90% of the matter in the universe. Solar-like MHD and plasma processes are gaining interest for many astrophysical objects — not only solar-like cool stars or flare stars, but also accretion disks, jets, AGN's *etc.* This context brings a change of attitude, from disliking solar detail to appreciation of the diagnostic richness of the plasma laboratory that the Sun offers for close inspection. The proximity of our star implies that a great many plasma processes may be studied in good hope of observational verification.

3. TWO REGIMES

The scales imposed by physical processes on what is ultimately resolvable are very different between the photosphere on the one hand and the chromosphere and corona on the other. In fact, nearly everything is different between these two regimes. Figure 2 gives bullet lists which we follow here.

First of all, the nature of the physics which dominates the observed phenomena differs between the photosphere (regime A) and the upper atmosphere (regime B). In the photosphere and below, the magnetic field behavior is dictated by the gas motions unless the density of the magnetic field elements (fluxtubes) is large. A principle of mutual avoidance is at work between gas and field. The cell structures of turbulent convection, from granules to supergranules, expel fluxtubes from their interiors to their boundaries, whereas convection is suppressed where fields dominate, in fluxtubes, plage and spots. On the other hand, in the upper chromosphere and corona the gas motions are dictated by the fields. The plasma β–parameter, measuring gas pressure over magnetic pressure, flips through unity in the low chromosphere, deeper down within magnetic elements. In the low–β environment of the outer atmosphere the gas can only flow along field lines. Very steep density and temperature gradients can therefore be maintained across field lines. Thus, radiation and hydrodynamics are the major constituents of photospheric physics outside active regions, whereas MHD and plasma physics dominate higher up.

This distinction is evident in the evolution of solar physics disciplines. The understanding of spectral line formation is very mature. Of course, much work remains to be done in multi-dimensional radiative transfer ([17] – [26]), in partial redistribution theory (*e.g.,* [27] – [31]), in Stokes transfer theory (*e.g.,* [32] – [34]) and in diagnostic polarimetry (*e.g.,* [35] – [39]), but by and large, spectrometry has turned into a tool rather than a science *per sé.* Similarly, the computer revolution brings maturing of hydrodynamical insights as described above for turbulent convection, and increasing realism in the modeling of magnetic structures. The regime–A frontier now lies in the radiation hydrodynamics of the temperature minimum region and low chromosphere, while solar physics as a whole evolves towards the magnetohydrodynamics and plasma physics described below.

Second, an important difference between the regimes is that one may study photospheric physics without being concerned by what happens in the outer atmosphere. The reverse is not true, since the magnetic fields in the corona are continuously influenced by the photospheric footpoint motions. In electric circuit analogons (cf. [40]) the buffeting and shaking of photospheric fluxtubes by oscillations figures as imposed electromotive source. In other heating theories, the twisting and braiding of the fluxtubes governed by the convective motions cause continuous ("nanoflares") or discontinuous reconnection. Actually, a large variety of processes works together at various scales; for all, the photosphere supplies boundary conditions (cf. [41]).

The fundamental type *(iii)* scale limits differ tremendously between the two regimes. In the photosphere, the photon mean free path and the pressure and density scale heights are similar and measure about fifty kilometer. In optically thick conditions this measure is a lower limit, describing the steepest gradients which the intensity may display in the case of LTE control of the source function and the opacity. When scattering is important, as is the case for resonance line cores such as the Na I D lines or Ca II H & K, the smallest observable scale may be appreciably larger ([17] – [26]).

Higher up, the scales are set by electrodynamic processes. Basic scales such as the Debije length are far beyond any realistic type–*(ii)* limit, but important wave and current dissipation processes such as resonant Alfvén wave absorption, reconnection and double layer dissipation are expected to produce steep gradients with characteristic scale lengths from a tenth of a kilometer up to ten kilometer. Such small structures are observable even though the photon mean free path is much longer, at least in radiation in which they are optically thin. They then encode the emergent radiation without blurring from transfer effects such as scattering. This is the case for many lines in the ultraviolet, with Lyman–α an obvious exception.

The thick-thin dichotomy extends to the visible. Structures like filaments and spicules may be seen in optically thin conditions in projection against the optically thick solar disk. Thus, the continuum mean free path is the fundamental type–*(iii)* resolution limit for solar fluxtubes, penumbral striae, umbral dots *etc.*, but for the thin threads that make up a filament or fibril one may expect to see smaller scales across field lines even in the visible.

The outer atmosphere is accessible by ground-based observation to some extent. The era of mounting eclipse expeditions to view the corona is now past. It is over because the chance of success was always very small, and because intermittent glimpses, years apart, of phenomena that are all intrinsically variable at short time scales are not very useful. Outside eclipse, the chromosphere may be imaged in Hα; the transition region in He I 10830 Å. These lines are very difficult to interprete, however, and convey only limited information. It is therefore evident that studying processes and structures in the chromosphere, transition region and corona requires observation in the ultraviolet and X-ray domains, thus from space.

At the long wavelength end, far-infrared observation with high spatial resolution may eventually be informative to constrain the coolest components of the temperature minimum region (around $\lambda = 160$ microns) and low chromosphere. Likewise, the host of dynamic "burst" phenomena charted in the radio domain over the past decades contains much plasma physics encoding that eventually will help to constrain plasma theories. The frontier now, however, is to obtain image sequences with high spatial and temporal resolution at the short wavelengths where the primary energy-release processes are seen at work.

4. PHENOMENA AND PARADIGMS

Figure 3 is a schematic graph plotting solar phenomena (small characters) in a space–time display. The list of phenomena in this figure is far from complete; these are selected as archetype examples. The characteristic scales along the axes are not the phenomenon sizes nor their smallest type–*(iii)* limits, but indicate the desirable resolution for each phenomenon. This doesn't mean that observations at lower resolution are of no use, or that one wouldn't appreciate observations at yet higher resolution; by "desirable" I express the expectation that the specified resolution is the coarsest needed to identify the physical nature of the phenomenon to satisfaction. For example, prominences have lengths in excess of 10^5 km, but they require high spatial resolution because indirect diagnostics (Lyman-α) show that they actually consist of thin, as yet unresolved threads and have a prominence–corona interface layer with a thickness of less than 30 km (cf. [42]).

The dotted line shows the ground-based resolution limit. It is sloped because higher resolution is obtained when the exposures and duration of the observations are shorter. The upper half, below $0.5''$, is reached only occasionally at present, but will become available more regularly when speckle restoration and adaptive optics come to work (see below).

The items in capitals, to the right, are not observed phenomena but MHD *paradigms*, generally accepted modeling concepts which theoreticians invoke to explain magnetic phenomena on the Sun. At present, they stand for a large plasma physics literature, extending from tokamak experiments to quasars.

The phenomena fall into two distinct patterns. The ones to the left of the dotted line are primarily hydrodynamical in origin, the ones to te right magnetic. The lefthand ones are more or less resolved at present; indeed, much is known already for these — some are basically understood. The righthand phenomena are the primary ones to study with space interferometers.

4.1 Hydrodynamical phenomena

All phenomena left of the dotted line (granulations and oscillations) are hydrodynamical in origin. They all belong to the photospheric regime. These properties plus the fact that they are larger than the resolution limit explain that there are success stories in this part of the diagram. The first success story was the 5–min oscillation. Its identification as the complex interference pattern of millions of simple acoustic eigenmodes of the Sun has been "one of the cleanest discoveries of astrophysics" (Foukal, in [15]). This discovery came about when both the observed (k, ω)–diagram (Deubner [43]) and the computed (k, ω)–diagram (Ando & Osaki [44]) had sufficient resolution to show the parabolic ridges to which the solar p–modes are confined by their cavity properties. They were the same. This identification founded helio- and asteroseismology. The global oscillations literature is now very large; for an excellent introductory review see [45].

The 3–min and shorter-period oscillations are intensely being studied at the moment in the context of non-magnetic heating of the lower chromosphere, also both observationally ([46] – [53]) and theoretically ([54] – [62]), and also with good prospects for synthesis between observation and detailed computation.

The second hydrodynamical success story was the modeling of the solar granulation [63] in self-consistent, 3D time-dependent numerical simulations, as discussed above. The simulations advanced the theory of turbulent convection into the domain of physics experimentation. They are described in the proceedings edited by Rutten & Severino

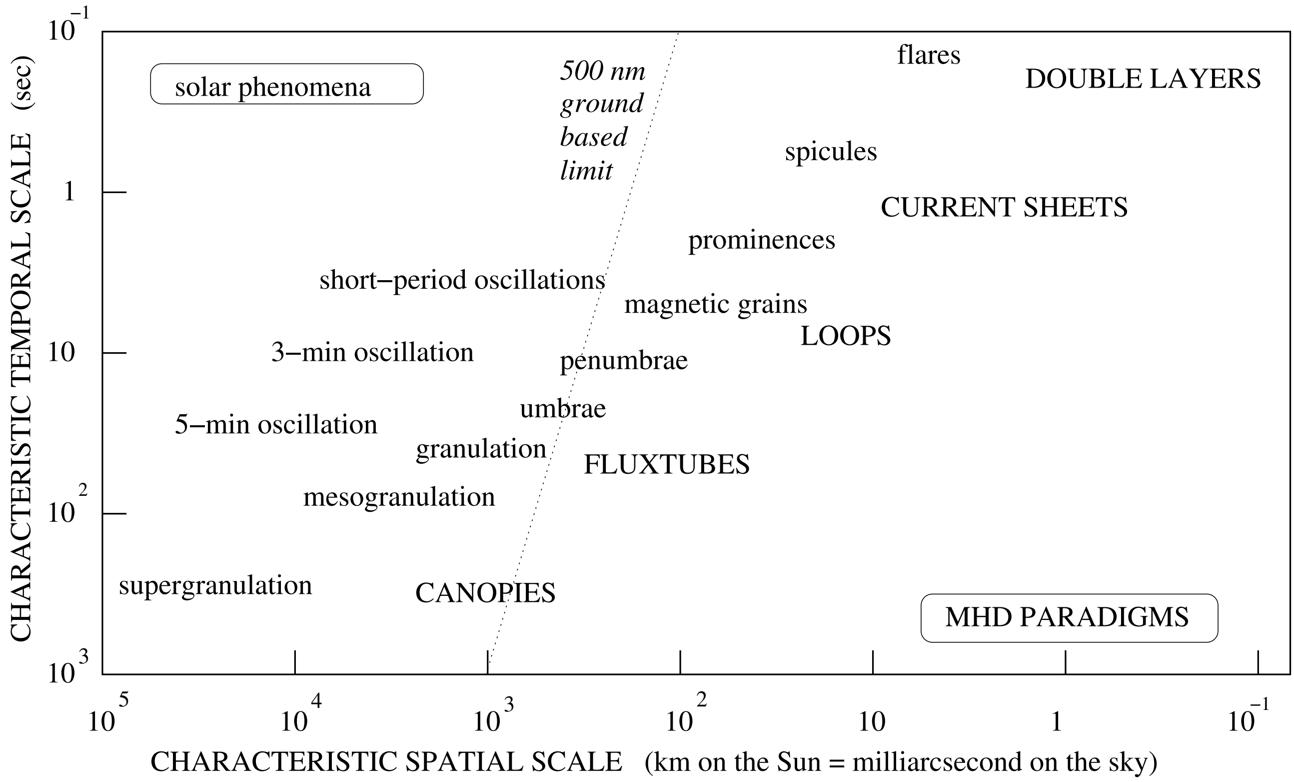

Fig. 3. Spacetime resolution characteristics of solar phenomena (small print) and solar-inspired paradigms of magnetohydrodynamics (capitals). The dotted line is the ground-based resolution limit including present developments. One arcsecond measures 725 km kilometer on the Sun.

[5] and the reviews by Spruit *et al.* [6] and Cattaneo & Malagoli [64]. The simulation results also serve as realistic photospheric boundary condition for other physical processes that sense the lower photosphere, such as spectral line formation ([11], [65] – [71]).

The larger convection patterns of mesogranulation ([72] – [75]), supergranulation and the magnetic network are not understood from the numerical hydrodynamics simulations as yet, because these do not reach the required volume with present computer capabilities. However, the fractal and percolation formalisms advocated by Schrijver *et al.* seem to provide a valid description ([76] – [80]). The need here is for long sequences of images with sufficient spatial resolution to measure the location and migration of the smallest magnetic elements. This example illustrates that single high-resolution snapshots are not satisfactory; long-duration sequences are typically needed to follow the dynamical topology of solar phenomena.

4.2 Magnetohydrodynamical phenomena

All other phenomena in Figure 3 are of magnetic origin. They are harder to observe and they are harder to understand. These are the phenomena that provide observational constraints to the MHD paradigms at right; together, they constitute the main frontier of solar astrophysics.

At the moment, there is progress especially for sunspot penumbrae (see [81]), which is not surprising because their striae are just about resolvable from the ground. The fine structure of network bright points, prominence threads, spicule fibrils and especially flare kernels requires much higher resolution. They also require observation in the ultraviolet where that resolution is not hampered by optically thick radiative transfer and because they extend upward in the outer atmosphere, not seen in the visible.

The solar MHD literature is vast and expands rapidly; there is no point in listing research papers here. The following references supply suitable entry points. For magnetoconvection see [82] – [86]. Small-scale magnetic fields ("fluxtubes") have been discussed by Schüssler [87] [88], Solanki [89] [90], Stenflo [91] and Steiner [92]; a very extensive review by Solanki will appear in *Space Science Reviews*. Sunspots are the topic of a recent workshop of which the proceedings [81] contain an excellent introduction for non-specialists by Thomas & Weiss. Prominences are the topic of a book edited by Priest [93] and proceedings by Ruždjak & Tandberg-Hanssen [94]. Coronal loops are discussed extensively in Priest & Hood [95]. For flares, see the proceedings edited by Haisch & Rodono [96] and by Dubois *et al.* [97]. Finally, chromospheric and coronal heating are covered by Kuperus *et al.* [40], Ulmschneider *et al.* [98] and Narain & Ulmschneider [99].

5. GROUND-BASED OBSERVATION

Increase of spatial resolution is the major driver for most solar physics instrumentation developments (again excepting helioseismology), on the ground as well as in space. The dichotomy between ground-based photospheric-regime studies and space-based outer-atmosphere studies made above is artificial in the sense that most atmospheric structures and processes extend through both regimes: fibrils and spicules jut out from the magnetic network, prominences and flares have to do with photospheric dynamics. This implies that one cannot concentrate on space missions in the ultraviolet without adequate coverage of the photospheric counterparts seen in the visible. *Holistic* approaches are necessary, combining optical diagnostics, perhaps from ground-based telescopes, with space interferometry.

It is therefore worthwhile within the context of this meeting to discuss the prospects of ground-based solar observing techniques. The fact that the outer atmosphere regime is not accessible from the ground at all immediately implies the *necessity* of going to space for regime–B studies, but does not imply that ultraviolet and X-ray solar observing are independent of the ground-based developments. Instead, ground and space based have to advance in tandem.

Concerted holism is indeed essential. All solar processes and structures are highly time dependent, are constrained by velocity fields and magnetic fields, and extend with much variation from the subsurface layers to the outer heliosphere. They require high-resolution imaging in a number of spectral diagnostics, including narrow-band images in lines from various heights (photosphere, temperature-minimum region, chromosphere, transition region, corona), Dopplergrams and magnetograms, also at different heights. These must be taken co-spatially and synchronously, in rapid but long sequencing.

On the ground, this approach is making appreciable advances at the moment in addressing photospheric-regime issues (including the chromosphere as seen in Na I D, Ca II K and Hα). There is a spade of new telescopes at very good sites, with more to come; active-mirror image stabilisation is in daily use; new narrow-band imagers are available that cycle rapidly through sequences of different spectral-line windows; there are rapid developments in registration, storage and analysis technology (CCD cameras, digital videocassette recording, videodisk movie analysis); last but not least, powerful software algorithms produce clean diagnostics by which one phenomenon is well separated from another.

5.1 New instrumentation

A list of new high-resolution solar physics facilities:

• recently completed Canary Island telescopes:

– Swedish Vacuum Solar Telescope (SVST, 48 cm, La Palma)

– German Gregory Coudé Telescope (GGCT, 45 cm, Tenerife)

– German Vacuum Tower Telescope (GVTT, 70 cm, Tenerife)

• forthcoming Canary Island telescopes:

– Dutch Open Solar Telescope (45 cm, La Palma)

– French THEMIS telescope (90 cm, Tenerife)

– international LEST telescope (250 cm, La Palma)

• real-time image motion correctors employing active mirrors:

– Lockheed pore tracker (SVST and GVTT)

– autocorrelation tracker, for pores and granulation (GVTT and the NSO/SP Vacuum Tower Telescope at Sacramento Peak)

• tunable narrow-band imagers

– Lockheed SOUP tunable filtergraph (SVST and GVTT)

– tandem tunable-filter/Fabry-Perot (NSO/SP)

– lithium niobate etalons (David Rust, various telescopes)

– NCAR Stokes-2 polarimeter (NSO/SP)

– ETH Zürich Stokes polarimeter (SVST)

5.2 State of the art

Let me briefly illustrate current observation techniques. Only occasional images reach the diffraction limit of a small telescope; that requires *super seeing* which is rare even at the best sites. Brandt *et al.* [100] specify that the Fried parameter r_0 at NSO/SP sits between 3.5 cm and 20 cm during 90% of the observing time. The sharpest solar images come from Pic du Midi (super seeing only when snow falls in the summer) and the SVST at La Palma. The latter telescope [101] has probably the best optics of all telescopes. Scharmer uses it with a real-time video frame selector [102] which "grabs" and stores the best video frame per preset interval, *e.g.,* ten seconds. The 17 ms video exposure time nearly freezes the seeing. The grabber-selected frames are subsequently re-registered to take out image motion, rubber-sheet deformed (image-to-image local autocorrelation) to correct large-scale seeing motions, and 3D Fourier-filtered in x, y and t simultaneously. The latter filtering passes subsonic motions over the solar surface but takes out fast small-scale seeing excursions as well as solar p-mode oscillations. These procedures, mostly developed at Lockheed, have generated the best solar movies sofar (granulation and penumbrae).

The Lockheed group employs the same telescope in tandem with Scharmer's frame grabber. They have a fast agile mirror which stabilizes the image from an offset solar pore at high frequency, and they use the Spacelab 2 SOUP tunable filter in sequences which deliver continuum images, Hα images, Dopplergrams and magnetograms in rapid succession. Multiple beams feed the SOUP, grabber and a Ca II K filter simultaneously, all spewing data on to Exabyte data cassettes at a rate of Gigabytes per sequence. Reduction employs laser-videodisk inspection and selection of the best parts, followed by the extensive correction procedures listed above. Analysis typically employs human vision to find patterns in speeded-up video displays and "cork" movies constructed from the reduced data. Further descriptions and results are given in *e.g.,* [3] and [103] – [106].

5.3 Prospects

The next step is to obtain solar movies with similar quality as Scharmer's frame-grabbed ones, not only in the broad band continuum but also in narrow-band diagnostics such as magnetograms. The low readout noise of the latest CCD cameras permits building up a long low-flux exposure from short-exposure subframes. Frame selection, image motion compensation and rubber-sheet correctins may then be applied before summing to get reduce the photon noise.

A step further is to apply narrow-band speckle interferometry by slaved wide-band and narrow-band speckle cameras. This technique has recently been demonstrated by Keller and von der Lühe [107] and is very promising. Its principle is that the wide-band camera, which registers solar granulation or solar plage fine structure, has sufficient signal to noise to permit a full speckle reconstruction from 10 ms specklegrams. The synchronized narrow-band frames are swamped in photon noise and cannot be used for reliable reconstruction. However, one may derive the point spread function from the wide band channel and use that to deconvolve the narrow-band results. The technique works, first, because the Sun offers a sufficiently large number of continuum photons per isoplanatic patch (which isn't the case for most other astrophysical objects) to permit seeing-freezing 10 ms exposures, and, second, because the white-light solar surface contains suitable fine structure at all spatial scales up to at least the diffraction limit of a 50 cm telescope, and probably higher. These are the granulation in quiet areas and the "abnormal" granulation of active regions. They provide suitable point spread function encoding all over the solar surface. The technique works over the full image, not only a single isoplanatic patch, and results in sharpening of the narrow-band image whatever it portrays — the chromosphere, Doppler velocities or magnetic fields. Note that one cannot apply speckle restoration or even simple destretching to chromospheric images, even apart from signal to noise considerations, because they do not contain appropriate long-lived all-over-the-place fine structure such as granulation. Chromospheric fibrils are long and thin and vary much too quickly. Thus, the trick is to restore *any* narrow-band channel from granulation morphology. The next generation of workstations is probably fast enough to achieve such reconstruction in real time or nearly in real time.

The ultimate step is to apply adaptive optics, using a pore or again the granulation morphology as wavefront disturbance encoder. In many discussions at this meeting, adaptive optics is promised for the rather distant future (and then used against the necessity of space observation in the visible). It is appropriate here to point out that a solar adaptive system has been developed, has been demonstrated and will soon go into regular deployment. This is the Lockheed system tested at the NSO/SP Tower Telescope. It has a segmented mirror with three piezo actuators correcting the tilt and axial position of each of the 19 segments. The impressive demonstration movie shows a solar pore to be sharpened to $0.5''$ in 1–$2''$ seeing.

In summary, ground-based solar observing still has tricks up its sleeve. Frame selection alone can produce a factor 2–3 improvement over the ambient seeing [108]; multi-band speckle restoration may add another factor of two, independent of exposure time [107], adaptive optics is coming along, and eventually, multi-conjugate adaptive optics [109] may become a reality. This all holds for the visible and near-infrared; these advances therefore apply to regime–A type science. As stated above, the optically-thick photospheric type–*(iii)* limit is about 50 km or $0.1''$; thus, it is quite possible that ground-based techniques will reach the fundamental limit of photospheric physics within the present decade.

6. SPACE-BASED OBSERVATION

6.1 Why space?

From the above, it is obvious that one needs to do regime–B solar physics from space: solar plasma astrophysics *requires* observing in the ultraviolet and X-ray domains.

However, it will be good to include the visible in such space observation. The reason is the requirement of holism. Together with the regime–B upper-atmosphere diagnostics, one needs to monitor foot-point motions and other photospheric boundary conditions co-spatially and synchronously. This may (and will) of course be done from the ground; nevertheless, having a visible channel covering the same field of view (or rather, a larger one) will be useful because the absence of any seeing in space makes precise co-registration much simpler.

6.2 Why interferometry?

I sometimes have the feeling that, in the community assembled here, it is bad manners to use a normal telescope and worse to employ an interferometer for goals where a normal telescope might do. However, interferometry is nothing but a clever way to synthesize a large aperture, or at least a long baseline, permitting gaps in the mirror. *Any* telescope is an interferometer, with or without holes!

A classical reflector is conceptually simple, but it is actually very hard to build and to operate at the diffraction limit when its size exceeds about half a meter and the wavelength is short. Note that the design specification for the HST imaging quality was far below the diffraction limit given by its diameter.

The regime–B solar physics requirement is to observe solar fine structure in the ultraviolet with resolution in the 10–0.1 km ballpark (Figures 2 & 3). This translates into baseline lengths of 2–5 m. The ideal *Gedankentelescope* is, obviously, a solar Space Telescope with a filled aperture. In practice, the very large heat removal problem and the very large cost suggest sparser apertures and, therefore, interferometry. Rotational tomography brings the cost further down by permitting use of a linear array. Thus, *interferometry is the cheap way out,* as it always has been.

6.3 Prospects

The bad news is that NASA is in a bad shape. It is not for me to say so, of course, but reading the lucid and authorative account [110] by Col. S. Pete Worden — a former speckle pioneer — of what has gone wrong and remains wrong with the principal space agency on our planet convinces me that there is no hope of America launching the *Orbiting Solar Observatory* or any comparable solar physics mission that would address the science described above in a suitably complete and holistic fashion within a decade or so.

The good news is that the Japanese YOHKOH satellite is a resounding success, and that ESA is in pretty good shape, at least in setting long-term science policies and keeping to its plan. Solar space interferometry is not a definite part of the plan as yet, but ESA has been willing to spend some of its accounting units on procuring design studies on the SIMURIS project, detailed by Damé elsewhere in these proceedings. This is the only space interferometry project that has reached industrial scrutiny. Although I find it incredily complex, experts tell me that its concept contains all the right choices, and even that it should work. If it does, it brings precisely the type of holistic solar science I have advocated here.

7. CONCLUSION

As editor of an EPS—EAS European solar physics newsletter, I happen to know that there about 800 persons in Europe who are professionally involved in solar physics. This is a large and very varied community, with a strong tradition of plasma physics in many countries (including those in the former East Block). Plasma physics isn't so well known in non-solar astronomy yet; the point I have tried to make above is that plasma astrophysics has come to stay, and that solar physics is an excellent way of learning it.

Solar physics requires space interferometry. ESA asks for a transition from *Gedankeninstruments* to realistic projects; the detailed SIMURIS design studies accomplish just that right now. Solar space interferometry is definitely something to go for.

REFERENCES

[1] Coradini, M., Damé, L., Foing, B., Haskell, G., Kassing, D., Olthof, H., Mersch, G., Rutten, R. J., Thorne, A. P., and Vial, J.-C.: 1991, "SIMURIS — Solar, Solar System and Stellar Interferometric Mission for Ultrahigh Resolution Imaging and Spectroscopy", *ESA SCI (91)* **7**, 1

[2] Damé, L. and Guyenne, T.-D.: 1992, *Solar Physics and Astrophysics at Interferometric Resolution*, ESA SP-344, ESA Publ. Div., ESTEC, Noordwijk

[3] Title, A., Tarbell, T., Shine, R., Topka, K., and Frank, Z.: 1992, "High-resolution observations: the state of the art and beyond", in L. Damé and T.-D. Guyenne (Eds.), *Solar Physics and Astrophysics at Interferometric Resolution*, ESA SP-344, ESA Publ. Div., ESTEC, Noordwijk, 9

[4] Zirin, H.: 1992, "Solar Optical Instrumentation", in J. T. Schmelz and J. C. Brown (Eds.), *The Sun: A*

Laboratory for Astrophysics, NATO ASI Series C 373, Kluwer, Dordrecht, 379

[5] Rutten, R. J. and Severino, G. (Eds.): 1989, *Solar and Stellar Granulation*, NATO ASI Series C 263, Kluwer, Dordrecht

[6] Spruit, H. C., Nordlund, Å., and Title, A. M.: 1990, "Solar Convection", *Ann. Rev. Astron. Astrophys.* **28**, 263

[7] Nordlund, Å. and Dravins, D.: 1990, "Stellar granulation. III. Hydrodynamic model atmospheres", *Astron. Astrophys.* **228**, 155

[8] Dravins, D.: 1987, "Stellar granulation I. The observability of stellar photospheric convection", *Astron. Astrophys.* **172**, 200

[9] Dravins, D.: 1987, "Stellar granulation II. Stellar photospheric line asymmetries", *Astron. Astrophys.* **172**, 211

[10] Dravins, D.: 1989, "Stellar granulation: modeling of stellar surfaces and photospheric line asymmetries", in R. J. Rutten and G. Severino (Eds.), *Solar and Stellar Granulation*, NATO ASI Series C 263, Kluwer, Dordrecht, 493

[11] Dravins, D. and Nordlund, Å.: 1990, "Stellar Granulation. IV. Line formation in inhomogeneous stellar photospheres", *Astron. Astrophys.* **228**, 184

[12] Dravins, D. and Nordlund, Å.: 1990, "Stellar Granulation. V. Synthetic spectral lines in disk-integrated starlight", *Astron. Astrophys.* **228**, 203

[13] Priest, E. R.: 1982, *Solar Magnetohydrodynamics*, Reidel, Dordrecht

[14] Stix, M.: 1989, *The Sun. An Introduction*, Springer, Berlin

[15] Foukal, P.: 1990, *Solar Astrophysics*, Wiley and Sons, New York

[16] Schmelz, J. T. and Brown, J. C. (Eds.): 1992, *The Sun: A Laboratory for Astrophysics*, NATO ASI Series C 373, Kluwer, Dordrecht

[17] Jones, H. P. and Skumanich, A.: 1976, "A Review of the Physical Effects Introduced by Radiative Transfer in Multi-Dimensional Media including Models of the Solar Atmosphere", in C. J. Cannon (Ed.), *Interpretation of Atmospheric Structure in the Presence of Inhomogeneities*, Commision 12, General Assembly IAU, Grenoble, University of Sydney Printing Office, Sydney, 1

[18] Jones, H. P. and Skumanich, A.: 1980, "The physical effects of radiative transfer in multidimensional media including models of the solar atmosphere", *Astrophys. J. Suppl. Ser.* **42**, 221

[19] Jones, H. P.: 1986, "The interpretation of spectrum lines formed in small solar structures", in W. Deinzer, M. Knölker, and H. H. Voigt (Eds.), *Small Scale Magnetic Flux Concentrations in the Solar Photosphere*, Abhandl. Akad. Wiss. Göttingen, Math.-Phys. Klasse Dritte Folge Nr. 38, Vandenhoeck und Ruprecht, Göttingen, 127

[20] Mihalas, D., Auer, L. H., and Mihalas, B. R.: 1978, "Two-dimensional radiative transfer. I. Planar geometry", *Astrophys. J.* **220**, 1001

[21] Owocki, S. P. and Auer, L. H.: 1980, "Two-Dimensional Radiative Transfer. II. The Wings of Ca K and Mg k", *Astrophys. J.* **241**, 448

[22] Kneer, F.: 1981, "Multidimensional Radiative Transfer in Stratisfied Atmospheres", *Astron. Astrophys.* **93**, 387

[23] Lites, B. W.: 1985, "Future Directions for the Theory of Radiative Transfer in Chromospheric Structures", in H. U. Schmidt (Ed.), *Theoretical Problems in High Resolution Solar Physics*, MPA/LPARL Workshop, Max-Planck-Institut für Physik und Astrophysik MPA 212, München, 273

[24] Kneer, F. and Trujillo Bueno, J.: 1987, "Multidimensional radiative transfer in stratified atmospheres V. Energy transport by radiation", *Astron. Astrophys.* **183**, 91

[25] Trujillo Bueno, J. and Kneer, F.: 1987, "Multidimensional Radiative Transfer in Stratified Atmospheres", *Astron. Astrophys.* **174**, 183

[26] Nordlund, Å.: 1991, "NLTE spectral line formation in three dimensions", in L. Crivellari, I. Hubeny, and D. G. Hummer (Eds.), *Stellar Atmospheres: Beyond Classical Models*, NATO ASI Series C 341, Kluwer, Dordrecht, 61

[27] Linsky, J.: 1985, "Observed and computed stellar line profiles: the roles played by partial redistribution, geometrical extent and expansion", in J. E. Beckman and L. Crivellari (Eds.), *Progress in Stellar Spectral Line Formation Theory*, NATO ASI Series C 152, Reidel, Dordrecht, 1

[28] Hubený, I.: 1985, "General aspects of partial redistribution and its astrophysical importance", in J. E. Beckman and L. Crivellari (Eds.), *Progress in Stellar Spectral Line Formation Theory*, NATO ASI Series C 152, Reidel, Dordrecht, 27

[29] Uitenbroek, H.: 1989, "Operator Perturbation Method for Multi–Level Line Transfer with Partial Redistribution", *Astron. Astrophys.* **213**, 360

[30] Uitenbroek, H.: 1989, "An Efficient Method for the Evaluation of General Redistribution Integration Weights", *Astron. Astrophys.* **216**, 310

[31] Uitenbroek, H. and Bruls, J. H. M. J.: 1992, "The formation of helioseismology lines. III. Partial redistribution effects in weak solar resonance lines", *Astron. Astrophys.* **265**, 268

[32] Bommier, V., Landi Degl' Innocenti, E., and Sahal-Bréchot, S.: 1991, "Resonance line polarization and the Hanle effect in optically thick media. II. Case of plane-parallel atmosphere", *Astron. Astrophys.* **244**, 383

[33] Landi Degl' Innocenti, E., Bommier, V., and Sahal-Bréchot, S.: 1991, "Resonance line polarization for arbitrary magnetic fields in optically thick media. I. Basic formalism for a 3-dimensional medium", *Astron. Astrophys.* **244**, 391

[34] Landi Degl' Innocenti, E., Bommier, V., and Sahal-Bréchot, S.: 1991, "Resonance line polarization for arbitrary magnetic fields in optically thick media. II. Case of plane-parallel atmosphere and absence of Zeeman coherences", *Astron. Astrophys.* **244**, 401

[35] Skumanich, A. and Lites, B. W.: 1985, "Radiative Transfer Diagnostics: Understanding Multi-Level Transfer Calculations", in J. E. Beckman and L. Crivellari (Eds.), *Progress in Stellar Spectral Line Formation Theory*, NATO ASI Series C 152, Reidel, Dordrecht, 175

[36] Skumanich, A. and Lites, B. W.: 1986, "Radiative Transfer Diagnostics: Understanding Multilevel Transfer Calculations. I. Analysis of the Full Statistical Equilibrium Equations", *Astrophys. J.* **310**, 419

[37] Lites, B. W., Skumanich, A., Rees, D. E., Murphy, G. A., and Carlsson, M.: 1987, "Stokes profile analysis and vector magnetic fields. III. Extended temperature minima of sunspot umbrae as inferred from

Stokes profiles of Mg I λ4571", *Astrophys. J.* **318**, 930

[38] Bruls, J. H. M. J., Lites, B. W., and Murphy, G. A.: 1991, "Non-LTE formation heights of Stokes profiles of Fe I lines", in L. J. November (Ed.), *Solar Polarimetry*, Proc. NSO/SP Summer Workshop No. 11, Sunspot, New Mexico, 444

[39] Bruls, J. H. M. J. and Solanki, S. K.: 1993, "The chromospheric temperature rise in solar magnetic fux tubes", *Astron. Astrophys.* **273**, 293

[40] Kuperus, M., Ionson, J. A., and Spicer, D. S.: 1981, "On the Theory of Coronal Heating Mechanisms", *Ann. Rev. Astron. Astrophys.* **19**, 7

[41] van den Oord, G. H. J.: 1992, "Small scale processes in solar and stellar plasmas", in L. Damé and T.-D. Guyenne (Eds.), *Solar Physics and Astrophysics at Interferometric Resolution*, ESA SP-344, ESA Publ. Div., ESTEC, Noordwijk, 97

[42] Heinzel, P. and Vial, J.-C.: 1992, "The fine structure of prominences", in L. Damé and T.-D. Guyenne (Eds.), *Solar Physics and Astrophysics at Interferometric Resolution*, ESA SP-344, ESA Publ. Div., ESTEC, Noordwijk, 57

[43] Deubner, F.-L.: 1976, "Observations of low wavenumber nonradial eigenmodes of the Sun", in R. Cayrel and M. Steinberg (Eds.), *Physique des mouvements dans les atmosphères stellaires*, Colloques Internationaux du CNRS (Nice) No. 250, Éditions du CNRS, Paris, 259

[44] Ando, H. and Osaki, Y.: 1975, "Nonadiabatic Nonradial Oscillations: An Application to the Five-Minute Oscillation of the Sun", *Publ. Astron. Soc. Japan* **27**, 581

[45] Christensen-Dalsgaard, J.: 1992, "Seismic investigation of the solar interior", in J. T. Schmelz and J. C. Brown (Eds.), *The Sun: A Laboratory for Astrophysics*, NATO ASI Series C 373, Kluwer, Dordrecht, 29

[46] Deubner, F.-L. and Fleck, B.: 1989, "Dynamics of the solar atmosphere. I. Spatio-temporal analysis in the quiet atmosphere", *Astron. Astrophys.* **213**, 423

[47] Deubner, F.-L. and Fleck, B.: 1990, "Dynamics of the solar atmosphere. III. Cell-network distinctions of chromospheric oscillations", *Astron. Astrophys.* **228**, 506

[48] Fleck, B. and Deubner, F.-L.: 1989, "Dynamics of the solar atmosphere. II. Standing waves in the solar chromosphere", *Astron. Astrophys.* **224**, 245

[49] Deubner, F.-L.: 1991, "Observations of Waves and Oscillations", in P. Ulmschneider, E. Priest, and B. Rosner (Eds.), *Mechanisms of Chromospheric and Coronal Heating*, Heidelberg Conference, Springer Verlag, Berlin, 6

[50] Rutten, R. J. and Uitenbroek, H.: 1991, "K_{2V} cell grains and chromospheric heating", in P. Ulmschneider, E. R. Priest, and R. Rosner (Eds.), *Mechanisms of Chromospheric and Coronal Heating*, Proc. Heidelberg Conf., Springer Verlag, Berlin, 48

[51] Rutten, R. J. and Uitenbroek, H.: 1991, "Ca II H_{2V} and K_{2V} Cell Grains", *Solar Phys.* **134**, 15

[52] Brandt, P. N., Rutten, R. J., Shine, R. A., and Trujillo Bueno, J.: 1992, "Dynamics of the Quiet Solar Atmosphere: K_{2V} cell grains versus magnetic elements", in M. S. Giampapa and J. A. Bookbinder (Eds.), *Cool Stars, Stellar Systems, and the Sun*, Proc. Seventh Cambridge Workshop, Astron. Soc. Pacific Conf. Series, Vol. 26, 161

[53] Lites, B. W., Rutten, R. J., and Kalkofen, W.: 1993, "Dynamics of the Solar Chromosphere. I. Long-Period Network Oscillations", *Astrophys. J.* **414**, 345

[54] Ulmschneider, P.: 1986, "Short period acoustic heating theory and its applications to the construction of models of the chromosphere", in W. Deinzer, M. Knölker, and H. H. Voigt (Eds.), *Small Scale Magnetic Flux Concentrations in the Solar Photosphere*, Abhandl. Akad. Wiss. Göttingen, Math.-Phys. Klasse Dritte Folge Nr. 38, Vandenhoeck und Ruprecht, Göttingen, 191

[55] Ulmschneider, P.: 1990, "Acoustic heating of stellar chromospheres and coronae", in G. Wallerstein (Ed.), *Cool Stars, Stellar Systems and the Sun*, Proc. Sixth Cambridge Workshop, Astron. Soc. Pacific Conf. Series, Volume 9, 3

[56] Ulmschneider, P.: 1991, "Acoustic heating", in P. Ulmschneider, E. Priest, and B. Rosner (Eds.), *Mechanisms of Chromospheric and Coronal Heating*, Heidelberg Conference, Springer Verlag, Berlin, 328

[57] Rammacher, W. and Ulmschneider, P.: 1992, "Acoustic waves in the solar atmosphere IX. Three minute pulsations driven by shock overtaking", *Astron. Astrophys.* **253**, 586

[58] Deubner, F.-L., Fleck, B., Marmolino, C., and Severino, G.: 1990, "Dynamics of the solar atmosphere IV. Evanescent waves of small amplitude", *Astron. Astrophys.* **236**, 509

[59] Fleck, B. and Schmitz, F.: 1991, "The 3–min oscillations of the solar chromosphere — a basic physical effect?", *Astron. Astrophys.* **250**, 235

[60] Kalkofen, W., Rossi, P., Bodo, G., and Massaglia, M.: 1992, "The 3 min Oscillations in Chromospheric Bright Points", in M. S. Giampapa and J. A. Bookbinder (Eds.), *Seventh Cambridge Workshop on Cool Stars, Stellar Systems and the Sun*, Astron. Soc. Pacific Conf. Series, Vol. 26, 543

[61] Carlsson, M. and Stein, R. F.: 1992, "Ca II K2V Bright Grains Formed by Acoustic Waves", in M. Giampapa and J. M. Bookbinder (Eds.), *Cool Stars, Stellar Systems and the Sun*, Proc. Seventh Cambridge Workshop, Astron. Soc. Pacific Conf. Series, Vol. 26, 515

[62] Carlsson, M. and Stein, R. F.: 1992, "Non-LTE radiating acoustic shocks and Ca II K2V bright points", *Astrophys. J.* **397**, L59

[63] Müller, R.: 1989, "Solar Granulation: Overview", in R. J. Rutten and G. Severino (Eds.), *Solar and Stellar Granulation*, NATO ASI Series C 263, Kluwer, Dordrecht, 101

[64] Cattaneo, F. and Malagoli, A.: 1992, "Numerical models of stellar convection", in M. S. Giampapa and J. A. Bookbinder (Eds.), *Seventh Cambridge Workshop on Cool Stars, Stellar Systems and the Sun*, Astron. Soc. Pacific Conf. Series, Vol. 26, 139

[65] Nordlund, Å.: 1985, "NLTE spectral line formation in a three-dimensional atmosphere with velocity fields", in J. E. Beckman and L. Crivellari (Eds.), *Progress in stellar spectral line formation theory*, NATO ASI Series C152, Reidel, Dordrecht, 215

[66] Nordlund, Å. and Stein, R. F.: 1991, "Dynamics of and radiative transfer in inhomogeneous media", in L. Crivellari, I. Hubeny, and D. G. Hummer (Eds.), *Stellar Atmospheres: Beyond Classical Models*, NATO ASI Series C 341, Kluwer, Dordrecht, 263

[67] Holweger, H. and Kneer, F.: 1989, "Spatially resolved spectra of solar granules", in R. J. Rutten and G. Severino (Eds.), *Solar and Stellar Granulation*, NATO ASI Series C 263, Kluwer, Dordrecht, 173

[68] Steffen, M. and Freytag, B.: 1991, "Hydrodynamics of the Solar Photosphere: Model Calculations and Spectroscopic Observations", in G. Klare (Ed.), *Reviews in Modern astronomy, Vol. 4*, Springer

[69] Bruls, J. H. M. J. and Rutten, R. J.: 1992, "The formation of helioseismology lines. II. Alkali lines with granulation", *Astron. Astrophys.* **265**, 257

[70] Bruls, J. H. M. J.: 1993, "The formation of helioseismology lines. IV. The Ni I 676.8 nm intercombination line", *Astron. Astrophys.* **269**, 509

[71] Bruls, J. H. M. J.: 1992, *Formation of diagnostic lines in the solar spectrum*, PhD thesis, Utrecht University

[72] November, L. J., Toomre, J., Gebbie, K. B., and Simon, G. W.: 1981, "The Detection of Mesogranulation on the Sun", *Astrophys. J.* **245**, L123

[73] Oda, N.: 1984, "Morphological study of the solar granulation I. The Mesogranulation", *Solar Phys.* **93**, 243

[74] Brandt, P. N., Ferguson, S., Scharmer, G. B., Shine, R. A., Tarbell, T. D., Title, A. M., and Topka, K.: 1989, "Variation of granulation properties on a mesogranular scale", in O. von der Lühe (Ed.), *High Spatial Resolution Solar Observations*, 10th Sacramento Peak Summer Workshop, NSO, Sunspot, New Mexico, 473

[75] Deubner, F.-L.: 1989, "Mesogranulation: a convective phenomenon", *Astron. Astrophys.* **216**, 259

[76] Balke, A. C., Schrijver, C. J., Zwaan, C., and Tarbell, T. D.: 1993, "Percolation theory and the geometry of photospheric magnetic flux concentrations", *Solar Phys.* **143**, 215

[77] Lawrence, J. K. and Schrijver, C. J.: 1992, "The effect of fractal distribution on the evolution of solar surface magnetic fields", in K. L. Harvey (Ed.), *The Solar Cycle*, Procs. 12th NSO/Sacramento Peak Summer Workshop, Astron. Soc. Pacific Conf. Series27, 48

[78] Lawrence, J. K. and Schrijver, C. J.: 1993, "Anomalous diffusion of magnetic elements across the solar surface", *Astrophys. J.* **411**, 402

[79] Schrijver, C. J., Zwaan, C., Balke, A. C., Tarbell, T. D., and Lawrence, J. K.: 1992, "Patterns in the photospheric magnetic field and percolation theory", *Astron. Astrophys.* **253**, L1

[80] Schrijver, C. J., Zwaan, C., Balke, A. C., Tarbell, T. D., and Lawrence, J. K.: 1992, "Fractals in magnetograms", in K. L. Harvey (Ed.), *The Solar Cycle*, Procs. 12th NSO/Sacramento Peak Summer Workshop, Astron. Soc. Pacific Conf. Series27, 67

[81] Thomas, J. H. and Weiss, N. O. (Eds.): 1992, *Sunspots: Theory and Observations*, NATO ASI Series C 375, Kluwer, Dordrecht

[82] Hurlburt, N. E. and Weiss, N. O.: 1987, "Interaction between Magnetic Fields and Convection", in E.-H. Schröter, M. Vázquez, and A. A. Wyller (Eds.), *The Role of Fine-Scale Magnetic Fields on the Structure of the Solar Atmosphere*, Cambridge University Press, Cambridge, 35

[83] Hughes, D. W. and Proctor, M. R. E.: 1988, "Magnetic fields in the solar convection zone: Magnetoconvection and Magnetic Buoyancy", *Ann. Rev. Fluid Mech.* **20**, 187

[84] Weiss, N. O.: 1989, "Time dependent compressible magnetoconvection", in R. J. Rutten and G. Severino (Eds.), *Solar and Stellar Granulation*, NATO ASI Series C 263, Kluwer, Dordrecht, 471

[85] Nordlund, Å. and Stein, R. F.: 1990, "Solar magnetoconvection", in J.-O. Stenflo (Ed.), *The Solar Photosphere: Structure, Convection and Magnetic Fields*, Proceedings IAU Symposium 138 (Kiev), Kluwer, Dordrecht, 191

[86] Stein, R. F., Brandenburg, A., and Nordlund, Å.: 1992, "Magneto-convection", in M. S. Giampapa and J. A. Bookbinder (Eds.), *Seventh Cambridge Workshop on Cool Stars, Stellar Systems and the Sun*, Astron. Soc. Pacific Conf. Series, Vol. 26, 148

[87] Schüssler, M.: 1990, "Theoretical aspects of small-scale photospheric magnetic fields", in J.-O. Stenflo (Ed.), *The Solar Photosphere: Structure, Convection and Magnetic Fields*, Proceedings IAU Symposium 138 (Kiev), Kluwer, Dordrecht, 161

[88] Schüssler, M.: 1992, "Small-scale photospheric magnetic fields", in J. T. Schmelz and J. C. Brown (Eds.), *The Sun: A Laboratory for Astrophysics*, NATO-ASI Series C 373, Kluwer, Dordrecht, 191

[89] Solanki, S. K.: 1990, "Empirical models of photospheric flux tubes", in J.-O. Stenflo (Ed.), *The Solar Photosphere: Structure, Convection and Magnetic Fields*, Proceedings IAU Symposium 138, Kluwer, Dordrecht, 103

[90] Solanki, S. K.: 1994, "Properties of magnetic features from the analysis of near-infrared spectral lines", in J. T. Jefferies, D. Deeming, and D. R. Rabin (Eds.), *Infrared Solar Physics*, Proceedings IAU Symposium 154 (Tucson), Kluwer, Dordrecht, 393

[91] Stenflo, J.-O.: 1989, "Small-scale magnetic structures on the Sun", *Astron. Astrophys. Rev.* **1**, 3

[92] Steiner, O.: 1994, "Theoretical models of magnetic flux tubes: structure and dynamics", in J. T. Jefferies, D. Deeming, and D. R. Rabin (Eds.), *Infrared Solar Physics*, Proceedings IAU Symposium 154 (Tucson), Kluwer, Dordrecht, 407

[93] Priest, E. R. (Ed.): 1989, *Dynamics and Structure of Quiescent Solar Prominences*, Kluwer, Dordrecht

[94] Ruždjak, V. and Tandberg-Hanssen, E. (Eds.): 1990, *Dynamics of Quiescent Prominences*, Proc. IAU Coll. 117 (Hvar), Hvar Observatory Bulletin 13, Lecture Notes in Physics 363, Springer, Berlin

[95] Priest, E. R. and Hood, A. (Eds.): 1991, *Advances in solar system magnetohydrodynamics*, Cambridge Univ. Press, Cambridge UK

[96] Haisch, B. M. and Rodono, M. (Eds.): 1989, *Solar and stellar flares*, Proc. IAU Colloquium 104, Solar Phys. 121, Kluwer, Dordrecht

[97] Dubois, M. A., Bely-Dubau, F., and Gresillon, D. (Eds.): 1989, *Solar plasma phenomenon*, Les éditions de physique

[98] Ulmschneider, P., Priest, E. R., and Rosner, R. (Eds.): 1991, *Mechanisms of Chromospheric and Coronal Heating*, Proc. Int. Heidelberg Conf., Springer, Berlin

[99] Narian, U. and Ulmschneider, P.: 1990, "Chromospheric and Coronal Heating", *Space Sc. Rev.* **54**, 377

[100] Brandt, P. N., Smartt, R. N., and Mauter, H. A.: 1987, "Day-time seeing statistics at Sacramento Peak Observatory", *Astron. Astrophys.* **188**, 163

[101] Scharmer, G., Brown, D., Petterson, L., and Rehn, J.: 1985, "Concepts for the Swedish 50–cm vacuum solar telescope", *Appl. Opt.* **24**, 2558

[102] Scharmer, G. B.: 1989, "High Resolution Granulation Observation from La Palma: Techniques and First Results", in R. J. Rutten and G. Severino (Eds.), *Solar and Stellar Granulation*, NATO ASI Series C 263, Kluwer, Dordrecht, 161

[103] Brandt, P. N., Scharmer, G. B., Ferguson, S. H., Shine, R. A., Tarbell, T. D., and Title, A. M.: 1988, "Vortex Flow in the Solar Photosphere", *Nature* **335**, 238

[104] Tarbell, T., Ferguson, S., Frank, Z., Shine, R., Title, A., and Topka, K.: 1990, "High-Resolution Observations of Emerging Magnetic Fields and Flux Tubes in Active Region Photosphere", in J.-O. Stenflo (Ed.), *The Solar Photosphere: Structure, Convection and Magnetic Fields*, Proceedings IAU Symposium 138 (Kiev), Kluwer, Dordrecht, 147

[105] Title, A. M., Shine, R. A., Tarbell, T. D., Topka, K. P., and Scharmer, G. B.: 1990, "High Resolution Observations of the Photosphere", in J.-O. Stenflo (Ed.), *The Solar Photosphere: Structure, Convection and Magnetic Fields*, Proceedings IAU Symposium 138 (Kiev), Kluwer, Dordrecht, 49

[106] Title, A. M., Topka, K. P., Tarbell, T. D., Schmidt, W., Balke, A. C., and Scharmer, G.: 1992, "On the differences between plage and quiet Sun in the solar photosphere", *Astrophys. J.* **393**, 782

[107] Keller, C. U. and von der Lühe, O.: 1992, "Solar speckle polarimetry", *Astron. Astrophys.* **261**, 321

[108] Beckers, J. M.: 1989, "Improving solar image quality by image selection", in R. J. Rutten and G. Severino (Eds.), *Solar and Stellar Granulation*, NATO ASI Series C 263, Kluwer, Dordrecht, 55

[109] Beckers, J. M.: 1989, "Solar image restoration by adaptive optics", in R. J. Rutten and G. Severino (Eds.), *Solar and Stellar Granulation*, NATO ASI Series C 263, Kluwer, Dordrecht, 43

[110] Worden, S. P.: 1992, "On self-licking ice cream cones", in M. S. Giampapa and J. A. Bookbinder (Eds.), *Seventh Cambridge Workshop on Cool Stars, Stellar Systems and the Sun*, Astron. Soc. Pacific Conf. Series, Vol. 26, 599