SOLAR MICROSCOPY: UNVEILING THE SUN'S BASIC PHYSICAL PROCESSES AT THEIR INTRINSIC SCALES

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ABSTRACT

Many of the basic physical processes on the Sun responsible for solar activity and the Sun's influence on the Earth take place at intrinsic scales that have yet to be observationally resolved. These or similar processes also take place in a variety of other astrophysical systems, but are even further from being resolved. The Sun provides the most promising physical system on which such processes will finally be resolved. We briefly identify some important physical scales and estimate the sizes of solar instruments needed to resolve such scales. Given the very large size of the ideal instrument, we also briefly discuss instrumentation that would have a resolution intermediate between the one currently achievable and that needed to resolve fully the basic processes. This instrumentation could form the core payload of a next-generation solar mission.

Key words: Sun, basic physical processes, high resolution.

1. INTRODUCTION: KEY ISSUES

The Sun's activity and irradiance determine space weather and influence climate on Earth, a fact which is of utmost importance and relevance for mankind and human activities in space. A grand solar science goal is to follow observationally (and to understand) the transport of mass, energy, momentum and magnetic flux from the Sun's interior to its atmosphere and beyond, to the Earth or the outer heliosphere. This transport takes place in many steps and involves many, often complex physical processes.

The experience gained in past solar studies and by previous space missions indicates that understanding the Sun and its global workings requires even more detailed observations, capable of resolving the relevant processes at their intrinsic physical scales. In complex and turbulent physical systems the processes at microscopic and macroscopic scales are intimately coupled. The Sun is such a complex system (in the Sun's case the ion gyroradius or collision free path is about 1 km in the lower atmosphere, and the solar radius is about 700000 km), and it is the only star amenable to close-up observations.

Nature is complex, and even seemingly simple systems such as fluids and plasmas upon closer scrutiny reveal a rich variety of structures and processes. Complexity (with respect to the range of scales, morphology and evolution) is found in many small-scale systems accessible in the laboratory, as well as in the large-scale systems encountered in distant astrophysical environments. Often this complexity is related to turbulence. In solar-system and astrophysical plasmas magnetic fields add a further level of complexity, because the turbulent interactions between the magnetic field and plasma particles cause a wide range of phenomena, both in the laboratory and in nature. Such interactions can in particular lead to the release of copious amounts of energy, which was previously stored in the magnetic field. The magnetic energy may be converted into random thermal energy by plasma heating and directed kinetic energy by particle acceleration, occurring for example in solar flares. Moreover, such complex interactions can produce instabilities (such as those that drive coronal mass ejections) or can be responsible for outflows.

Many of the non-thermal and energetic processes acting in various astrophysical systems have considerable basic similarities (although they may differ in detail). Thus, instabilities caused by complex interactions similar to those found in the solar atmosphere act, e.g., in fusion plasmas and in galactic or accretion disks. Also, outflows are accelerated as jets emanating from Active Galactic Nuclei and as stellar winds from hot coronae of cool stars.

A paramount characteristic that many of these processes have in common is that the spatial and temporal scales at which the basic interactions and fundamental processes take place are much smaller than the scales of the systems themselves. For example, in the solar corona and in stellar coronae the length scales of energy conversion (e.g. in thin electric current sheets or wave dissipation layers) may be of order meters. Similarly, in the solar photosphere the best current MHD simulations indicate that the magnetic field is structured on scales below a few tens of km (which is currently about the limit of the spatial resolution of the numerical simulations). However, the physically relevant scales are set by diffusion and magnetic resistivity and lie at a scale on the order of a kilometer.

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The intrinsic scales of the processes occurring in the atmospheres of cool stars and in other astrophysical systems need to be compared with the spatial resolution currently achievable. Of all the astrophysical systems mentioned above, by far the highest spatial resolution is presently achievable for the Sun, for which, due to its proximity, it is most worthwhile to increase the spatial resolution in future observations. As compared to stars, a major advantage of observing the Sun is its apparent brightness. This is important, because the smaller the features the more likely they are to change over a short time. Hence, high spatial resolution is always coupled with high temporal resolution, which requires a short exposure time, so that even for the Sun we will suffer from low photon fluxes.

On the Sun the highest achievable resolution corresponds to roughly 100 km in the visible (comparable to the barometric scale height, the horizontal photon mean free path, or the diameter of a small flux tube generated by magneto-convection in the photosphere) and 700 km in the ultraviolet (the resolution of the TRACE imagers observing the transition region and corona, where the resolution corresponds to two spatial pixels). The Solar Orbiter (Marsch et al. , 2005) will certainly improve on these values, in particular in the ultraviolet regime (with a planned spatial resolution of 150 km). Yet even with that improvement, which will undoubtedly open up a whole new world, we will still be far from the resolution necessary to study the basic plasma physical processes at their intrinsic scales.

Here we present a brief discussion of the relevant physical scales and new ideas about a possible mission aiming to take a significant step towards resolving these physical scales.

2. FUNDAMENTAL LENGTH SCALES

2.1. Scales in photosphere and chromosphere

When considering the fundamental length scales on the Sun we need to distinguish between different layers in the solar atmosphere. In the photosphere the following length scales play an important role:

- Stratification: pressure and density scale heights are ≈ 100 km. They are set by the gravitational acceleration and the photospheric temperature.
- Convective length scale: ≈ 1000 km. This scale determines the size of convective granules. It is set by the density scale height, the upflow velocity and the requirement of mass conservation.
- Horizontal size of the smallest magnetic features: < 30 km. This scale is obtained from numerical simulations, which show magnetic structures with horizontal extents at around the spatial resolution of the simulations.
- Diffusive length scale: 1–5 km. This determines the width of the boundary of a photospheric magnetic feature (e.g. the thickness of the walls of a photospheric magnetic flux tube).
- Resistive length scale: 1–5 km.
- Horizontal mean free path of photons: ≤ 50 km.

Derivations of many of the above estimates are given by Schüssler (1986). Except for the largest ones, the convective length scale and to a certain extent the density scale height, none of these scales can currently be resolved. A few words to the photon mean free path, whose value is particularly critical since it in principle determines the smallest scales that can be seen without being washed out through the horizontal interchange of photons. The classical value of 50 km is obtained for a plane parallel atmosphere and has often been used to argue that it makes little sense to observe at higher resolution. In a structured atmosphere, however, locations with a much shorter photon mean free path will be found, in particular around flux-tube boundaries, where the height of the optical depth unity surface changes drastically. This has been demonstrated by Bruls and von der Lühe (2001), who carried out 2-D radiative transfer computations in the presence of small-scale magnetic features. In the abstract of their paper they write: “We conclude that the size limit below which photospheric structure cannot be observed due to smoothing radiative transfer effects must lie well below 10 km. A spatial resolution limit for telescopes based on photon mean free path arguments should therefore be abandoned.”

2.2. Scales in the transition region and corona

Some fundamental length scales of importance for the transition region and corona are the:

- Coulomb collisional free path: 1000 km.
- “Resistive” length scale (typical width of current sheets): < 1 km.
- Wave dissipation length scales: 0.1–1 km.
- Widths of loop substructure: < 350 km (size of a TRACE pixel).
- Photon mean free path is irrelevant (since the medium is optically thin), but S/N is a major issue for coronal observations.

There is considerable spectroscopic evidence for fine substructure of coronal magnetic loops (small filling factors of emitting plasma). For example, based on ultraviolet spectra Dere et al. (1987) argued that in the transition zone sub-resolution filaments with typical radii of 3-30 km are present. The upper limit on the size from direct imaging is in contrast quite large, being 350 km as given by the pixel size of the TRACE imager.

Generally, the coronal plasma beta is rather low, $\beta = 0.1$–0.001, so that all particles are strongly magnetized, which means that they are confined by the field and cannot easily cross field lines, yet can move "freely" parallel to them. How ineffective Coulomb collisions are in causing cross-field diffusion becomes obvious when considering an estimate of the Coulomb diffusion coefficient: $D_e = \rho_e^2 \nu_e \approx 1 \mathrm{m}^2 \mathrm{s}^{-1}$, where ρ_e is the electron gyroradius and ν_e the Coulomb collision frequency. Here we assumed an electron Larmor radius, $\rho_e \approx 25$ cm, and collision frequency, $\nu_e \approx 10\,\mathrm{s}^{-1}$, respectively proton gyroradius, $\rho_p \approx 10$ m, for a field of $B \approx 1$ G and electron density of $n_e \approx 10^8 \mathrm{cm}^{-3}$ in the corona.

Given a loop transverse scale of $a \approx 1$ Mm, the cross diffusion time is $t_D = a^2/D \approx 10^{12}$ s. This means it takes ages for an electron to switch its field line by collisional effects. Moreover, even in the corona the collisional free path, $\lambda_c = V_e/\nu_e \approx 1$ Mm, is comparatively large, i.e. of the pixel size of the SOHO imagers and spectrometers. Here V_e is the electron thermal speed. Therefore, it is clear that enhancing the transport requires anomalous processes, which is to say small-scale waves, turbulence, particle drifts and flows, or stochastic fields, to the effect that one may replace ν_e by for example Ω_e, as a typical high frequency being possibly associated with transverse displacements of the electrons across the magnetic field.

Understanding the coronal transport phenomena may finally require to resolve these rather tiny natural scales of kinetic plasma physics. Presently, we are far from being able to do so. In the remainder of this article we will address realistic approaches and feasible future steps to the ultimate goal of resolving the basic processes at their intrinsic scales.

3. A STEP CLOSER TO OBSERVING THE INTRINSIC SCALES: A NEXT GENERATION HIGH RESOLUTION SOLAR SPACE MISSION

The balloon-borne solar observatory, Sunrise (Solanki et al. , 2003), and large telescopes on the ground, like the future 4-m-aperture Advanced Technology Solar Telescope (ATST; Keil et al. 2003), have been proposed for making novel solar observations from the visible to the near infrared. Combined with new developments in adaptive optics such telescopes will significantly reduce the smallest spatial resolution element accessible to observations (in principle from currently 100 km to roughly 25-35 km).

However, to address the complexity of solar radiation in combination with magnetic and plasma processes in the Sun's interior and atmosphere, thereby covering it throughout from the photosphere to the outer corona, is beyond the capabilities of ground-based observatories. Such observations require a multi-wavelength and comprehensive remote-sensing approach, including imagery, spectroscopy, polarimetry and radiometry. The spectrum below the atmospheric cutoff at around 300 nm cannot be observed from the ground, because the Earth's atmosphere is opaque there. Many processes manifest themselves at wavelengths not accessible from the ground, so that the corresponding measurements must be made from spacecraft.

To achieve these aims novel space-based instruments, substantially larger than those currently being built or designed, will be required. In order to resolve 1 km on the Sun at the wavelength of Lyman α requires a 23-m-diameter telescope in Earth orbit. At EUV (Extreme Ultraviolet) wavelengths, the mirror size may in principle be reduced by a factor of 10 relative to the above estimate, but in practice probably a size substantially larger than the one corresponding to the diffraction limit will still be needed in order to get a sufficiently high signal-to-noise ratio in the data.

Therefore, a high resolution solar mission aiming to achieve a resolution of 1 km on the Sun, although a very strong ultimate goal, is very likely beyond the mid-term financial possibilities of space agencies and will pose significant technical problems for its realization.

Consequently, we consider here a mission that has a resolution achievable with meter-class telescopes or smaller, but whose resolution is none-the-less much higher than of other present or planned instruments.

A 1.5 m telescope will give resolution of roughly 15 km at the wavelength of Lyman α. This will represent a 10-fold increase over the already high spatial resolution of Solar Orbiter. As mentioned above, however, even with a filled aperture, such an instrument may have difficulty achieving the S/N ratio needed for a robust analysis at its diffraction limit. Due to the much higher Alfvén speed in the corona than in the photosphere, the demands for shorter exposures are much more stringent when making coronal observations. Note that at a resolution of 15 km and an Alfvén speed of 1000 km s^{-1}, exposures will have to be shorter than than the corresponding wave transit time of 15 ms, in order to avoid image smearing due to solar disturbances.

However, at wavelengths considerably shorter than Lyman α, an instrument of 1.5 m aperture would definitely lead to much higher resolution than possible with any other planned instrument, if the substantial technological challenges can be overcome. One such challenge is to ensure that the main mirror will keep a sufficiently precise figure while being in space exposed to the full heat load produced by the intense solar radiation (1.36 kW m^{-2}).

It appears unlikely that it will be possible to accommodate more than one such instrument on a single space platform in the next 15-20 years. Therefore, clever ways of distributing the light, with as little loss as possible, to post-focus instruments would be worth some thought. A minimum requirement is to have rapid, highest resolution imaging at a selected set of wavelengths. Spectroscopy would also be very exciting with such an instrument, but (as mentioned below) a smaller spectrograph also has the potential of providing significantly new results.

In addition to a large instrument, also smaller instruments are conceivable which could provide fundamental and new information, even if they could only reach a resolution that is still far from the intrinsic physical scales. Three such instruments are mentioned below.

a) A coronal magnetic field mapper.
Besides the routine measurement of the magnetic field in the photosphere, there is a strong scientific need to measure directly the magnetic field in the transition region and entire corona (vector magnetic field mapping). For example, magnetic field measurements in the corona are indispensable for making progress in the understanding of the complex magnetic activity and strong radiative variability of the corona.

A combination of different measurement techniques is needed to achieve this goal. This includes radio and infrared measurements, which already are being successfully carried out, but have their limitations. A significant advance is expected from EUV polarimetric measurements of the Hanle effect in coronal emission lines, supported by field extrapolation from photospheric magnetograms. Novel instrumentation to perform such measurements on spacecraft should be designed and developed.

Such an instrument, even if it had an aperture below a meter and hence a resolution considerably worse than what we propose here, will open a new window into the solar corona. Note, however, that due to the fact that the Hanle signal is only a small fraction of the total intensity, a large aperture is extremely important for such an instrument to obtain a large signal-to-noise ratio. A more detailed description of the aims and the feasibility of such a "Solar Coronal Magnetic Field Mapper" are provided by Solanki et al. in these proceedings.

b) A fast, high-resolution imaging spectrograph.
Although a number of spectrographs are currently flying (SUMER and CDS on SOHO), or will be flying in the coming years (EIS on Solar-B and EUS on Solar Orbiter), they all have or will have their limitations. The spectrometer with the highest spatial resolution by far, EUS on Solar Orbiter, will suffer from a very limited data rate, so that it will not be able to provide full spectra at high cadence, and therefore regular rapid scans of regions on the Sun will not be possible. A concept such as that of RAISE (Rapid Acquisition Imaging Spectrograph) proposed by D. Hassler and co-workers, which allows very rapid spatial scans while providing important spectral information, appears very attractive for the future, in particular if improved to yield a higher spatial resolution.

c) A fast, high-resolution spectral imager.
Another novel and highly promising instrumental concept for chromospheric and coronal studies is the Multi-Order Solar EUV Spectrograph (MOSES) of Kankelborg and Thomas (2001), being tested as a sounding rocket payload. This approach uses a slitless imaging spectrograph operating in a narrow spectral band, with separate imaging detectors at three orders. It can in principle simultaneously provide images of line intensity, Doppler shift and line width, thus allowing high spectral, spatial and temporal resolution to be achieved.

4. CONCLUSION

The quest for resolving physical processes on the Sun and in astrophysical systems at their intrinsic scales will be a major focus for 21st century space science and astrophysics. Among all astrophysical systems, the Sun is the object which will most easily allow us to access these scales. An ultra-high-resolution solar physics space mission would therefore be of great benefit, not just for solar physics but for astrophysics in general. However, even for the Sun, many of the intrinsic physical scales are so much smaller than the spatial resolution which is currently achievable that, realistically, only a mission with an intermediate resolution will be possible. But such a mission appears necessary to make further scientific progress. It would contain a large EUV/FUV telescope of 1-2 m in diameter, and would require resources that would put it in the ESA cornerstone class. We strongly encourage any work leading to a credible definition of such a mission.

REFERENCES

Bruls, J.H.M.J., von der Lühe, O., 2001, A&A 366, 281

Dere, K. P., Bartoe, J.-D. F., Brueckner, G. E., Cook, J. W., & Socker, D. G., 1987, Solar Phys., 114, 223

Kankelborg, C. C., & Thomas, R. J., 2001, Proc. SPIE, 4498, 16

Keil, S. L., et al., 2003, Proc. SPIE, 4853, 240

Schüssler, M., 1986, Small Scale Magnetic Flux Concentrations in the Solar Photosphere (Eds.): W. Deinzer, M. Knölker, and H.H. Voigt, Göttingen: Vandenhoeck & Ruprecht, 103

Solanki, S. K. & the SUNRISE Team, 2003, in: Innovative Telescopes and Instrumentation for Solar Astrophysics, Ed.: S. L. Keil, S. V. Avakyan, Proc. SPIE, 4853, 129

Marsch, E., Marsden, R., Harrison, R., Wimmer-Schweingruber, R., & Fleck, B., 2005, Solar Orbiter – mission profile, main goals and present status, 2005, Adv. Space. Res., 36, 1360