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THE LOWER POLAR ATMOSPHERE AND THE SOLAR DYNAMO: PERSPECTIVES FOR THE SOLAR ORBITER

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ABSTRACT

The Solar Orbiter will, by flying out of the ecliptic, allow its battery of remote-sensing instruments to focus on the Sun's polar regions, providing solar physicists with a unique opportunity to study this enigmatic part of the Sun for the first time. Some of the scientific questions which may be addressed by the Solar Orbiter in its out of the Ecliptic phase are presented here, with emphasis being placed on those related to the lower solar atmosphere and the solar interior.

Key words: Sun: photosphere - Sun: chromosphere - Sun: magnetic field - solar dynamo - solar poles.

1. INTRODUCTION

The Sun provides us with an excellent opportunity to study physical processes at scales close to those on which they occur. Examples are magnetoconvection, non-radial oscillations, magnetic structuring of the atmosphere and chromospheric and coronal heating. The Sun is also sufficiently bright that there are enough photons to observe these phenomena at the relevant time scales. These unique properties make the Sun an attractive subject of investigation and have helped to provide the many impulses radiating from solar physics to the rest of astrophysics.

Stars, however, are numerous and varied, whereas we only have a single Sun to study. In reality, we are even more restricted, because so far we have only been able to observe the Sun from the ecliptic, i.e. from near its equator. For stars this limitation does not hold and at least some of the differences in property from one cool star to the next could be due to the different inclinations of their rotation axes relative to the observer (e.g. Schatten 1993).

The Solar Orbiter will for the first time allow us to observe the Sun from out of the ecliptic. This novel vantage point gives us the opportunity to tackle a set of questions that cannot otherwise be answered. In the following I shall give a brief introduction to some of these questions and how the Solar Orbiter can help to answer them. It will become clear that for some of these answers simultaneous observations with an Earth-orbiting spacecraft such as the Solar Dynamics Observatory (SDO) are essential. This is important to bear in mind when considering the timing for the Solar Orbiter.

2. THE POLAR MAGNETIC FIELD

When studying the polar magnetic field of the Sun from the ecliptic using the Zeeman effect we face three problems. Firstly, at least for observations in the visible spectral range, the longitudinal Zeeman effect gives by far the largest signal from the typical strong fields (sunspots, magnetic elements). For this effect the sensitivity to magnetic fields scales roughly as $\cos\gamma$, where γ is the angle between the magnetic vector and the line-of-sight (LOS). Since the strong-field magnetic features are on average vertical in the photosphere $\gamma \approx \theta$, where θ is the heliocentric angle. For the pole we thus find that the signal is reduced by a factor of $cos\ 83° = 0.12$ relative to the equator due to this effect alone. This factor is valid for the most optimistic geometry, namely when the studied pole is pointing towards Earth by the maximum amount. When observing from Solar Orbiter θ at the pole can decrease to 52° (near the end of the extended mission), so that $\cos\theta = 0.61$ can be reached. This implies a 5-fold gain in sensitivity relative to the best results possible from the ecliptic.

The second problem is that due to foreshortening we lose spatial resolution. The impact of this effect is made worse by the fact that opposite magnetic polarities seemingly cancel out if they come to lie in the same spatial resolution element due to spatial smearing. This can significantly reduce the measured signal and distort it in favour of large unipolar regions. The reduction in the magnetic signal affects estimates of the Sun's total magnetic flux and is the limiting factor hindering us from determining,

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Proceedings of "Solar Encounter: The First Solar Orbiter Workshop", Puerto de la Cruz, Tenerife, Spain, 14 – 18 May 2001 (ESA SP-493, September 2001) e.g. the magnetic structure at the footpoints of polar plumes. Thus one important quantity which can only be properly determined from a location above the pole is the total magnetic flux at solar activity minimum. At that time a significant fraction of the solar magnetic flux passes through the polar caps. Due to the reduced sensitivity of the longitudinal Zeeman effect and the foreshortening near the pole, when observed from the ecliptic, we generally only see the stronger elements of flux in larger unipolar patches. The flux in regions of mixed-polarity field is greatly suppressed in the observations. This not only suppresses the measured total magnetic flux, but also the ratio of flux in the two magnetic polarities, which plays a role in determining the properties of coronal holes etc.

The solar surface area sampled by a pixel of a detector is proportional to $\cos\theta$. This means that a $2'' \times 2''$ pixel of the Michelson-Doppler Interferometer (MDI) onboard SOHO samples an area corresponding to at least $16'' \times 2''$ at the solar pole, while a $0.5'' \times 0.5''$ pixel of the planned SDO magnetograph effectively samples $5'' \times 0.5''$. Again, by just leaving the ecliptic the Solar Orbiter gains a factor of roughly 5 compared to a similar instrument in the ecliptic. For the instruments on the strawman payload this amounts to pixels sampling solar surface area as small as 35 × 70 km at the pole! This is an order of magnitude better than achievable, e.g., with SDO.

A third reason why the Solar Orbiter is expected to reveal the Sun's polar magnetic field in unprecedented detail lies in the filamented nature of the photospheric magnetic field. As was first pointed out by Van Ballegooijen (1985), the Stokes V signal (net circular polarization, i.e. the signal produced by the longitudinal Zeeman effect) due to a thin flux tube drops much more rapidly than $\cos\gamma$, the result expected for a homogeneous field. Although the magnitude of this effect is probably not so large as originally thought it cannot be neglected for small tubes (Solanki et al. 1998). Hence the improvement in Zeeman signal achieved when going out of the ecliptic may even be larger than the factor of 5 deduced from assuming the signal to be proportional to its $\cos\gamma$.

3. THE SOLAR DYNAMO

The magnetic field of the Sun is thought to be produced by a dynamo residing at the interface between the convection zone and the radiative core. Schematically, this dynamo converts poloidal into toroidal field and back again in the course of the 11-year activity cycle. During the toroidal phase of the cycle the field emerges from the solar interior in the form of loops. Depending on the amount of flux in a loop it results in an active region (near the equator in the so-called activity belts) or in a smaller ephemeral active region (present also outside the activity belts, i.e. both at low and high latitudes). Alternatively, the ephemeral regions may be the result of a different dynamo process.

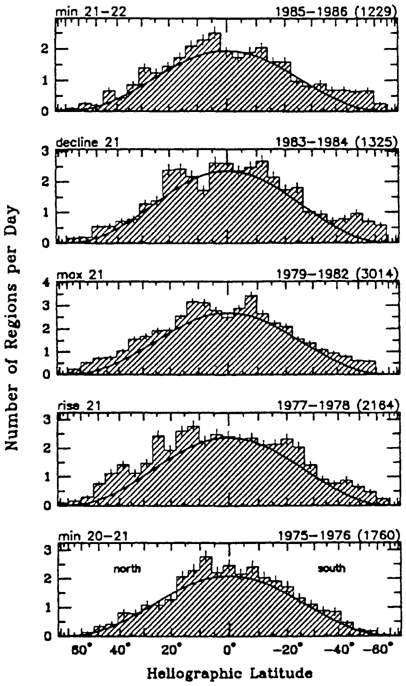

Figure 1. Distribution of ephemeral regions in heliospheric latitude ϕ during five phases of cycle 21. The hatched histograms in equal surface area bins in $\sin\phi$ *are the data. The visibility function is shown by the solid curves (from Harvey 1993).*

Most of the magnetic flux emerges in the ephemeral regions. It is of interest for at least two reasons to know the latitudinal distribution of ephemeral regions, in particular the rate at which they emerge close to the pole. This question is firstly of interest since according to theory the distribution of flux–emergence latitude and properties of the emerging bipolar regions (e.g. their orientations) gives information on the sub-surface structure of the field (e.g. D'Silva et al. 1993, Schüssler et al. 1994), information that cannot otherwise be obtained.

Such a measurement could also help to answer another, even more fundamental question: Are the ephemeral regions the product of a local dynamo acting in the near-surface layers of the convection zone or are they produced by the main dynamo residing in the overshoot layer below the convection zone? In the second case they are the smaller counterparts of the active regions. If there is a significant decrease in the number density of ephemeral regions close to the pole this would settle the question in favour of the main dynamo. The distribution of the number of ephemeral regions with latitude is plotted in Fig. 1 (histograms), taken from Harvey (1993). The number density does decrease rather rapidly towards higher latitudes. However, the comparison with the thick smooth curves, which describe the visibility function, reveals that the present data are rather inconclusive. When studying the Sun from a latitude larger than 30° the visibility function will be non-zero right up to the poles, so that the Solar Orbiter will be able to address this question with far more precision.

It may of course be that the local dynamo is not responsible for ephemeral active regions, but produces even smaller bipolar regions, such as intranetwork fields.

A similar, although more difficult, study of intranetwork fields could address the same question for them. Thus the Solar Orbiter could determine which types of bipolar magnetic regions are produced by the main dynamo and thus set limits on the flux produced by a local dynamo.

For such a study a high sensitivity full-disk magnetograph would be the ideal instrument (noise level $10^{-3}I_c$ for ephemeral regions, $10^{-4}I_c$ for intranetwork field required), with 0.5-2$''$ pixels and an image rate of 1 frame per h for ephemeral regions and 1 frame per 5 min for intranetwork fields.

Another question, which can only be addressed by using observations made from out of the ecliptic regards the geometric distribution of the field near the pole. Depending on the strength of the meridional flow, the diffusion of magnetic flux across the solar surface and the differential rotation, the field will be peaked more narrowly or broadly at the solar poles. By comparing the results of models (such as those of Sheeley 1992) with the observations provided by Solar Orbiter it should be possible to constrain these parameters and processes, which play an important role in dynamo theory.

One relatively new, successful and highly promising class of dynamo models are the so-called flux-transport dynamos first considered by Choudhuri et al. (1995), and further developed by e.g., Charbonneau et al. (1999), Dikpati & Gilman (2001), Durney (1995, 1996). For example, these are so far the only dynamo models that explain something as basic as polarity selection, i.e. that the dipole is the preferred magnetic configuration of the Sun.

The meridional flow, a steady flow of matter from the equator to the poles at a rate of 20-50 m s^{-1} at the solar surface (and a hypothesized return-flow towards the equator near the bottom of the convection zone) plays a central role in this type of dynamo. Together with the differential rotation the strength and latitudinal dependence of the flow not only determines the distribution of the magnetic flux on the solar surface, but also the length of the activity cycle.

Near the solar poles both the form of the differential rotation and of the meridional flow are poorly known. At the solar surface the meridional flow has been followed to near the poles (Hathaway 1996) and the rotation of the Sun near the poles has also been measured, although different results are obtained depending on the technique used (Stenflo 1990, Snodgrass 1983, Snodgrass & Ulrich 1990). Knowledge of the meridional flow (Braun & Fan 1998, Giles et al. 1997) and the differential rotation (e.g. Schou et al. 1998, Gizon private communication 2001) below the solar surface are restricted to latitudes below 60-75°, however. From a vantage point of 30-38° in heliographic latitude the Solar Orbiter will be able to fill the gaps in our knowledge near the solar poles.

Required are local helioseismic measurements (e.g. time-distance heliseismology) during the phases of largest heliographic latitude. Relatively short measurement periods of the order of a day are needed to determine the sub-surface structure of differential rotation and meridional flow right to the pole.

Flux transport dynamos also make definite predictions regarding the concentration of magnetic flux at the solar surface around the poles. Thus for a given form of the meridional circulation Choudhuri et al. (1995) find a strong concentration of poloidal magnetic field very close to the poles. The development of both the toroidal and poloidal magnetic field with time is illustrated in Fig. 2. By supplementing the velocity measurements by magnetograms it will be possible to determine all the components (differential rotation, meridional circulation and poloidal field) and thus to stringently test dynamo models.

4. SOLAR IRRADIANCE

Changes in solar irradiance have attracted considerable attention in connection with their possible influence on climate (cf. Friis-Christensen et al. 2000). In addition to the uninterrupted monitoring of irradiance, best carried out along the Sun-Earth line observations are needed which pinpoint the physical causes of irradiance variations. This need arises from the fact that direct observations only cover 2 solar cycles so far, cycles that are relatively similar to each other. The influence of solar irradiance variations on the Earth's climate is expected to be most significant on longer time scales, however (e.g. due to the large heat capacity of the oceans), so that models are needed to deduce past irradiance variations and to predict future variations.

Solar Orbiter will contribute significantly to deducing the physics underlying solar irradiance variability by dint of observing the irradiance and the magnetic field from other vantage points than the Sun-Earth line-of-sight. See also the paper by Schmutz et al. (2001).

4.1. Solar luminosity variations

Although the changes in the brightness of the Sun as seen from the direction of the Earth are well documented, there is considerable uncertainty about the

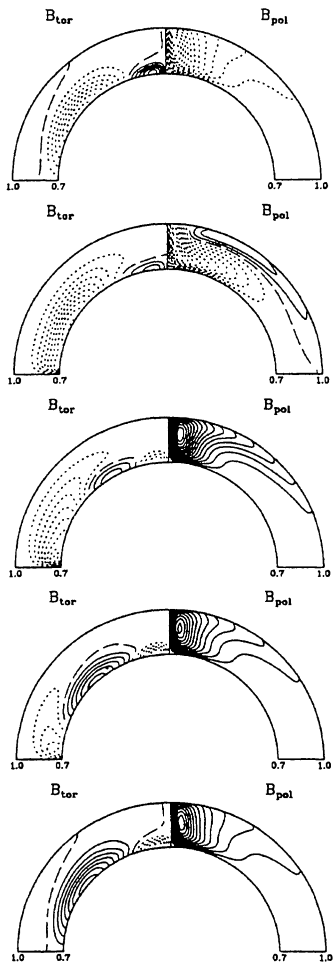

Figure 2. Time evolution of field configurations in a meridional cut of the convection zone. Contour lines of the toroidal field on the left-hand side, poloidal field lines are drawn on the right-hand side of the panels. Note the increasing concentration of the poloidal field at the poles with time (from Choudhuri et al. 1995).

amount by which the total power radiated by the Sun integrated over all directions varies with time. This has partly to do with the fact that we only see one face of the Sun at a time. Solar Orbiter will help resolve this problem by measuring the magnetic field and the irradiance on the hidden side of the Sun. In this way it will be able to determining whether brightenings in one hemisphere are accomparied, e.g., by darkenings in the other.

Of far greater importance are the poles. It is unknown by how much the irradiance changes in directions pointing out of the ecliptic. The comparison with Sun-like stars and model calculations indicates that this variation may be significantly (a factor of 2-4) larger than in the ecliptic (Lockwood et al. 1992, Schatten 1993). Other models, however, indicate that brightness variations seen from above the ecliptic should be enhanced by a much smaller amount (Radick et al. 1998, Knaack et al. 2001). We can distinguish between these different models only by observing the Sun from above the ecliptic using a radiometer and a magnetograph.

Resolving this question is important because of the large variability of other 'Sun-like' stars. If their excess variability turns out not to be due to the inclination of the rotation axis of the stars relative to the observer, it would imply that the Sun is currently in a state of abnormally low irradiance variability, and could revert to a 'normal' i.e. more variable state in the future. This would have significant implications for the Earth's climate. Hence this question needs to be addressed with high priority not only for astronomical reasons.

4.2. Physical causes of irradiance variations

Another major open question concerns the solar irradiance changes. Are they due to changes in the surface magnetic field or are they due to processes acting in the solar interior, e.g. variations in convection, or in the magnetic field at the bottom of the convection zone). This question can in principle be tested by reconstructing the irradiance using magnetograms and the center-to-limb variation of the intensity in sunspots, in faculae and in the network (Fligge et al. 2000a, b).

The weakest link in the chain of reasoning is the inaccurate knowledge of the CLV of the facular and network contrast. The problem is that the contrast depends strongly on the magnetic filling factor, but since only the longitudinal component of the field is sampled near the limb this quantity is not so well known near there. Simple solutions, such as employing B/μ (where $\mu = \cos\theta$ and θ is the heliocentric angle) as has been done by, e.g. Topka et al. (1997), Ortiz et al. (2001), are not sufficiently precise (e.g. Van Ballegooijen 1985, Solanki et al. 1998). Following a region across the disk is also only of limited value since faculae and the network evolve too rapidly.

The only way to resolve this problem is to observe the brightness and the magnetic field of the same region on the Sun from different directions. Thus, data from a magnetograph in Earth orbit (e.g. on SDO) could be combined with data from the Solar Orbiter, so that one would simultaneously measure the magnetic filling factor and the brightness at two different values of μ. By choosing the part of the solar surface such that one of the pair of instruments sees it at chose to $\mu = 1$ the true CLV of the facular and network contrast can be determined.

Required is a magnetograph/visible-light imager on the Solar Orbiter. The planned high-resolution instrument will provide very high-quality data of this

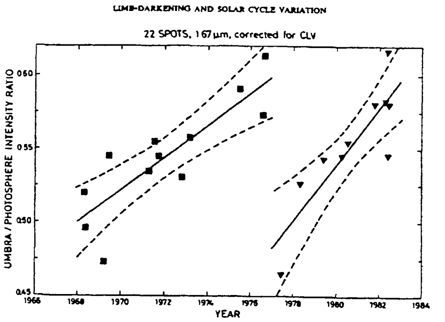

Figure 3. Umbra/photosphere intensity ratio at 1.67μm as corrected for center-limb variation (CLV) plotted as function of time. Observations cover cycle 20 (squares) and the first part of cycle 21 (triangles). All large sunspots observed during good seeing conditions are included. Least squares regression lines are given, together with theit 95% confidence limits (from Albregtsen et al. 1984).

type. To facilitate such observations, as well as to allow magnetograms of different parts of the Sun to be interpreted together it s necessary that either the Solar Orbiter and SDO obtain their magnetograms in the same spectral line, or that some observations of the same solar region be made by both missions for intercalibration purposes when Solar Orbiter is close to the Sun-Earth line. Note that there is no earlier opportunity for carrying out such measurements since the STEREO (Solar Terrestrial Relations Observatory) spacecraft will not carry a magnetograph.

5. SUNSPOT PHYSICS

Although sunspots are definitely a low-latitude phenomenon, the Solar Orbiter in its out-of-the-ecliptic phase can help resolve an intriguing question concerning them. One of the most puzzling observations related to sunspots is the change in umbral brightness over the solar cycle (Albregtsen & Maltby 1978), with the umbrae of sunspots formed later in the cycle being brighter than the umbrae of those formed earlier. One explanation for this effect, which is illustrated in Fig. 3, may be related to the fact that the latitude at which sunspots appear also decreases with the solar cycle. Thus the cycle variation may simply be an artefact of the incomplete removal of the CLV of the sunspot contrast. Albregtsen et al. (1984) have argued against this on statistical grounds; the correlation with cycle phase is somewhat tighter than with limb distance. A more direct test, as could be provided by the Solar Orbiter when outside the ecliptic is needed.

It would be sufficient for the Solar Orbiter to observe from a latitude of roughly 30° sunspots of the old and of the new cycle near the minimum of solar activity. At this phase of the cycle the spots from the old cycle are at low latitude and, according to Albregtsen & Maltby (1978), warmer, while the spots belonging to the new cycle lie approximately 30 degrees from the equator and are apparently cooler. Solar Orbiter can easily check if the apparent change in brightness with the cycle is real or a CLV effect. Whereas from the ecliptic sunspots of the new cycle are closer to the limb, from the out-of-ecliptic vantage point of the Solar Orbiter the situation is reversed, with the spots from the new cycle lying closer to the limb. Hence, it will clearly and easily be possible to disentangle solar cycle from limp distance effects.

To carry out such an observation the point-spread-function of the Solar Orbiter's VIM would need to be known to high accuracy, in particular the stray light. It is thus important to carry out the necessary calibrations.

6. POLAR CORONAL HOLES

Ulysses observations indicate that the polar coronal holes present at solar minimum are different from those at lower latitudes, seen mainly close to activity maximum. E.g., in interplanetary space the speed of the solar wind emanating from the polar holes during sunspot minimum is higher than the speed of the wind from low-latitude holes around activity maximum (Woch private communication 2001). These findings are corroborated by recent SOHO obserations (Miralles et al. 2001).

During the fast latitude scan of 1994/1995 Ulysses sampled both holes at nearly the same phase of the solar cycle. At that time the magnetic field (when projected onto a constant radial distance from the Sun) did not differ greatly over the north and south solar poles (e.g. Forsyth et al. 1996). However, the 0^{+7} to 0^{+6} number ratio seem to be significantly different between the poles (von Steiger 1998, Woch private communication 2001). This ratio is a measure for the freezing-in temperature, which is related to the electron temperature in the corona at 1-2 solar radii above the solar surface. The difference in ratio implies a difference in this temperature of roughly 10 to 20% between the 2 holes, with the north polar hole being cooler. Possibly related to that is a slightly higher wind speed observed in the northern coronal hole (McComas et al. 2000). It is rather surprising that these differences are not reflected in the heliospheric magnetic field. There is some suggestion of a few % difference in magnetic field strength, but it cannot be ruled out that this isn't due to residual errors in converting the measured values to a constant radius.

We must recall, however, that by the distance of Ulysses only the global bipolar component of the field survives, with all the higher order structures having decayed away well before the Alfvèn radius (since after that the wind dominates and, e.g., a residual quadropolar component would be visible as a corresponding asymmetry between the heliospheric magnetic field of the two poles). Since the Alfvèn radius lies at 10-30$R_\odot$, the freezing-in temperature samples gas far closer to the solar surface, which may be affected by higher order magnetic multipoles. It is therefore necessary to have a good knowledge of the polar magnetic field distributions in order to resolve this question. However, only Solar Orbiter, by going to higher latitudes can provide magnetograms with the sensitivity and spatial resolution required to detect both magnetic polarities near the pole. Furthermore, it will resolve the still existing ambiguities between hemispheric asymmetries and solar cycle effects.

7. DEPENDENCE OF CONVECTION ON LATITUDE

The solar rotation through the Coriolis force also influences solar convection, with the expected effect being larger for larger convection cells. Hence, we expect the largest easily detectable convection cells, supergranules, to differ somewhat between the equator and the poles. The effect of the Coriolis force is seen rather clearly in sunspot super-penumbrae recorded in H_α, which exhibit a strongly spiral structure (e.g. Peter 1996). Other causes for supergranules to exhibit a latitude dependence in properties (e.g. interaction with meridional flow, zonal flows or differential rotation) are also conceivable.

However, whether the properties of supergranules are really latitude dependent is not known. The problem, once more, is that properties of super granules near the poles are difficult to determine from current data, mainly due to the foreshortening.

The Solar Orbiter, by dint of the factor of 5 reduced foreshortening, will allow the properties of the supergranules (and also of the granules) to be determined with far greater accuracy than currently possible. Thus it will hopefully be able to detect differences between supergranules at different latitudes.

8. EXPLOSIVE EVENTS

Explosive events are short-lived, localized extreme broadenings of transition region spectral lines (e.g. Brueckner & Bartoe 1983, Dere et al. 1989). One model for such events is based on small-scale magnetic reconnection and observations made with the SUMER instrument; Innes et al. (1997) provide support for this hypothesis. They reveal a change of the wavelength of the line as one spatially scans over the event, changing from an extreme blue shift, via a symmetric broadening to an extreme red shift within a few arc secs. This has been interpreted in terms of reconnection jets pointing in opposite directions away from the point of magnetic reconnection. According to this model the jets are relatively narrow beams of plasma.

Other models are also conceivable. One such scenario, which also can reproduce the SUMER observations, is the unwinding of a twisted flux rope. Magnetic reconnection at possibly quite a distant location along a flux rope could lead to its relaxation, accompanied by a sudden unwinding. Again, a signal somewhat similar to that observed by Innes et al. (1997) may be produced, with blue, respectively red shifts dominating at the two sides of the flux tube and a combination of them at the center if the tube is not resolved. In this case, however, the same signal is seen in all directions in the plane perpendicular to the flux-tube axis.

This difference in geometry between the 2 scenarios can be used to distinguish between them by observing the same explosive events on the Sun from 2 spacecraft with different lines of sight. Statistically the 2 spacecraft should find the number of events which both of them can recognize to drop, as the difference between the angles at which they observe them increases. However, this drop could be considerably more rapid in the first case than for the second.

Such an observation does not require the Solar Orbiter to be at high latitudes, but does assume that high-resolution spectrometers capable of resolving the profiles of EUV emission lines are flown not only on Solar Orbiter but also on an Earth orbiting spacecraft flying at the same time.

9. CONCLUSION

The main aim of this paper is to give a flavour of the richness of the science possible from the Solar Orbiter once it leaves the ecliptic. A number of highly interesting topics that would fit into this paper here have not been dealt with, including the physics of prominences, coronal loops and the like. These topics are partly covered by Antonucci (these proceedings). On the other hand, some of the topics touched upon here do not strictly require the Solar Orbiter to leave the ecliptic, relying more strongly on parallel observations between Solar Orbiter and a spacecraft in Earth orbit (cf. Lites, these proceedings).

However, I am convinced that the present topics, in particular the more concrete examples, are far from exhaustive and that new and exciting possibilities for doing science during the out-of-ecliptic phase of the Solar Orbiter will continue to be uncovered.

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