Mem. S.A.It. Vol. 84, 396

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Scientific synergy between Solar Orbiter and other new observatories

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Abstract. With previously unavailable observational capabilities provided by a suite of in-situ and remote-sensing instruments in a unique orbit, the Solar Orbiter mission promises to deliver ground-breaking science. At the same time, its challenging 'deep space' trajectory also imposes constraints, e.g. on the total volume of science data that can be downlinked per orbit. This contribution highlights the science goals of Solar Orbiter and addresses the scientific synergy between this joint ESA/NASA mission and other new space- and ground-based observatories, which will play a key role in maximizing the science return of Solar Orbiter.

Key words. Sun – Instrumentation – Techniques

1. Introduction

With a suite of in-situ and remote-sensing instruments and its inner-heliospheric mission design, Solar Orbiter will address the central question of heliophysics: How does the Sun create and control the heliosphere? This primary, overarching scientific objective can be expanded into four interrelated top-level scientific questions that will be addressed by Solar Orbiter:

- What drives the solar wind and where does the coronal magnetic field originate from?
- How do solar transients drive heliospheric variability?
- How do solar eruptions produce energetic particle radiation that fills the heliosphere?
- How does the solar dynamo work and drive connections between the Sun and the heliosphere?

These questions represent fundamental challenges in solar and heliospheric physics today. By addressing them, Solar Orbiter is expected to make major advances in our understanding of how the inner solar system works and is driven by solar activity. To answer these questions, it is essential to make in-situ measurements of the solar wind plasma, fields, waves, and energetic particles close enough to the Sun that they are still relatively pristine and have not had their properties modified by subsequent transport and propagation processes. This is one of the fundamental drivers for the Solar Orbiter mission, which will approach the Sun to as close as 0.28 AU.

Relating these in-situ measurements back to their source regions and structures on

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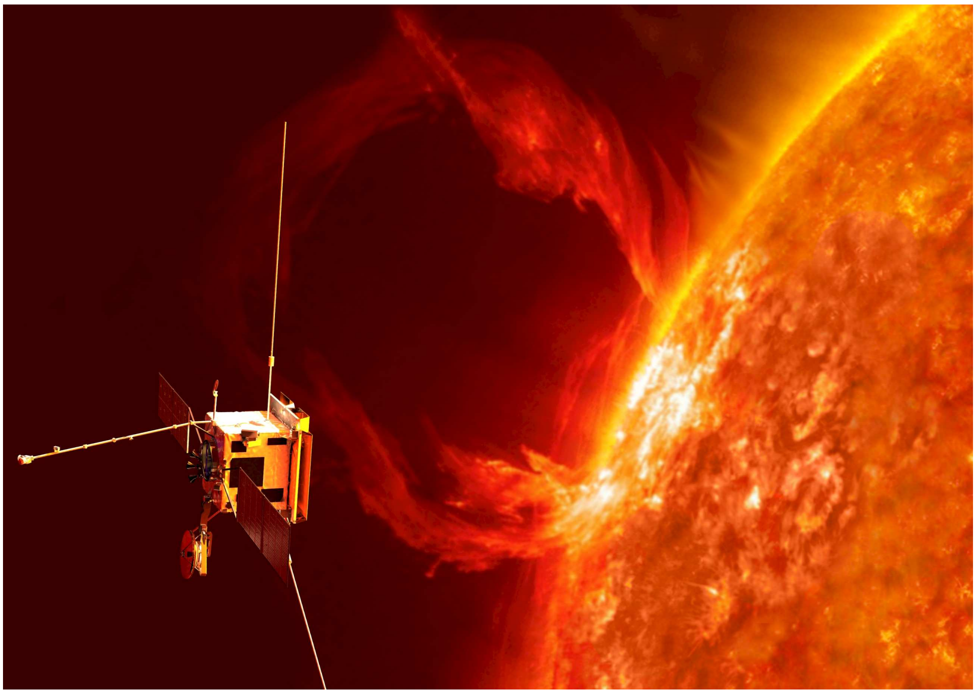

Fig. 1. Solar Orbiter will explore the Sun-Heliosphere connection.

the Sun requires simultaneous, high-resolution imaging and spectroscopic observations of the Sun in and out of the ecliptic plane. The resulting combination of in-situ and remote-sensing instruments on the same spacecraft, together with the new, inner-heliospheric perspective, distinguishes Solar Orbiter (Figure 1) from all previous and current missions, enabling science which can be achieved in no other way.

Even more so than for previous solar missions, Solar Orbiter's science return will benefit from coordinated observations with other missions, e.g. NASA's Solar Probe Plus, as well as ground-based observations, e.g. with the future Advanced Technology Solar Telescope (ATST).

In this paper, we will first describe the payload and mission design of Solar Orbiter and then highlight synergies between Solar Orbiter and other new missions (Solar Probe Plus and Solar-C) and ground-based observatories (ATST). For a more detailed overview overview of the Solar Orbiter mission, the reader is referred to Müller et al. (2012).

2. Scientific payload

The scientific payload elements of Solar Orbiter will be provided by ESA member states, NASA and ESA and have been selected and funded through a competitive selection process. These are:

The in-situ instruments:

- The Energetic Particle Detector (EPD) experiment (J. Rodriguez-Pacheco, PI, Spain) will measure the properties of suprathermal ions and energetic particles in the energy range of a few keV/n to relativistic electrons and high-energy ions (100 MeV/n protons, 200 MeV/n heavy ions).
- The Magnetometer (MAG) experiment (T.S. Horbury, PI, UK) will provide de-

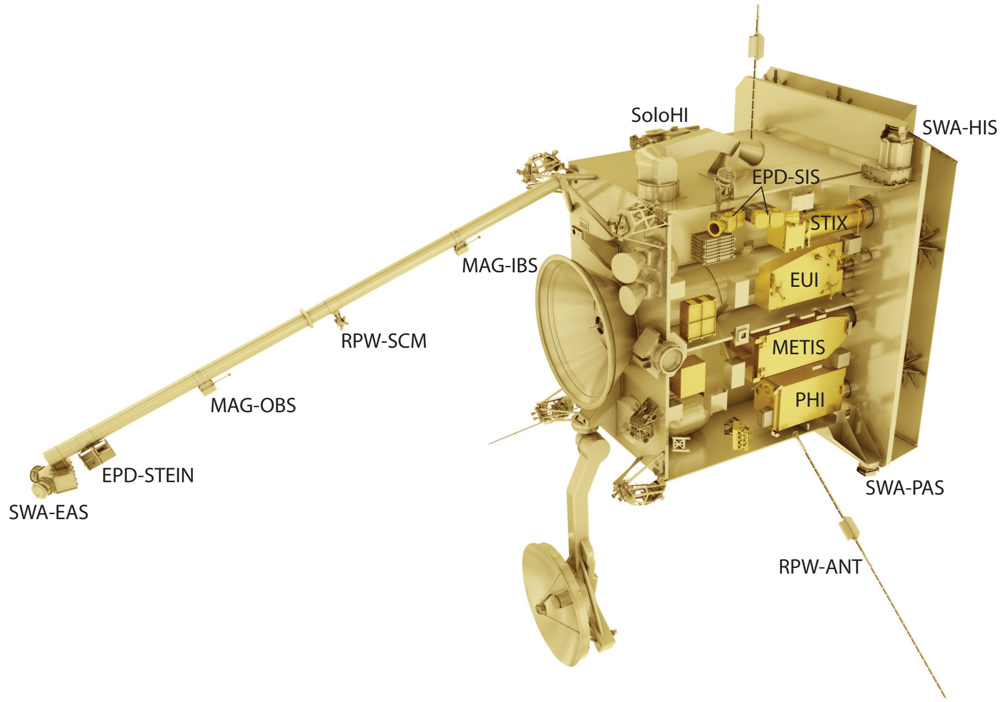

Fig. 2. Payload accommodation onboard Solar Orbiter. In this illustration, one side wall has been removed to expose the remote-sensing instruments mounted on the payload panel. The SPICE instrument (not visible) is mounted to the top panel from below.

tailed in-situ measurements of the heliospheric magnetic field.

- The Radio and Plasma Waves (RPW) experiment (M. Maksimovic, PI, France) will measure magnetic and electric fields at high time resolution and determine the characteristics of electromagnetic and electrostatic waves in the solar wind from almost DC to 20 MHz.
- The Solar Wind Analyser (SWA) instrument suite (C.J. Owen, PI, UK) will fully characterize the major constituents of the solar wind plasma (protons, α particles, electrons, heavy ions) between 0.28 and 1.2 AU.

The remote-sensing instruments:

- The Extreme Ultraviolet Imager (EUI, P. Rochus, PI, Belgium) will provide image sequences of the solar atmospheric layers from the chromosphere into the corona.
- The Multi Element Telescope for Imaging and Spectroscopy (METIS) Coronagraph (E. Antonucci, PI, Italy) will perform broad-band and polarized imaging of the visible K-corona and narrow-band imaging of the UV corona.
- The Polarimetric and Helioseismic Imager (PHI, S.K. Solanki, PI, Germany) will provide high-resolution and full-disk measurements of the photospheric vector magnetic field and line-of-sight velocity as well as the continuum intensity in the visible wavelength range.
- The Solar Orbiter Heliospheric Imager (SoloHI, R.A. Howard, PI, USA) will image both the quasi-steady flow and transient disturbances in the solar wind over a wide field-of-view by observing visible sunlight scattered by solar wind electrons.

- A European-lead extreme ultraviolet imaging spectrograph (SPICE) with contributions from ESA member states and ESA. This instrument will remotely characterize plasma properties of regions at and near the Sun.
- The Spectrometer/Telescope for Imaging X-rays (STIX) (S. Krucker, PI, Switzerland) provides imaging spectroscopy of solar thermal and non-thermal X-ray emission from $\sim 4 - 150$ keV.

The accommodation of the science payload onboard the spacecraft is illustrated in Figure 2. A detailed description of the payload elements, as well as traceability matrices of the science goals are given in Marsden & Müller (2011).

2.1. Mission design

The baseline mission is scheduled to start in January 2017 with a launch on a NASA-provided launch vehicle from Cape Canaveral, which will place the spacecraft on a ballistic trajectory that will be combined with planetary gravity assist maneuvers (GAM) at Earth and Venus (Figure 3). The second Venus GAM places the spacecraft into a 4:3 resonant orbit with Venus at a perihelion radius of 0.284 AU. The first perihelion at this close distance to the Sun is reached 3.5 years after launch. This orbit is the start of the sequence of resonances (4:3-4:3-3:2-5:3) that is used to raise gradually the solar inclination angle at each Venus GAM (Figure 4). The resulting operational orbit has a period of 168 days during the nominal mission with a minimum perihelion radius of 0.28 AU. The end of the nominal mission occurs 7 years after launch, when the orbit inclination relative to the solar equator reaches 25°. The inclination may be further increased during an extended mission phase using additional Venus GAMs, to reach a maximum of 34° for the January 2017 baseline and 36° for a launch in March 2017.

3. Science operations

One of the strengths of the Solar Orbiter mission is the synergy between in-situ and remote-sensing observations, and each science objective requires coordinated observations between several in-situ and remote-sensing instruments. Another unique aspect of Solar Orbiter, in contrast to near-Earth observatory missions like SOHO, is that Solar Orbiter will operate much like a planetary encounter mission, with the main scientific activity and planning taking place during the near-Sun encounter part of each orbit. Specifically, observations with the remote-sensing instruments will be organized into three 10-day intervals (so-called remote-sensing windows) centered around perihelion and either maximum latitude or maximum corotation passages. As a baseline, the in-situ instruments will operate continuously during normal mission operations. From a science operations standpoint, another important aspect of this mission is that every science orbit is different, with different orbital characteristics. Science and operations planning for each orbit is therefore critical, with specific orbits expected to be dedicated to specific science problems. This will be similar to what has been used successfully in the ESA/NASA SOHO mission's Joint Observation Programs (JOPs).

As an example, Figure 5 illustrates the first orbit of Solar Orbiter's nominal mission phase for a January 2017 launch. The three nominal 10-day windows during which both the remote-sensing and in-situ instruments will operate are highlighted in color. It can be seen that the remote-sensing windows centered around maximal northern latitude and perihelion overlap. In cases like this, the observing windows will be adjusted to yield either one contiguous 20-day window or several shorter non-overlapping windows, depending on the science goals for the particular orbit. The plot in the bottom right panel shows the Stonyhurst heliographic longitude of Solar Orbiter as a function of time. The origin of the Stonyhurst heliographic coordinate system is at the intersection of the solar equator and the central meridian as seen from Earth. Thus, the coordinate system remains fixed with respect to Earth, while the Sun rotates underneath it, and the longitude increases towards the Sun's West limb (Thompson 2006). The plot shows that the sub-spacecraft point on the Sun's surface,

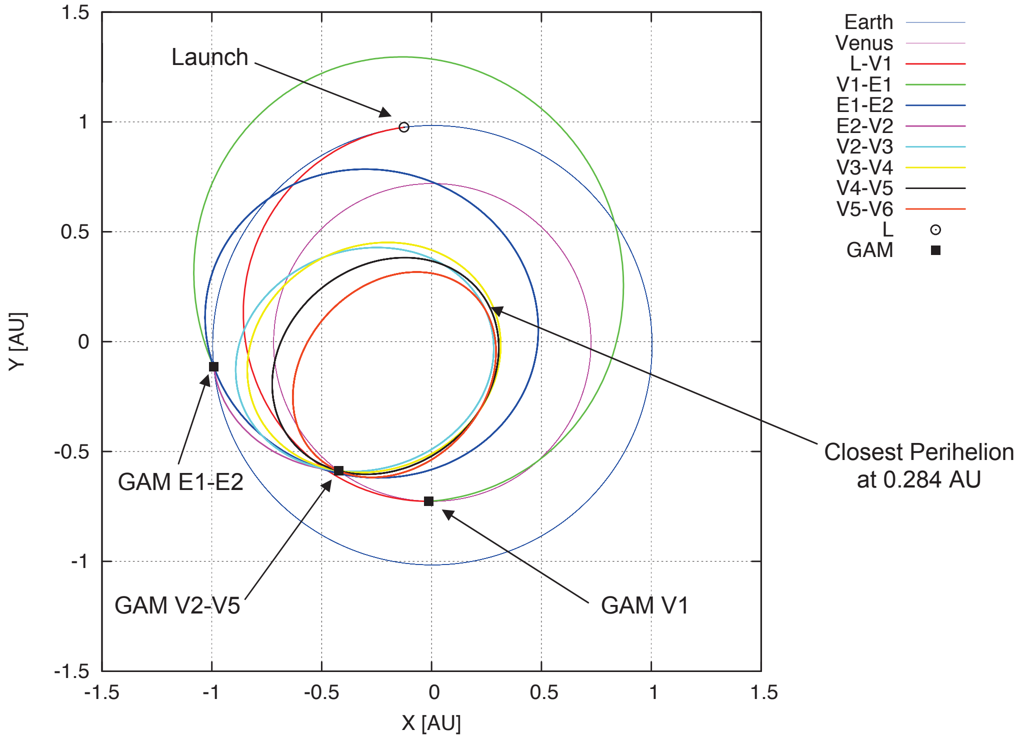

Fig. 3. Solar Orbiter's trajectory viewed from above the ecliptic for a January 2017 launch. The gravity assist maneuvers (GAM) at Earth (E) and Venus (V) are indicated, along with the orbits of these two planets.

i.e. the intersection between the Sun's surface and the line connecting the spacecraft to the Sun's center, is visible from Earth (and points along the Sun–Earth line) before and during the first remote-sensing window, which makes it possible to 'preview' possible observing targets for the first remote-sensing window from Earth and, equally important, to then jointly observe these targets with Solar Orbiter and Earth- and near-Earth-based assets.

The remote-sensing window centered around maximal southern latitude, on the other hand, occurs while Solar Orbiter is almost exactly behind the Sun as seen from Earth. This means that 'precursor' observations before the start of this window are required to meaningfully define an observing target for the high-resolution imagers onboard Solar Orbiter. At the same time, this orbital configuration is particularly well suited for stereoscopic helioseismology studies as combining full-disk data from Solar Orbiter's PHI instrument with data from corresponding Earth- and near-Earth-based instruments will provide almost full surface coverage of the Sun, thereby reducing leakage effects in global helioseismological studies.

4. Synergies

The unique aspects of Solar Orbiter – data from a complete suite of remote-sensing and in-situ instruments from an inner-heliospheric vantage point down to 0.28 AU and out-of-ecliptic perspective – impose constraints in other areas. In particular, Solar Orbiter by itself will be limited in telemetry due to the mission's orbital profile, combined with technical, as well as budgetary, limitations: The baseline science telemetry will be about 560 Gbit per 168-day

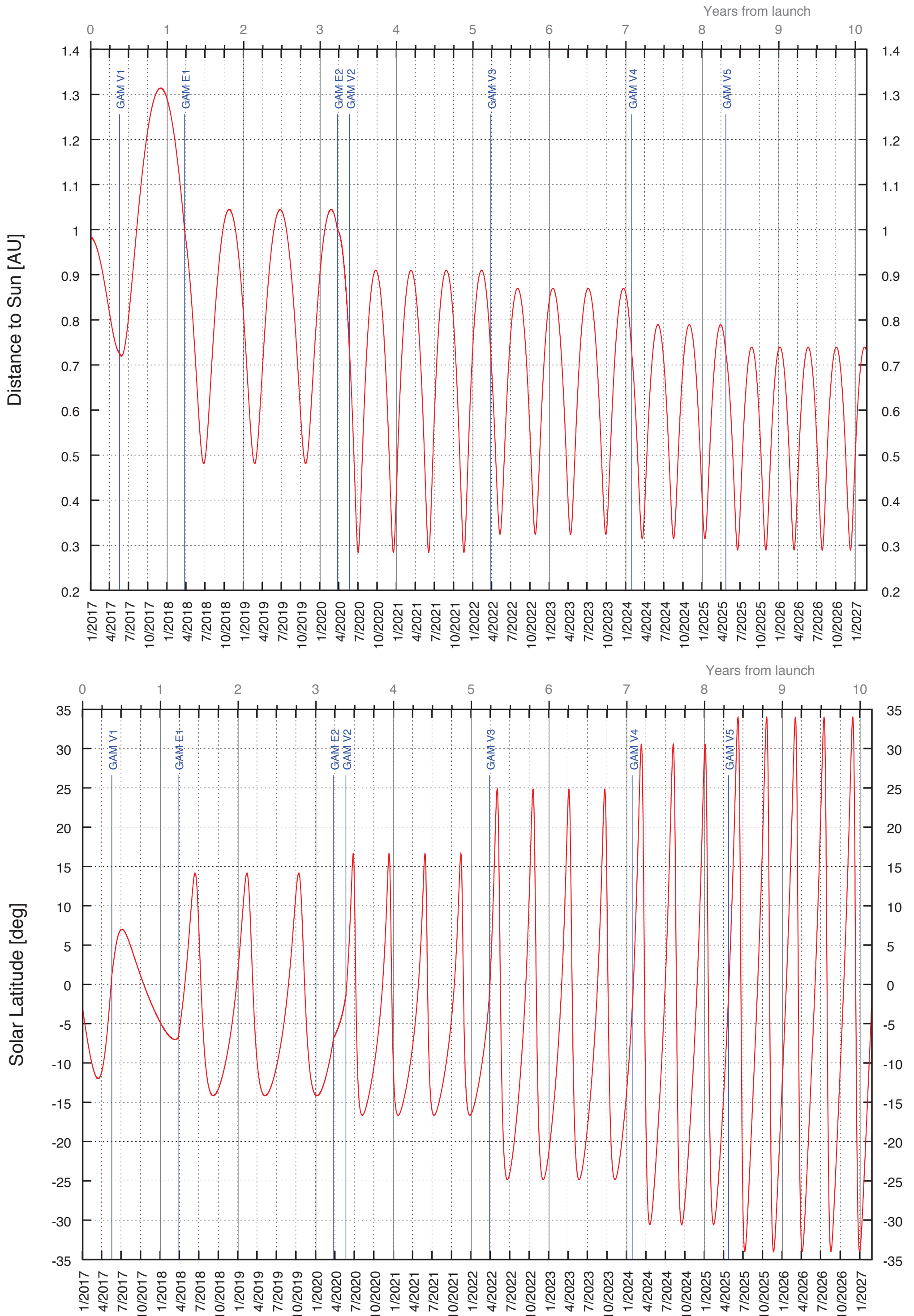

Fig. 4. Mission profile for a January 2017 launch, showing heliocentric distance (top) and latitude (bottom) of Solar Orbiter as a function of time. Also indicated are the times at which gravity assist maneuvers at Venus and Earth occur (blue).

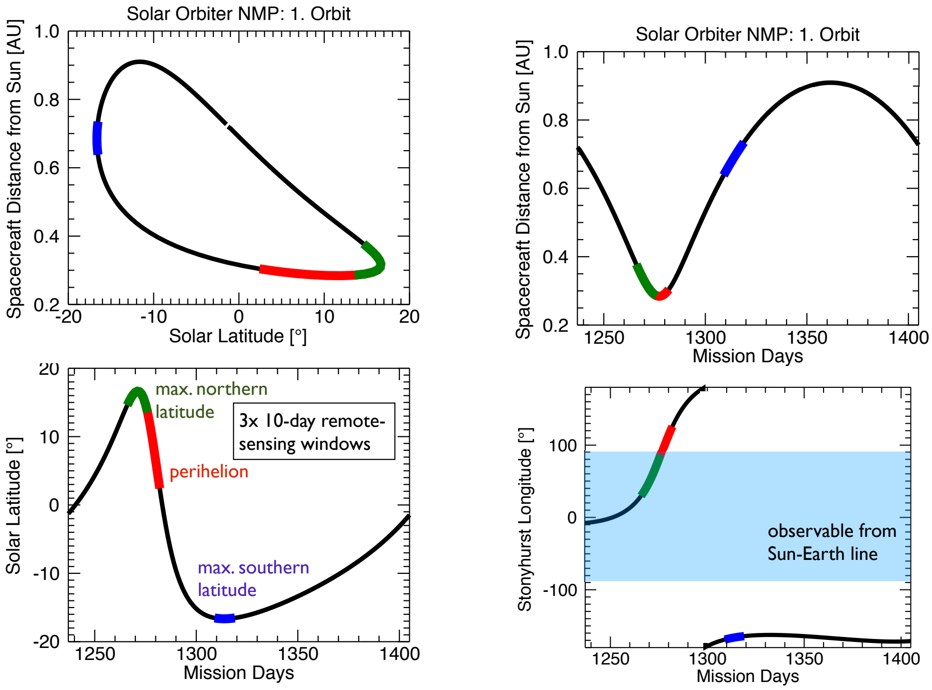

Fig. 5. First orbit of Solar Orbiter's nominal mission phase (NMP) for a January 2017 launch. The three 10-day windows during which both the remote-sensing and in-situ instruments will operate are highlighted in color (green: maximal northern solar latitude; red: perihelion; blue: maximal southern solar latitude). *Top left*: spacecraft distance as a function of solar latitude, *top right*: spacecraft distance as a function of time, *bottom left*: solar latitude as a function of time, *bottom right*: Stonyhurst longitude of Solar Orbiter as a function of time. The solar longitudes visible from Earth are shaded in blue.

orbit, with remote-sensing observations taking place during 30 days per orbit.

Future near-Earth assets like Solar-C or ATST, on the other hand, have the advantage of much higher data return, but are limited to their vantage points on or close to the Sun-Earth line.

Depending on the orbital configuration, significant (and obvious) synergy can therefore be achieved by combining Solar Orbiter's remote-sensing data with either high-resolution and/or high-cadence co-spatial data from other observatories that provide additional spatial coverage, which will for example be very beneficial for helioseismology (see Section 3 for an example).

Finally, NASA's Solar Probe Plus mission will approach the Sun even closer than Solar Orbiter, but can only accommodate a total payload mass of < 50 kg, compared to Solar Orbiter's 180 kg, and implement predominantly in-situ instrumentation (see below).

4.1. Solar Probe Plus

NASA's Solar Probe Plus (SPP) is a mission devoted to the in-situ exploration of the outer solar corona, and is therefore highly complementary to Solar Orbiter. Solar Probe Plus is a ∼ 7-year mission, planned to be launched in 2018, whose final elliptical orbit has an 88-day period and a perihelion of 9.5 R_{Sun}. Since its scientific payload consists primarily of in-situ instruments, complemented by a wide field imager (WISPR), SPP and Solar Orbiter can together address many questions in powerful new ways. Significant examples are different types of alignment, illustrated in Figure 6, which occur about 15-20 times during nominal missions: the left panel shows the case of SPP and Solar Orbiter radially aligned. In this configuration, the radial evolution of solar wind properties, including shock and turbulence properties, can be studied directly. The middle panel shows cases of alignment along a nominal interplanetary magnetic field spiral, where energetic particles travelling past one of the two spacecraft will later move past the other, permitting direct tests of energetic particle transport and scattering since the source function is determined at one of the spacecraft and result is seen at the other. The right panel shows cases of quadrature alignment, where Solar Orbiter remotely observes plasma low in the corona that later passes by SPP, allowing tests of radial evolution of solar wind plasma, shocks, and other structures. When Solar Orbiter enters the high latitude phase of its mission, alignments with SPP will allow latitude gradient studies. Since both spacecrafts orbital motions are in the same direction, these alignment periods can range from a few days to over a month, depending on the radial distances at the time. Finally, there are many periods when Solar Orbiter, SPP and Earth lie within a 30° – 60° wedge, which is ideal for studies of larger structures such as high-speed streams or large interplanetary shocks driven by coronal mass ejections (CMEs).

4.2. Solar-C

JAXA's Solar-C is Japan's next-generation solar physics mission that is presently under study. The model payload consists of a 1.5 m solar UV-visible-infrared telescope (SUVIT), an EUV/FUV high-throughput spectroscopic telescope (EUVST/LEMUR) and an X-ray imaging telescope (XIT). This payload will offer excellent synergies with Solar Orbiter by combining Solar-C's focus on remote sensing from a geo-synchronous orbit, which permits larger telescope apertures and higher telemetry, with Solar Orbiter's unique out-of-ecliptic perspective and combined remote-sensing and in-situ instrumentation.

4.3. Advanced Technology Solar Telescope

The Advanced Technology Solar Telescope (ATST) is a 4 m solar telescope for which construction has recently started at the Haleakalā High Altitude Observatory site on Hawaii (scheduled start of operations: 2019, funding agency: NSF). ATST will be the world's largest solar telescope, designed to have a field-of-view of $3'$ (minimum) to $5'$ (goal), a wavelength range or 300 nm – 35 μm, spatial resolution of $< 0.1''$ (using adaptive optics) and polarization accuracy of better than $10^{-4} \cdot I$ (cf. http://atst.nso.edu/science/intro). The key science driver for large apertures is that a spatial resolution of better than $< 0.1''$ is needed to resolve the photon mean-free path and pressure scale height in the photosphere, scales on which elementary physical processes are taking place.

At Solar Orbiter's closest perihelion (0.28 AU), the high-resolution imaging telescopes of its EUI and PHI instruments, with fields-of-view of $17' \times 17'$, are imaging areas of similar size on the Sun as the ones of ATST's instruments. While PHI and EUI will have a spatial resolution of down to 180 km, ATST is expected to resolve structures less than 70 km in size. The difference in the volume of science data generated, however, is large: ATST's Visible Broadband Imager (VBI) will generate 6.5 TB/h of raw data. After speckle reconstruction with 80:1 data reduction and assuming a duty cycle of 4 h/day, this will result in a science data rate of $\sim$ 350 GB/day (Reardon 2012), i.e. 700 times the average daily data rate of all of Solar Orbiter's instruments. For comparison, NASA's Solar Dynamics Observatory (SDO), launched in 2010, downlinks 1.4 TB/day, most of which is distributed between the HMI and AIA instruments.

This brief comparison highlights the fact that Solar Orbiter's remote-sensing observations will need to be planned carefully to take maximal advantage of the missions unique aspects, e.g. by measuring the Sun's polar fields and by using Solar Orbiter's viewpoint to eliminate the ambiguity in the azimuth of the inferred magnetic field, and to benefit from the

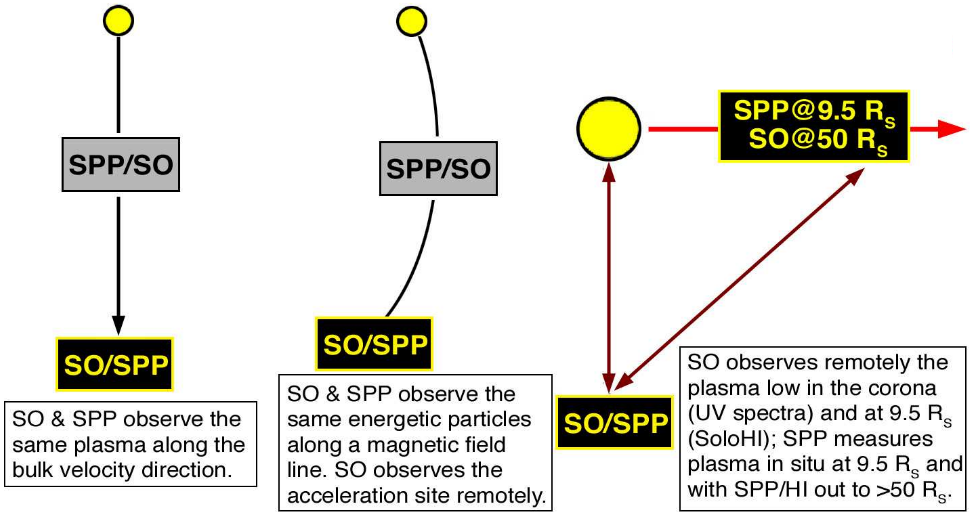

Fig. 6. Solar Orbiter and Solar Probe Plus will provide multiple opportunities for coordinated observations from complementary vantage points (adapted from Marsden & Müller 2011).

specific strengths of complementary missions and observatories during joint observations.

5. Summary

Understanding the connections and the coupling between the Sun and the heliosphere is of fundamental importance to understanding how our solar system works. To reach this goal, Solar Orbiter will make in-situ measurements of the solar wind plasma, fields, waves, and energetic particles as close as 0.28 AU from the Sun, simultaneously with high-resolution imaging and spectroscopic observations of the Sun in and out of the ecliptic plane. The combination of in-situ and remote-sensing instruments on the same spacecraft, together with the new, inner-heliospheric perspective, distinguishes Solar Orbiter from all previous and current missions, enabling breakthrough science which can be achieved in no other way. At the same time, the challenging orbit of Solar Orbiter also imposes constraints, e.g. on the total science data volume that can be downlinked. Solar Orbiter has therefore important synergies with Solar Probe Plus, Solar-C as well as the ATST, and coordinated observations with these and other new missions and ground-based observatories will contribute greatly to our understanding of the Sun and its environment.

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