THE BELEINOS CORNERSTONE: THE SUN, THE STAR CLOSE TO EARTH

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Abstract

The recent solar missions have provided new challenges for solar physicists: for instance, the need for the overall understanding of the solar magnetic field from its generation to its dissipation and propagation into the heliosphere. In order to raise to this new challenge, one must find the necessary answers to the following fundamental questions: What is the structure and dynamics of the solar core? What are the mechanisms sustaining the solar magnetic field and leading to its modulation? What are the reconnecting processes taking place above the photosphere?

We present various mission scenarii that will allow addressing these three questions. One of the mission concepts includes a fleet of spacecraft orbiting the Sun at various latitudes aiming at detecting solar gravity modes using complementary seismic techniques. Other mission concepts envisioned two spacecraft probing the Suns surface from very close distance while observing the Sun at high resolution across a large spectral range. Other innovative mission concepts will be presented.

Key words: Sun: magnetic field – internal structure – space

1. Introduction

Although the Sun is very close, this proximity provides neither a better understanding of that star over other stars nor of the physics at work inside the Sun. The need for the overall understanding of the solar magnetic field from its generation to its dissipation and propagation into the heliosphere[1] leads to find the necessary answers to the following fundamental questions: :

- What is the structure and dynamics of the solar core?
- What are the mechanisms sustaining the solar magnetic field and leading to its modulation?
- What are the reconnecting processes taking place above the photosphere?

The *first question* is related to physics taking place at a few tens of million Kelvin for which helioseismology cannot yet provide reliable inferences. The detection of internal solar gravity waves known as g modes is still key for that aim.

The *second question* is related to the so-called dynamo theory that cannot predict the reversal of the solar magnetic field every 11 years, nor can it predict the amplitude of the magnetic field oscillation.

The *third question* is related to the interaction of the solar magnetic field with the heliosphere. The challenge of the next decades is to develop a global theory, from the solar surface to the planets atmospheres, linked by the magnetic field.

These three questions can only get answered from space in the following manner:

- **The solar core**: detection of g modes using gravitational waves, or advanced time-distance techniques or other classical seismic techniques
- **Solar activity mechanism**: long duration observation of the solar poles
- **Reconnection**: in-situ and remote sensing observation a few solar radii above the photosphere, high resolution observation (0.1 arcsec or lower)

The first answer can be obtained using laser ranging and few-photon interferometry from the Earth orbit, or using seismic techniques (global or local). The second answer can be obtained from observation above the poles using solar sails, technology still to be developed. The third answer can be obtained from observations performed from a few solar radii from the photosphere, or from high-resolution spatial and spectroscopic observations (EUV to visible) using large telescope or interferometric techniques.

Here we present various mission scenarii that will allow addressing these three questions. These scenarii are examples but more elaborate mission concept can be envisaged combining these scenarii together.

2. On detecting g modes

2.1. How?

The detection of g modes remains one of the major goal of helioseismology. These modes would provide a wealth of information about the dynamics and structure of the solar core. So far, the detection were based upon looking for periodic signals in solar radial velocities, intensity fluctuations and/or limb observations (See Appourchaux,

[1] See also Turck-Chièze et al, these proceedings

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2003, for a review). The upper limit to g-mode amplitudes is 10 $mm.s^{-1}$ for singlet after Appourchaux et al. (2000) , and 1 $mm.s^{-1}$ for multiplet after Turck-Chièze et al. (2004). The currently planned solar missions (for instance the Solar Dynamics Observatory to be launched in 2008) will not provide any improvement on these amplitude limits. The French mission PICARD using limb measurement will use the amplification of the modes at the limb to detect the g modes; forecast is difficult to make as no one knows how the noise will be amplified at the limb as well. Similar uncertainties might affect future concepts such as GOLF-NG. This may not be the case of AstroD for which we have a lower detection limit. One of the goal of AstroD is to detect gravitational waves using laser ranging of 2 spacecraft located on the solar far side at 2 AU from the Earth with an accuracy 30 times better than LISA (Cruise et al., 2000). It will use the technology developed for LISA (drag-free spacecraft, laser). Christensen-Dalsgaard (2002) and Appourchaux (2003) both derived equivalent radial velocity amplitudes of less than 0.1 $mm.s^{-1}$.

2.2. Challenges

AstroD is an ambitious mission. Besides reusing LISAs technologies, other technological developments are required such as:

- Weak-light phase locking (to 100 fW)
- Light-weight precision clocks
- Stabilized lasers to 10^{-15}
- Very low noise accelerometers

In order to prepare for these challenges, an AstroD I mission is planned by the Chinese Space Agency in order to test some critical technologies. Astro-I is currently in pre Phase-A (Ni and The Astrod I Study Team, 2005). This AstroD-I mission could be launched as early as 2010, while AstroD is planned in 2017. In the context of Cosmic Vision, the time frame is timely to start an ESA-China collaboration on AstroD.

3. On viewing the solar poles

3.1. How?

In 2015, Solar Orbiter will be able to provide a view of the solar poles at a latitude of 35^o (Marsch et al., 2002). This pioneering mission will provide exceptional close-up views of the poles of the Sun. The high-resolution views will be accessible for 30 days around the perihelie. Still longer observations are required for a deeper understanding of the magnetic activity of the Sun, and reconnection processes.

In order to observe and monitor the solar magnetic activity, its origin and its emergence, one could use solar sails to devise non-Keplerian orbits as anticipated by McInnes (2003): the orbit plane is out of the ecliptic plane and parallel to the latter. In addition, solar sails offer a significant advantage over other propellant: the ability of changing non-Keplerian orbit for Keplerian orbits. The main advantages of these non-Keplerian orbits are the exceptional view points above either pole (North or South) and their geosynchronicity. In that latter case, the spacecraft will be at an unvarying distance from the Earth. We can anticipate that by the years 2020 high optical telemetry rate will be available, or that a Next-Generation Deep Space Network will be available for reaching rates up to few Mbps!

When designing a solar sail mission, one has to bear in mind that the ratio of spacecraft mass (M) to solar sail surface (S), in g/m^2, is given as:

$$M/S = 1.55\rho/\lambda \tag{1}$$

Where ρ is the efficiency of the solar sail (reflection factor) and λ is the lightness ratio (the ratio of the radiation pressure force to the gravitation force). In Fig. 1, we show the lightness ratio required for Earth-synchronous orbits. A typical lightness number of 1 is needed for observing above a latitude of 60^o, which give a ratio M/S of 1.4 g/m^2 (with a 90% efficiency). With solar sails studied for the Solar Polar Orbiter (SPO) having a surface of 25000 m^2, we need a spacecraft mass of less than 35 kg! A solution technically less challenging would be to have an SPO mission having its orbital plane nearly perpendicular to the ecliptic plane, as studied by the Science Payload and Advanced Concept Office of ESA[2] or as the Solar Polar Imager studied by JPL (Socker and Liewer, 2005). In that case the lightness ratio obtained is 0.14, and the ratio M/S is about 8 g/m^2 providing a spacecraft mass of 250 kg for a solar sail surface of 25000 m^2. The spacecraft orbits then at 0.5 AU with an orbital period of 4.25 months with an inclination of 83^o.

3.2. Challenges

Such a mission will require the development of microsatellites, miniaturised payload, solar sail and efficient deep space communications. If one spacecraft is not enough to carry the payload, we can imagine a fleet of spacecraft orbiting above the poles, or at various latitudes. This is clearly an ambitious project, but technological developments should be anticipated that will enable such a mission for the years 2020.

Nevertheless, with today technology, it is far more practical to have an SPO mission with an orbital plane perpendicular to the ecliptic, in a similar fashion to that of the ESA mission Ulysses. In that case, the SPO mission studied by ESA would provide for a spacecraft mass of 250 kg, still very light but more manageable as far as the payload mass is concerned...

[2] SPO is a Technology Reference Mission of ESA, more info can be found at http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=36025

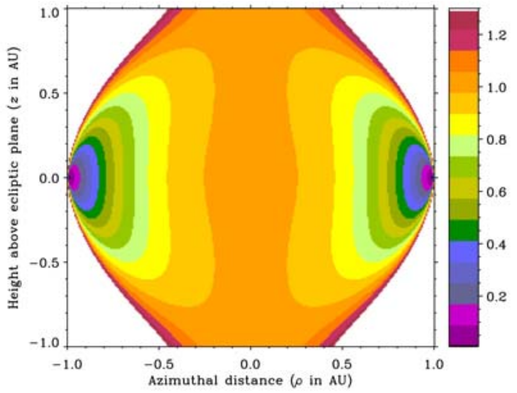

Figure 1. Lightness ratio map in the (ρ, z) plane for spacecraft orbiting with a 1-year period, where (ρ, z) are the cylindrical coordinates of the spacecraft. The lightness is the ratio of the radiation pressure force to the gravitation force. A lightness ratio of 1 means equilibrium between these two forces; in that case on could envisage a stationary spacecraft above the solar poles at $\rho = 0$.

4. On getting close to the edge

4.1. High-resolution spectral images of the Sun

The resolution obtained by Solar Orbiter will be equivalent to a 0.1-arcsec resolution from the Earth. The images provided by Solar Orbiter will be obtained during several perihelie passages lasting 30 days each. Although the improvement provided by Solar Orbiter will be tremendous, solar images with 0.1-arcsec resolution will not be available on a routine basis by the year 2020. An Earth orbiting spacecraft with very high telemetry rate would be an excellent solution. Such a resolution in the visible require a 1-m diameter telescopes. In the EUV, this is not the wavelength that limits the resolution but the available flux. With a 1-m diameter telescope, images in the EUV would be obtained at a cadence of 10 Hz. With such a large telescope, one can also envisage to perform spectropolarimetry with very high signal-to-noise ratio. The focal plane would be equipped of Stokes polarimeter, UV Fourier transform spectrometer (Millard et al., 2005). The EUV version of the telescope could be equipped with a gigantic aluminium filter for cutting down the visible light. If Blind-to-the-Optical-Light Detectors (BOLD) (Schuehle et al., 2004) are available by the years 2020, a single focal plane hosting EUV, UV and visible instrumentation could be envisaged.

4.2. At the origin of the solar wind

Solar Probe (McComas and Solar Probe Science and Technology Definition Team, 2005) or Ramses (Lequeau et al., 1998) is a challenging mission aiming at a very close look at our star from about 4 solar radii. This mission would be humanitys first visit to our star to explore the complex and time varying interplay of the Sun and Earth which affects human activity. This mission is being studied by NASA/Applied Physics Laboratory. The main scientific objectives are as follows:

- Determine the acceleration processes and find the sources of the high and low speed solar wind
- Locate the source and trace the flow of energy that heats the corona.
- Identify the acceleration mechanisms and locate the source regions of energetic particles

A combined remote sensing and in-situ sampling from within the solar corona itself will provide a ground truth never before available from astronomical measurements made from spacecraft in the Earths orbit or Lagrange points.

4.3. Discussion and conclusion

Here we have presented various mission concepts. Each of the concepts can be combined with the other to provide a better understanding of the Sun. The era of single spacecraft concept is a thing of the past. There has been many precedent where fleets of spacecraft are flown together or at the same time in order to get more Science (SOHO+Cluster; Stereo, etc).

Beleinos is not a mission. It is a cornerstone on which an ambitious road map should be built in order to gain a better and deeper understanding of our nearest star. We have given several tracks that could be followed for building the Next-Generation solar missions. A multi spacecraft approach where the in-situ and remote sensing instruments are separated is also convenient. We could imagine an orbiting high-resolution imager and spectral telescope looking at the solar surface where solar probes would be plunging. At the same time, stereoscopic views of the solar poles from Polar Orbiters would provide the necessary information on the CMEs, the solar internal dynamics and using telechronoseismology information on the structure of the solar core.

The Beleinos concept is not closed. It should enable our community to work in synergy and in open spirit for getting more Science. In response to the new challenges in Solar Physics, we propose as the next solar mission a fleet of spacecraft aiming at a global knowledge of the Sun from its interior to the heliosphere, and its impact on the Earths magnetosphere.

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