Probing the heliosphere using *in situ* payloads on-board Aditya-L1

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Aditya-L1, the first ever Indian scientific space mission dedicated to probe the Sun, our nearest star, is slated for launch by the Indian Space Research Organisation (ISRO) in 2020, the year coinciding with the start of the rising phase of solar cycle 25. Of the seven science payloads on-board Aditya-L1, three are *in situ* instruments, namely the Aditya Solarwind Particle EXperiment, the Plasma Analyser Package for Aditya and a magnetometer package. These three payloads will sample heliospheric data from the L1 Lagrangian point of the Sun–Earth system, at a distance of ~1% of the distance to the Sun, along the Sun–Earth line. This is therefore a unique opportunity for the solar physics community to gain a better understanding of the inner heliosphere and predict space weather more accurately.

Keywords:

Introduction

THE Sun is an excellent plasma laboratory with varied nature of plasma inhabiting its atmosphere – the solar corona. The lower corona, having a particle density of 10^8 cm^{-3}, extending to about 1.5 R_{sun}, is primarily considered to be collisional and dominated by a strong magnetic field of the order of 10^5 nT. On the other hand, at the Sun–Earth distance of 1 AU, i.e. the solar corona is collisionless with a density of 4 cm^{-3} (ref. 1) and an ambient magnetic field of the order of nanotelsa. The collisional mean free path around this region is of the order of 1 AU. Consequently, the physics prevailing in these two regions is different. Close to the surface of the Sun the plasma can be considered as a fluid, whereas a particle description is more appropriate in describing the solar wind plasma at 1 AU.

After the detection of the solar wind by the Mariner 2 spacecraft (mainly dedicated to explore Venus)[2,3], several space missions were launched to study the solar atmosphere. Instruments on-board these spacecraft were primarily of two categories – for remote sensing and *in situ* measurements. Remote sensing instruments mainly use imaging or spectroscopic techniques to derive the plasma parameters, while *in situ* instruments directly sample the local plasma. Helios 1 and 2, Ulysses, Wind, the Advanced Composition Explorer (ACE), the Solar and Heliospheric Observatory (SOHO), the Solar Terrestrial RElations Observatory (STEREO) and the Solar Dynamic Observatory (SDO) are a few such missions which have contributed enormously to our understanding, in unprecedented detail, of the solar atmosphere. These spacecraft studied the Sun from various locations in the heliosphere to have an overall idea of its atmosphere.

However, several challenges still remain to be addressed and resolved, and precise data at different locations around the Sun are required to achieve that goal. India's first solar mission, Aditya-L1 will observe the Sun from the vantage point L1. At around the same time, missions from ESA and NASA, namely the Solar Probe Plus and the Solar Orbiter will explore various parts of the heliosphere to give a detailed view of the solar corona.

In this article, we focus on the *in situ* instruments on-board Aditya-L1 and their role in probing the inner heliosphere, as well as the questions they aim to resolve. In the following section, we briefly introduce the three *in situ* instruments on-board AdityaL1. In the next section, we discuss the corresponding open science problems to be addressed by the findings from these instruments. We end with a discussion on the future aspects of the mission.

In situ detection payloads

There are two *in situ* particle detection payloads on-board Aditya-L1 – the Aditya Solar wind Particle EXperiment

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(ASPEX) and the Plasma Analyser Package for Aditya (PAPA). The third instrument is a flux gate magnetometer (FGM) package mounted on a 6 m long boom to sample 3D magnetic field data. The primary objective of ASPEX is to gain a better understanding of the origin and acceleration mechanism of solar wind ions and the ions associated with energetic events such as coronal mass ejections (CMEs) and corotating interaction regions (CIRs). ASPEX consists of two ion spectrometers, viz. the Solar Wind Ion Spectrometer (SWIS) and the Supra Thermal and Energetic Particle pectrometer (STEPS) to cover both the low (0.1–20 keV) and high energy range (20 keV/n – 20 MeV/n), respectively.

The other particle detector, PAPA, will simultaneously probe heliospheric ions and electrons. It consists of two sensors, viz. the Solar Wind Electron Energy Probe (SWEEP) and the Solar Wind Ion Composition AnalyseR (SWICAR). While SWEEP, an energy analyser, will measure electrons in the energy range 10 eV–3 keV, SWICAR, an energy and mass analyser for ions, will cover a wide energy spectrum (0.01–25 keV) and differentiate ions in the mass range 1–60 amu. In addition, PAPA will be also able to produce the solar wind electron velocity distribution function (EVDF). While SWICAR (PAPA) will observe solar wind ions over a limited field of view (FOV), the SWIS (ASPEX) payload will have a FOV of 2π and accept particles from all directions.

The third instrument package consists of two FGMs mounted on a 6 m long boom. The main science objective of the FGM experiment is to measure the magnitude and nature of the interplanetary magnetic field (IMF) locally, and study the disturbed magnetic conditions and extreme solar events by detecting CMEs from Sun as transient events. The secondary science objectives include study of the impact of interplanetary structures and shock solar wind interaction on geo-space environment and to detect low-frequency plasma waves emanating from the solar corona at L1. The magnetic field measurements are expected to provide important insights into the physical processes occurring in the interplanetary medium, and supplement the particle measurements from both ASPEX and PAPA.

Science objectives

Solar wind

The existence of the solar wind was predicted by Parker[4] and verified by the Mariner 2 spacecraft. However, the observed bulk velocity of the solar wind is greater than the predictions for a thermally driven wind[5]. A satisfactory resolution of this conundrum therefore requires an extra deposition of energy into the solar corona. This problem can certainly be considered as an extension of the famous coronal heating problem, where the million degree corona above the 6000° photosphere demands the input of an extra source of energy. Our current understanding suggests that the Sun’s magnetic field is perhaps responsible for transferring energy from the Sun to its atmosphere. However, it remains unclear how such a large amount of energy can be carried by the magnetic field and to what distance it can be transferred.

Using plasma and magnetic field data from Mariner 5, Belcher and Davis[6] first identified the existence of Alfvén waves in the heliosphere. Since then, it is a assumed that hydromagnetic waves could carry energy into the heliosphere and fulfil the extra energy demand of the solar wind. Other compressible modes of hydromagnetic waves were not observed in the upper heliosphere and were believed to be heavily damped in the lower corona. The detection of Alfvén waves further led to efforts to identify its effects on heliospheric plasma.

Plasma emanating from the Sun initially moves along the magnetic field lines, since the magnetic field is stronger near the surface of the Sun. In this region, the magnetic energy in the fluid dominates over its kinetic energy. The point where the kinetic energy overtakes the magnetic energy, at about 10 solar radii, is known as the Alfvén point. Therefore, if there is indeed a transfer of energy from the magnetic field to the solar wind, most of it should happen within the Alfvénic radius. However, this leads to an extra concern. If the extra energy gets dumped close to the Sun, chances are that it would soon be returned to the solar surface via conduction, and will evaporate extra plasma from the Sun to the corona and the solar wind. This would make the solar wind denser[7]; this prediction has yet to be reconciled with the observations.

Solar wind is generally observed in two modes: fast (speed ~800 km/s) and slow (speed ~400 km/s). It is now clear after the Ulysses observations that the fast wind follows the open magnetic field lines emanating from coronal holes, whereas the slow wind emanates from the solar equatorial streamer belt region. It is found that the proton temperature of the fast wind along the magnetic field lines, $T_\perp$, is higher than its parallel temperature, $T_\parallel$ (ref. 8), whereas the trend is opposite for the slow wind. This suggests strong local wave heating for both kinds of solar winds, but the mechanism is most likely different for the slow and fast varieties. Local heating can be made responsible for differential ion velocities observed in the solar wind. Kasper *et al.*[9] showed that the temperature anisotropy, $T_\perp/T_\parallel$ is a strong function of the differential proton-alpha speeds in the solar wind.

ASPEX and PAPA measurements are expected to provide proton and alpha speeds separately and thus can determine local temperature anisotropy ($T_\perp/T_\parallel$) with confidence. This will shed light on the nature of the wave particle interactions that take place in this region and may be responsible for such local heating.

As mentioned in the beginning, solar wind at 1 AU is extremely tenuous. Infrequent collisions preclude equilibration of solar wind particles. In fact, *in situ* observations show that the velocity distribution function (VDF) is far from being Maxwellian. Furthermore, the observed velocity distribution changes spatially as well as temporally[10]. VDFs are seen to be different for different *in situ* conditions (e.g. CMEs, CIRs, etc.). Strong field aligned proton beams are often seen with drift speed greater than the Alfvén speed[11]. The velocity distributions of the electrons and protons are skewed and tend to be enhanced along the direction of the local magnetic field. Rarefied plasma in the ambient magnetic field can lead to complicated wave–particle interactions such as ion cyclotron instability, mirror instability, etc.[12].

Steady-state solar wind protons mostly travel with kinetic energy up to 3 keV. ASPEX-SWIS will be able to study particles in three dimensions, analyse them in terms of energy in the range 0.1–20 keV, and separate them into protons, alpha particles and higher masses. It also has a high cadence operational mode, scanning the entire energy range in 3*s*. Thus, it will be able to obtain 3D velocity distribution data at regular intervals to study its time evolution and highlight how solar wind gets heated in the heliosphere.

Unlike protons, electrons get relatively less attention in solar wind research because of their low mass. In fact, Lie-Svendsen *et al.*[13] using their numerical calculation negated the role of electrons in the solar wind acceleration mechanism. However, electron VDFs of the solar wind display several components – an isotropic core with cold electrons, a halo surrounding the core populated with hotter electrons and the ‘strahl’[14] inclined towards the local mean field direction, away from the Sun. Suprathermal strahl electrons are mostly observed in the fast wind and they disappear beyond 1 keV. Many researches have suggested the role of resonance interaction between the solar wind particles and whistler waves for such suprathermal electrons[15,16]. However, the issue is still debatable. PAPA/SWEEP will be in a position to address this further.

Minor ions are rare in the solar wind abundance-wise, but nevertheless they carry important information about solar wind acceleration. Therefore, a detailed understanding of individual minor ions can provide us with clues about the solar wind acceleration in interplanetary space. For instance, wave particle interaction may affect different minor ions differently, thereby affecting their VDF. A distribution function of minor ions is thus of great importance to the solar wind plasma physics community. PAPA/SWICAR with its capability of differentiating ion (of mass 1–60 amu) velocities should be able to address this issue with confidence.

Transient events

On the continuous background of the solar wind, transient events such as interplanetary coronal mass ejection (CMEs propagating in interplanetary space, also known as ICME) and CIR further complicate the dynamics in the local plasma atmosphere. The initial phase of CMEs can be imaged using on-board coronagraphs, but detecting ICMEs is non-trivial and receives considerable attention due to scientific as well as technological reasons. ICMEs carry a massive amount of plasma and magnetic field, the former of the order of 10^{15} *g* into interplanetary space[17], and interact with the ambient solar wind background while propagating outwards from the Sun.

CMEs whose projected size quickly becomes larger than the occulting disk of the coronagraph are known as halo CMEs[18]. They propagate towards the Earth and are responsible for the most extreme space weather conditions. Such CMEs are known as geoeffective CMEs and advanced prediction capabilities of these CMEs are important. It is thus necessary to have an indicator for ICMEs at the L1 point. More than 50% ICMEs show high alpha-to-proton ratio (8%)[19]. Therefore alpha-to-proton ratio at L1 can be employed as an ICME arrival indicator. It has been shown that the charged state of Fe ions could be a better indicator for ICMEs[20,21]. However, in spite of efforts to identify better signatures (e.g. Henke *et al.*[22]), no foolproof indicator is yet known to identify all ICMEs. Proton VDF is one of the characteristics of ICMEs which could potentially be one such signature, but has not been well studied so far[23].

ASPEX will initially measure the alpha-to-proton ratio *in situ* to identify ICMEs, but eventually a better measure will be looked for once data are available.

The *in situ* detection instruments on-board Aditya-L1 will ‘hand-shake’ with the remote sensing instruments on-board, such as the Visible Emission Line Coronagraph (VELC) or the Solar Ultraviolet Imaging Telescope (SUIT), to provide advanced prediction of CME arrival at 1 AU. After emanating from the Sun, CMEs take ~40 h to travel through interplanetary space to reach the Earth. The coronagraph of VELC is capable of imaging the initial phase of CMEs and hint at its propagation direction. This will allow *in situ* instruments to be prepared for the CME mode of observation and predict geo-effectiveness of CMEs more accurately.

Interaction between adjacent fast and slow solar wind streams may lead to the development of interplanetary shocks. When fast wind catches up with the slow wind, a stream interaction region (SIR) is formed. The SIR take a spiral shape that co-rotates with the Sun, moving past any fixed longitude in the heliospheric coordinate, also known as the CIR. Fast and slow winds get reflected about this CIR giving rise to waves. Generally reverse waves (towards the Sun) start propagating in the slow wind side, while forward waves (away from the Sun) start propagating in the fast wind side. CIRs are generally identified with two shock fronts (forward and reverse), via sudden jumps in the magnetic field and velocity data.

Both ICMEs and CIRs are great sources of solar energetic particles (SEPs). These may also be generated from solar flares. In general, SEPs are available throughout the heliosphere and carry the source information along with them. Their energy spectrum is spread over 1–1000 MeV. SEP events can last from several hours to several days[24]. Highly energetic particles may pose a significant risk of damage to space-based instruments[25] as well as biological systems, e.g. astronauts[26]. Simulations suggest that scattered ions resulting from CME and solar wind interaction initiate the onset of Alfvén waves in the shock front, accelerating particles to high energy[27]. For a detailed understanding of such interactions we need unambiguous data from such CME shocks.

ASPEX-STEPS will be invaluable in identifying protons from ICME shock fronts and CIRs. This can give us the spectrum of protons up to 20 MeV/n and time-series data at various energy bands. This package will be useful in investigating the particle acceleration processes during such energetic events. In addition, the on-board magnetometer observations will be useful in identifying the arrival of ICMEs, CIRs at L1 through characteristic variations in the magnetic field.

ASPEX can observe particles over 360°, both in and out of the ecliptic, and will thus enable one to achieve ion information from the anti-Sun direction as well. An opportunity to make such observations from the L1 point is rare. When the high-speed solar wind interacts with the Earth's magnetosphere, a bow shock is formed and energetic particles from a few kiloelectronvolts to 1–2 MeV have been observed upstream of the Earth's bow shock[28–30]. The origin and acceleration of these particles are not comprehensively understood. ASPEX is expected to play a definitive role in resolving this issue.

Discussion

India's first dedicated solar mission Aditya-L1 is slated for launch in 2020. The current solar cycle 24 has been one of the weakest experienced in the past ~100 years, and both solar polar magnetic fields and interplanetary magnetic fields have been steadily declining for over two decades now[31–35]. In light of this, the rising phase of solar cycle 25, from 2020 onwards will therefore be extremely interesting and unique as it approaches the next solar maximum. It is expected that during this phase the Sun will show changes in its nature, thus enabling scientists to study its different phases using all the payloads on-board the spacecraft. In particular, the *in situ* instruments can address challenging issues related to the heating and acceleration mechanisms of the solar wind.

Detecting ICMEs with certainty is a difficult task at present and requires a definitive identifier. Predicting the propagation of CMEs towards the Earth, and hence its geoeffectiveness, is also important for space weather forecast[36]. Understanding particle acceleration within the CME shock is a major target set for these payloads. Similar *in situ* instruments are foreseen from another mission being considered for the L5 point. Observations from the latter point, which makes a 60° angle to the Sun-L1 line, would benefit the mission further. It has been identified that ICME shock front has a longitudinal distribution[37]. A two-spacecraft view of the same from different angles would thus help understand its 3D structure, enabling us to predict the propagation direction of CMEs in a more definitive manner. Simultaneous inputs from other payloads such as the VELC or SUIT will allow for advance indication of major transient events (e.g. CMEs).

The Aditya-L1 mission, within a matter of a few years, promises to open up a highly productive and fruitful era for solar physicists. It is an exciting time for Indian science indeed.

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