SOLAR ORBITER NEUTRAL SOLAR-WIND DETECTOR

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ABSTRACT

Neutral hydrogen atoms, which give rise to the prominent solar Ly-α corona, are closely coupled to the emerging solar-wind plasma. The density ratio of neutral hydrogen to protons is minute, $\sim 10^{-6}$; therefore, the neutral atoms are tracers in the solar wind. In-situ observations of the neutral atoms, their flight paths (imaging), density, and velocity distributions are a new tool to the understanding of the Ly-α corona, i.e. setting limits on the plasma velocity distribution along the solar magnetic field lines. The other goal of the neutral solar-wind instrumentation is the in-situ observation of the interactions between solar wind plasma and dust grains near the Sun. We will discuss the science objectives and the potential "zero charge" solar-wind instrument envelope onboard Solar Orbiter.

1. INTRODUCTION

Neutral atoms have been observed in the inner and outer heliosphere, both via in-situ and remote sensing instrumentation. The energy of the neutral atoms ranges from a few eV for constituents of the local interstellar medium and some hundred eV to about 100 keV for atoms originating from solar wind or suprathermal energetic ions. Unlike charged particles, they can travel over large distances on ballistic trajectories through space, undisturbed by magnetic or electric fields.

Neutral atoms in the solar corona are a trace particle population in the solar-wind plasma, the ratio of the densities of neutral hydrogen to protons is low, $<10^{-6}$ to 10^{-7}. Nevertheless, neutral hydrogen causes the well-known solar Ly-α corona. The solar wind plasma drives the characteristics of the neutral atom distributions. The neutral hydrogen is coupled to the solar-wind protons via charge exchange processes, i.e. electron transfer processes. Ensuing charge transfer, the newly created hydrogen atoms reflect the proton distributions in density and velocity. Furthermore, the hydrogen atoms are coupled to the solar wind plasma via collisional ionisation by electrons, photo-ionisation and radiative recombination.

The most important aspect of any in-situ observations by a neutral solar wind detector in the vicinity of the

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Sun is the measurement of the flight paths, density and velocity distributions of neutral atoms along and perpendicular to the solar magnetic field orientation, in order to deduce the plasma parameters of the solar wind, i.e. via deconvolution and modeling, even in the solar-wind acceleration region. Other fields of interest include the plasma physics of CMEs and the "inner source" of pick-up ions, potentially interplanetary dust grains interacting with solar-wind plasma.

The primary scientific objectives of the neutral solar-wind detector (NSWD) onboard Solar Orbiter may be summarized as in the following:

• to measure the neutral solar-wind flux; thus deducing the velocity, density and temperature of the neutral solar wind;

• to comprehend the solar Ly-α corona, i.e. deduction of solar wind plasma velocity distributions anisotropy perpendicular and along the solar magnetic field lines from neutral solar wind observations;

• to study the solar wind acceleration region via the detection of the neutral solar wind hydrogen atoms and investigation of the temporal and spatial details of the solar wind using the co-aligned movement of the Solar Orbiter spacecraft with respect to the solar rotation;

• to observe the fast and slow neutral solar wind in different solar conditions, potentially including transitions regions and CMEs;

• to resolve the puzzle of the "inner source" of pick-up ion, thought to be dust grains in the solar atmosphere and out to the region within 0.2 AU interacting with solar-wind plasma.

In-situ instrumentation designs for the detection of the neutral solar wind have been discussed since a long time [1]. The design challenge lies in the instrument's capability to detect and measure the minute neutral solar-wind flux in the vicinity of the Sun with such a precision, so that the resulting velocity and temperature distributions can be compared with the measured parameters of the solar wind plasma.

A NSWD, consists of a neutral atom sensor able to detect and characterize (in terms of velocity and direction) the energetic neutrals flowing together the ionised particles within the solar wind, between ~0.05 keV/nuc and ~5 keV/nuc, is included in the Solar Orbiter High Priority Augmentation payload as a lightweight instrument, potentially attached to the main solar wind plasma analyser (SWA) package. The design of the ELENA instrument for ESA's BepiColombo mission, which uses mechanical shutters followed by time-of-flight analyzers [2], provides the most promising baseline for the design of the NSWD.

2. SCIENCE GOALS

Features in coronal Ly-α, emitted by neutral hydrogen, is indicative of the behaviour of the main solar wind component formed by protons out to at least 2-3 solar radii. In fact, beyond this distance the characteristic time for charge exchange between hydrogen atoms and protons becomes comparable to the coronal expansion time scale causing the neutrals to decouple from the charged solar wind. Hence, they retain information on the three-dimensional coronal distribution of hydrogen at the level where they are generated.

In the solar corona, up to 2-3 solar radii, neutral atoms are closely coupled to the emerging solar wind plasma and give rise to the prominent solar Ly-α corona mainly by resonant scattering of chromospheric HI Ly-α photons. From the measurement of the Ly-α spectral line profile, the hydrogen velocity distributions in the solar corona have been deduced [3, 4, 5]. These distributions generally reflect that of the protons up to about 2-3 solar radii. Above this altitude, because of the low coronal density, the neutral solar wind (NSW) decouples gradually more and more from the ionised component. Contrary to charged particles, the neutral atoms can cover long distances on ballistic trajectories through space, undisturbed by magnetic fields. They constitute a unique in-situ trace particle population of the solar wind plasma [6, 7, 8]. The understanding of the corona and hydrogen plasma interaction beyond 3 solar radii derives from the comparison between the neutral and the proton component of the solar wind. In fact, the former preserves some information about the corona, while the latter carries information on the wind evolution after decoupling from the neutrals. While most models assume an anisotropy of the plasma velocity components perpendicular and parallel to the solar magnetic field, the interpretation of the observations is influenced as well by the adopted electron density stratification and could be fitted without the assumption of anisotropic velocity distributions [9].

The in situ measurements of the NSW velocity distribution performed far from 3 solar radii (e.g. at the Solar Orbiter orbit) allow remote sensing of the three-dimensional coronal distribution of hydrogen. Hence, such observations represent a powerful diagnostic technique enabling to infer the degree of anisotropy, if any, in the neutral and charged coronal hydrogen from 3 solar radii downward. This diagnostics would then provide an extremely valuable test for deciding whether the ion cyclotron process is indeed acting on protons, since this would result in a broader velocity distribution, indicative of more effective heating, across the magnetic field than along the field direction, corresponding to the radial direction in polar coronal holes. Moreover, the proposed NSW measurements would also represent a unique remote diagnostics to infer the velocity distribution along the magnetic field direction, information that is not accessible via spectroscopic measurements of the coronal hydrogen emission; in fact with the field direction approximately perpendicular to the UV Coronagraph line-of-sight, the parallel velocity cannot be easily detected. This component, actually detectable by the NSWD and provided the direction of the incoming particle is measured, is indeed essential to establish the degree of anisotropy of the hydrogen velocity distribution in the corona [10, 11].

The previous considerations are related to a boundary limit for evaluating the source properties of the neutral distribution as observed at the Solar Orbiter position. In fact, even if the neutral and charged component decouple at approximately 3 solar radii, a neutral may still be ionised with a mean free path rapidly increasing with the radial distance. It will then be necessary to integrate along the lines of sight at different angles from the Sun, looking at the distribution function at each point and the probability that a neutral in that distribution will reach the detector. Only a small fraction of the neutral particles generated very near the Sun would be observed during the perihelion passage of Solar Orbiter, i.e. at 45 solar radii. Conversely, a large fraction of the neutrals generated at heliocentric distances greater than about 18 solar radii would fly unperturbed and eventually be detected by Solar Orbiter. On the other hand, in order to reconstruct the distributions back to within 3 solar radii, it is necessary to feedback the data with theoretical models of the solar wind evolution.

The heliocentric distance of ~18 solar radii is rather important since it represents the distance at which the corona stops to co-rotate with the surface of the Sun and the wind becomes super-Alfvénic. This distance was firstly evaluated by [12, 13], using Helios in-situ observations, setting the value between 10 and 30 solar radii. This distance acts as a filter for the Alfvénic turbulence since only outward propagating modes will be able to escape from the Sun. Inward modes, being faster than the wind bulk speed, will precipitate back to the Sun if they are generated before this point (for further reference refer to [14]). Thus, MHD turbulence is completely different moving across the Alfvén radius. Having information through the NSW about the kinetic state of the plasma around 18 solar radii and comparing it to in situ plasma measurement would be extremely valuable to understand wave-particle processes which are fundamental for solar wind heating and acceleration.

While the most important aspect of the planned measurements will be the remote sensing of the velocity distribution along the magnetic field direction and therefore deduce the distributions in the acceleration region of the solar wind, other fields of interest are CMEs and, possibly, the "inner source" and solar wind-dust interaction. For the latter, the orbit of Solar Orbiter is quite well suited with a perihelion of 0.21 AU. The connection between this "inner source" of the pick-up ions and the interplanetary dust cloud near the Sun remains an open question. The interactions of solar wind ions with the surface of the interplanetary grains provide one mechanism to explain the "inner source". If the ions traverse the grains, emerge neutralized and slowed down, then they can be ionized and become pick-up ions. The flux of the pick-up ions from the inner source is fairly high (few tons/s for oxygen ions picked up within 1 AU). It is therefore possible that the non-ionized fraction of the particles emerging from the grains may form a detectable part of the neutral solar wind. The main effect of the inner source would be just addition to the neutral solar wind. The neutrals emitted or traversing the grains are typically detected in the lower energy range. For particles traversing the grains, this mechanism is correct, but other mechanisms just give emitted neutrals co-moving with the grains [15, 16].

3. INSTRUMENT DESIGN CONCEPT

Since more than a decade, energetic neutral atom detectors for different particle populatons have been flown on space missions, e.g. SOHO, Cassini, IMAGE, Mars Express, and Venus Express.

At 0.21 AU, the neutral atom flux is expected to be about 100-1000 atoms cm^{-2} s^{-1}, but it could be up to 10^6atoms cm^{-2} s^{-1} within a CME. The NSWD should also measure energetic neutral atoms emitted from various coronal sources, and thus obtaining images of these coronal emission regions via rays of neutral atoms of different velocities. Detection of these fluxes of neutral atoms in the presence of intense solar radiation and solar-wind election and ion fluxes, however, is a challenge. In terms of UV scattered in the solar corona, even when the NSWD does not have the solar disk in its field of view, Ly-α must be suppressed by a factor of greater than 10^{-12}. Similarly, solar-wind ions and electrons must be discriminated by a factor of about 10^9, while transmitting neutral atoms unattenuated.

The neutral sensor concept for the NSWD instrument is based on micro-valve shutters gating the incoming neutral particles impinging on the detector entrance with a definite timing. Thanks to this approach neutral atoms can be processed and discriminated from ions with appropriate electrostatic deflectors, potentially without interacting with any impacting surface and thus preserving the directional information up to the stop detector. This technique, developed for the neutral atom camera ELENA in the frame of BepiColombo [2, 17] can allow an angular resolution better than 2° within a large 1-D FOV and cover an energy range from a few eV to about 5 keV.

The timing performances of the micro-valve choppers, which in last extent determine the Time-of-Flight (TOF) of the particles, are optimized basing the design on the state-of-the art of ultra-sonic oscillator (operated at frequencies up to 100 kHz) and high resolution gating nano-grids.

After passing through the instrument collimator, the impinging particles pass the entry chopper and pass into

a TOF chamber and are finally detected by a 2-dimesional array (e.g. based on Micro Channel Plates and discrete anodes sets), allowing reconstructing both velocity and direction of the incoming particles.
The signal of the detector is then composed of a sequence of pulses generated by the oscillation of the mask with respect to a fixed collimator. Randomization of the mask pattern could be also considered to improve the duty cycle, by associating the "opening/closing" state to pseudo-random sequences of ones and zeros, according to the technique described in [18]. With this mode, the duty cycle of the TOF chamber could be in the order of 50%.
Based on this concept as a reference design, the NSWD instrument on Solar Orbiter can be described as a neutral atom pinhole camera. The NSWD energy/nuc range is 0.05 to 5 keV/nuc, with resolution better than 0.05. Mass resolution is a very interesting, but presently secondary objective. The field of view of NSWD should be centred at about 25° off the spacecraft-Sun-centre line. A possible accommodation would be the +Y panel, in a position behind the sunshield and with an unobstructed field of view of +/- 20°, 25° off the S/C - Sun axis in the Sun-Satellite plane and about +/- 10° out of the plane (Fig. 1). The angular resolution should be better than 2°. Due to aberration of the impinging neutral atoms, the solar disk does not illuminate the NSWD entrance system at all (Fig. 2).

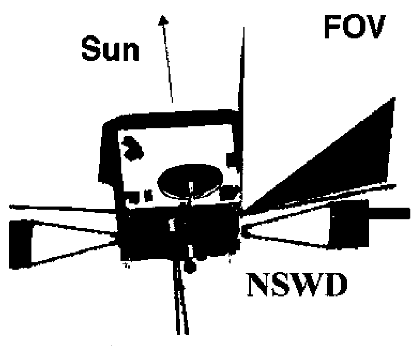

Figure 1. Potential accommodation and field of view (FOV) of Neutral Solar Wind Detector (NSWD)

A primary deflector and collimator can be housed in front of the gating chopper thus contributing in a first raw removal of the charged particles background, i.e. first solar wind plasma electrons and then ions. The TOF section within the sensor body can provide a longer fine discrimination path in which charge particles gated together with neutral can be rejected, deflecting and trapping the ion and the electrons out of the FOV neutral path. The collimator plate length, distance and potential would determine the cut-off of the charged-particle transmission (goal: about 40 - 100 keV/e). It can be achieved by means of high voltage biased plates within the instrument itself without protruding large external collimators [19]. In this respect sensor could be confined in a simple parallelepiped box with about 1cm^2 hole entrance. The first compartment can be also accommodates the baffle plates keeping out solar UV. The direct solar radiation is blocked by the solar orbiter sunshield (making use of the aberration of particles, see Fig. 2). For the suppression of scattered light within the collimator, the plates could be covered with sawtooth-like structures.
In this respect, one of the major merits of the nano-grids shuttering geometry is the capability to block the UV light by default, thanks to the minimal width of the slit apertures (goal width <100 nm) which may suppress Ly-α photons in a ratio better than 10^{-7}. Coupling a second shutter, driven by the same ultrasonic engine, but offering the opening state slightly later with respect to the main entrance shutter and thus shadowing completely the detector to the external UV environment might achieve further UV light background removal.
The NSWD can be built for a mass of about 1.3 kg, including about 0.2 kg for a, potentially shared, DPU. The power consumption would be about 2 W. The required telemetry rate is less than 0.32 kb/s. Spacecraft resources and real state maybe optimized by sharing DPU and mechanical structures with e.g. SWA.

Figure 2. Illustration of effect of aberration for Neutral Solar Wind Detector (NSWD)

4. CONCLUSIONS

The purpose of the NSWD on the Solar Orbiter is to directly measure the neutral, or "zero-charge state", solar wind in the vicinity of the sun. Together with the solar-wind plasma and magnetic field data, solar-wind acceleration models could be examined, and the atomic processes underlying the hydrogen-plasma coupling directly observed. Furthermore, the solar wind plasma - dust grain interactions, which are regarded as a potential candidate for the "inner source" for pick-up ions, could also be observed and studied via the data collected by the NSWD instrument.

The recent development in neutral particle instrumentation, e.g. ELENA for the BepiColombo Mission to Mercury, which incorporates active shutters in detectors using time-of-flight technique [2, 17], supports the technical feasibility of a NSWD for Solar Orbiter. The NSWD instrument can well be a part of the solar-wind analyzer (SWA), thus sharing resources such as digital processing and data handling.

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