SOLAR WIND IN-SITU MEASUREMENTS OF COHERENT ELECTROSTATIC FLUCTUATIONS ON STEREO

C. Salem(1), S.D. Bale(1), P.J. Kellogg(2), K. Goetz(2), J.L. Bougeret(3)

(1) Space Sciences Laboratory, University of California, Berkeley, USA
(2) School of Physics and Astronomy, Univ. of Minnesota, Minneapolis, USA
(3) LESIA, Observatoire de Paris-Meudon, Meudon, France.
ABSTRACT

One of the striking results obtained in the recent years concerns the small-scale structure of the solar wind plasma. Observations made by the Time Domain Sampler, an electric and magnetic waveform analyzer onboard WIND, have shed a new light on the nature of the "ion acoustic" electrostatic turbulence in the solar wind. This turbulence appears to consist of small amplitude coherent waves and solitary structures, many of which are weak double layers (WDL) with small potential drops of roughly 1 mV directed towards the Earth. It has been shown that those potential drops over a few tens of Debye lengths may be related to the large-scale interplanetary electric field needed to maintain the global charge neutrality in the solar wind.

The STEREO/WAVES experiment will have an improved, linear, waveform sampler experiment based on the WIND design. The STEREO/TDS instrument will sample from 3 orthogonal antennas; a further improvement over WIND's 2-axis system. We will discuss the prospect of using data from the two STEREO spacecraft to measure and compare WDL structures along two solar wind trajectories.
The large-scale interplanetary electric field

- The **solar wind** is the outward extension of the million-degree hot solar corona. It is a *weakly collisional, strongly turbulent plasma* in a *supersonic spherical expansion*. Since the electrons are less gravitationally bounded by the Sun than the protons, they tend to be displaced outward with respect to the protons.

- To maintain the global charge neutrality of the solar wind plasma, an **interplanetary electrostatic potential difference** $\Delta \Phi_{IP}$ sets in between the solar corona and “infinity”. The corresponding **electric field** $E_{IP}$ is **directed antisunward** and plays a key role in the solar wind expansion.

- Values of $\Delta \Phi_{IP}$ can be obtained from different models for solar wind expansion, for example, in a *two-fluid model* (where $E$ is related to the electron pressure) or in an *exospheric model* (where $E$ is such as there is equality between the escaping electron and the proton fluxes). These models predict a **potential difference** $\Delta \Phi_{IP}$ of the order of 400 to 600 Volts between the solar corona and the Earth orbit. **Such large-scale potentials cannot be measured directly in-situ.**
The small-scale structure of the solar wind plasma

- Since the solar wind is a weakly collisional plasma, it is usually argued that wave-particle interactions replace binary collisions in order to restore the fluid character of the flow by regulating the energy transport and dissipation. [Kellogg, 2000; Salem, 2000]

- Among the waves that can play a role in this respect, electrostatic waves in the ion acoustic frequency range \( f_{pi} < f < f_{pe} \) have been observed by several spacecraft in the solar wind. This broadband ion acoustic activity is an intermittent but almost permanent feature of the solar wind. [Gurnett, 1991; McDowall et al., 1996; Mangeney et al., 1999]

- Neither the wave mode nor the source of these waves have yet been unambiguously identified [Gurnett, 1991].

- Recently, high-time resolution data from the WAVES experiment on WIND have led to a major contribution to our understanding of this ion-acoustic-like wave activity in the solar wind, by revealing for the first time its highly coherent nature [Mangeney et al., 1999; Salem et al., 1999].
The WIND/WAVES experiment

- Our observations were taken in the ambient solar wind, at the Lagrange point L1, from May 20 – June 26, 1995.

- **The WAVES experiment on WIND** [Bougeret et al., 1995]:

  The electric field fluctuations are measured by two different instruments, from 2 orthogonal dipole antennas (100 m and 15 m tip to tip):

  - The **Thermal Noise Receiver (TNR)**, a spectral analyzer, measure continuously electric field power spectra from 4 to 256 kHz every 4.5 s (with an integration time of 1.472 s).

  - The **Time Domain Sampler (TDS)**, an electric (& magnetic) waveform analyzer, detects all the electric signals above a programmable threshold of ~ 50 µV/m), but only a few waveforms are transmitted to the ground (roughly, one every 10 min).

**Sampling rates**: 7500, 30000 and 120000 samples per second (time resolution up to 8 µs).
**Samples** of 2048 data points ⇒ **event duration** = 270, 70 or 17 msec.
Electric fluctuations measured by TNR

- Type III emission
- 2fp emission
- Langmuir waves
- Reverse shock
- Plasma line

Frequency (kHz) vs. Time (UT)
Electric fluctuations on TNR at a given frequency

- **Quasi-thermal noise (QTN):**
  [Meyer-Vernet & Perche, 1989; Meyer-Vernet et al., 1998; Issautier et al., 1999]
  
  at $E^2(f) \approx 10^{-13.5} - 10^{-13} \text{ V}^2/\text{Hz}$
  with Gaussian statistics.

- **Intermittent non thermal emission**, with a power-law distribution.

- Above 7 kHz, these nonthermal emissions disappear.
Electric waveforms on TDS

- In the “quiet” solar wind, all events detected by TDS are coherent electrostatic waves (CEW), with properties similar to those of ion acoustic waves [Mangeney et al., 1999].

- The typical wavelengths are:
  - $10 < \lambda/\lambda_D < 50$, for the wave packets,
  - $\Delta x/\lambda_D \approx 25$, for the solitary structures.

- They are parallel propagating waves, with $E // B$. 
Weak Double Layers (WDL) in the solar wind

About 30% of these CEW are solitary structures with a measurable net potential drop: 

\[ e\Delta \phi / k_B T_e \approx 10^{-4} - 10^{-3} \]

or

\[ \Delta \phi \geq 10^{-3} \text{ Volts} \]

The corresponding electric field is almost always directed towards the Earth \[\text{[Mangeney et al., 1999]}\].

Is \(\Delta \Phi_{IP}\) the result of a succession of small potential drops in weak double layers, due to small charge separations \((\delta N/N_e \sim 10^{-5})\) between the protons and the escaping electrons? \[\text{[Salem et al., 1999]}.\]
Occurrence of WDLs in the solar wind and estimation of $\Delta \Phi_{IP}$

[Lacombe, Salem et al., 2002]

- Comparing the **average spectral energy densities** on TDS and on TNR, over a common frequency range (between 4 and 6 kHz) has allowed us to estimate the **frequency of occurrence of CEW in the solar wind**: $N_{CEW} \sim 0.5 \, s^{-1}$.

- Since only 11% of the observed CEW’s contribute to the frequency range above 4 kHz, and 30% have a measurable potential drop, we concluded that the **number of WDLs** drifting past WIND would be : $N_{WDL} \sim 1-1.5 \, s^{-1}$.

- **Extrapolating this result** and assuming,
  - an average travel time of 3 105 sec for a solar wind plasma element between the solar corona and the WIND orbit,
  - both NWDL and the average potential difference $\Delta \phi$ across a WDL remain constant,

one may estimate the **total potential difference** (a lower estimate probably) :

$$(\Delta \Phi)_{IAU} \geq 400 \, Volts$$

which is **in the range of values needed to maintain charge neutrality** in the solar wind [Scudder and Olbert, 1979].
STEREO/WAVES Sensors

- 3 orthogonal monopoles of 6 m each.
- magnetic loop antenna?
STEREO/WAVES Time Domain Sampler (TDS)

- **TDS specifications**:  
  - TDS on STEREO is a **16 bit** A/D converter.  
  - TDS will sample from **3 orthogonal antennas**, measuring **3 components** of the AC electric field.  
  - TDS has **programmable sampling rates** with events of maximum **length of 16 ksamples**.  
  - The **possible sampling rates** are: 250,000 samples/s, 125,000 samples/s, 31,250 samples/s, and 7,812.5 samples/s.

- **Measuring small amplitudes events with STEREO/TDS**:  
  - On **WIND**, we actually measure the logarithm of the potential difference and **digitize to 8 bits**.  
  - On **STEREO**, the use of a **16 bit linear A/D converter** provides **sufficient dynamic range** with **much better fidelity**. This will produce a **more accurate representation** of the **lowest amplitude WDL events** in the solar wind.
Advantages of STEREO/WAVES/TDS

- TDS on STEREO will provide a much more accurate representation of the low amplitude signals than on WIND.

- The use of 3 orthogonal antennas on STEREO is a further improvement over WIND’s 2 axis system. This will allow us to determinate more accurately the wave properties (wavevector and its direction, direction of the small-scale electric field associated to the WDLs, etc.).

- The event duration will be long enough to allow a more accurate determination of the frequency of occurrence of the coherent electrostatic wave as well as of the weak double layers in the solar solar. For example, a 16 ksample event, sampled at 31,250 samples/s will correspond to a half-second duration event.

- Finally, a complete statistical study of the spatial distribution of weak double layers along the magnetic field lines, and the corresponding estimate of the total potential difference between the solar corona and the Earth orbit, on two different solar wind trajectories could be achieved using the two STEREO spacecrafts.
REFERENCES

• Bougeret J.L., et al., *Space Science Reviews*, 71, 231, **1995**.
• Gurnett D.A., in *Physics of the Inner Heliosphere II. Particles, Waves and Turbulence*, vol.21, Springer-Verlag, pp 135, **1991**.
• Issautier K., et al., *J. Geophys. Res.*, 104A, 6691, **1999**.
• McDowall R.J., et al., *Astron. & Astrophys.*, 316, 396, **1996**.
• Salem C., *PhD dissertation*, Université Paris 7/Observatoire de Paris, **2000**.
• Salem C., et al., in *Lecture Notes in Physics* “Nonlinear Waves and Turbulence”, vol.536, pp 251, **1999**.
• Scudder J.D., and Olbert S., *J. Geophys. Res.*, 84A, 6603, **1979**.