Characteristics of Solitary Waves and Weak Double Layers in the Magnetospheric Plasma

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The wave experiment of the Viking satellite frequently detected dynamic small-scale ($\simeq 100$ m), large-amplitude, rarefactive ($|\Delta n/n| \lesssim 50\%$) solitary waves of negative potential ($|\phi| \lesssim 2$ V) moving upwards along the magnetic field lines ($v = 5$ to > 50 km/s). The structures, which resemble ion holes, often have an upward-directed net potential drop ($\lesssim 1$ V) and are then interpreted as weak double layers.

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There is currently an interest in the appearance in space plasmas of small (Debye) scale solitary structures, such as ion acoustic solitions, ion holes, phase-space vortices, and weak double layers. While several laboratory studies,[1,2] computer simulations,[3,4] and theoretical investigations[5-7] have been performed, partly with space applications in mind, *in situ space experiments* revealing such structures are rare. The low-frequency wave experiment[8] of the Swedish Viking satellite (launched 22 February 1986, apogee 13527 km, perigee 817 km, inclination 98.8°) has verified the occurrence in the magnetospheric plasma of structures described as solitary waves (SW, with no net potential drop) and weak double layers (WDL, with a small net potential drop $|\phi| \lesssim kT_e/e$) first reported[9] from the S3-3 satellite. Our experiment has provided new information on their characteristics, i.e., spatial and temporal scales, direction of motion, typical velocities, density depletions, and the relation between density and potential variations.

The structures are of interest *per se*, but also for particle energizing processes which may be of universal occurrence. Specifically, it has been proposed that the simultaneous presence of a large number of WDL's along the geomagnetic field lines might, through their cumulative effect, contribute to the auroral particle acceleration,[9] and stochastic variations might provide a mechanism to explain observed energy spectra.[7]

The new, two-point measurements of relative plasma density variations ($\Delta n/n$) provided by two Langmuir probes on Viking proved particularly useful. Two spherical probes of diameter 10 cm were located 80 m apart at the end of wire booms in the spin plane (spin rate 3 rpm) of the spacecraft (inset in Fig. 1). The probes were biased positively (> 16 V), so that photoelectron currents were negligible, in order to collect electron currents proportional to the plasma density (n). The influence of electron temperature variations is discussed below, and other possible interference sources, such as capacitive coupling of potential fluctuations, have been estimated to be of minor importance (details must be omitted here). Logarithmic amplifiers followed by high-pass filters ($f > 05$ Hz) provided signals proportional to $\ln(1+\Delta n/n)$ for variations of sufficiently short temporal scale. The two Langmuir probes, and two similar probes on a perpendicular pair of wire booms, could also be operated in voltage mode with a negative current bias, i.e., on the photoelectron-dominated steep part of the current-voltage characteristic, in order to measure potential fluctuations. Two wave-form signals could be sampled simultaneously at a maximum rate of 853 s^{-1}.

Figure 1 shows the two $\Delta n/n$ signals at an instant when the probes were separated nearly along the magnetic field line (boom angle $\alpha \simeq 16°$). Structures (plasma holes) with density rarefactions of up to 50% are seen to be recorded first by the lower probe, then by the upper one. From the time delay, which varies from one structure to the next, field-aligned velocities of 16, 20, 14, and 12 km/s (relative to the spacecraft) are inferred for the samples of the figure. With the velocity known, the observed duration of each pulse may be converted to a spatial dimension; the extent along the field lines is then found to be about 100 m, which is $(5-50)\lambda_D$ for es-

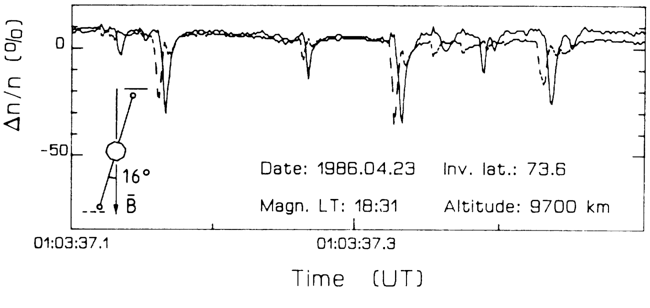

FIG. 1. Rarefractive solitary structures recorded by two spatially separated plasma density probes.

timates of $n = 10^6 - 10^7\ \mathrm{m}^{-3}$ and $T_e = 1-10$ eV.

The scale transverse to the magnetic field could not be measured directly. However, as one and the same structure generally, but not always, was recorded by both probes even when these were separated transverse to the magnetic field, we infer a characteristic transverse dimension larger than 80 m.

A difference in shape between corresponding pulses from the two probes (see Fig. 1) can be due either to temporal or spatial effects. For most boom angles the two probe signals derive from different parts of a structure. True temporal effects are monitored only around $\alpha = 0°, 180°$. Variations are seen, but there is no preponderant growth or decay of amplitude during the time for propagation from the lower to the upper probe. Evidently, the lifetime of the structures is at least about 10 ms.

For individual structures we can only determine an apparent (phase) velocity in the boom direction. From a large number of samples for different boom directions we can, however, derive the real direction of motion. Figure 2(a) shows a scatter plot of the time delay for the passage of a number of structures as a function of the boom angle. With a few exceptions all points show delays consistent with a motion upwards along the magnetic field lines, i.e., change of sign at 90° and 270° and maximum delays around 0° and 180°. The smooth ordering of data points is a strong indication that the structures are relatively flat and extended in the plane transverse to the magnetic field.

Assuming planar structures moving along the field lines we may convert the time delays also for $\alpha \neq 0°, 180°$ to field-aligned velocities $v_{\parallel}$. Figure 2(b) shows inferred parallel velocities; as expected there is no systematic dependence on the boom angle. A correction for the spacecraft velocity has been introduced; thus velocities are measured relative to the Earth. Values above 50 km/s are uncertain as the time delay only can be determined within ± 0.6 ms. The velocities are characteristically in the range 5–50 km/s, i.e., of the order of the ion acoustic velocity.

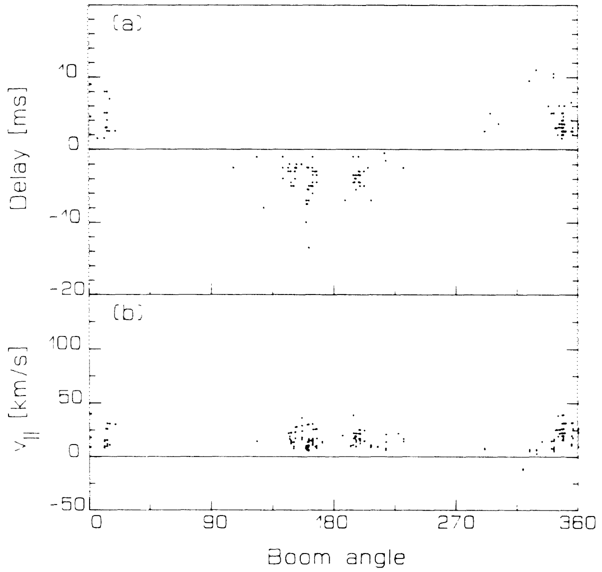

FIG. 2. (a) Delay between probe signals for different boom angles. (b) Inferred field-aligned velocities.

A difficulty in interpreting the motions is that we do not have any direct measurement of the possible flow velocity of the thermal plasma parallel to the magnetic field. The structures occur in regions of upward-directed beams of energetic ($\lesssim 1$ keV) ions (moving much faster than the structures) and downward-accelerated energetic electrons. In these acceleration regions thermal electrons and ions, when present, are expected to flow in the same directions as the energetic ones, contributing to an upward-directed electric current. Thermal ions would then flow upwards, even if they carry a minor fraction of the current. Also in the absence of a current, *thermal* ions may be moving upwards in a polar wind flow, which may be supersonic.[10] The observed upward motion could thus be structures moving with thermal ions, or even moving downwards relative to such ions, which would agree better with motions seen in some laboratory experiments.[1]

We have searched for a possible relation between propagation speed and amplitude of the structures, either such as 1D solitons obey or as expected for ion holes. Although we cannot follow the development of speed of individual structures a statistical study might reveal a relation. However, no systematic dependence has been found in our data.

Using the probes for potential measurements (lower panel of Fig. 3) we find the signatures of SW's and WDL's reported earlier[9] from S3-3. Probes separated along the magnetic field clearly show solitary structures for which the potential difference between the upper and lower probe goes first positive, then negative. This obser-

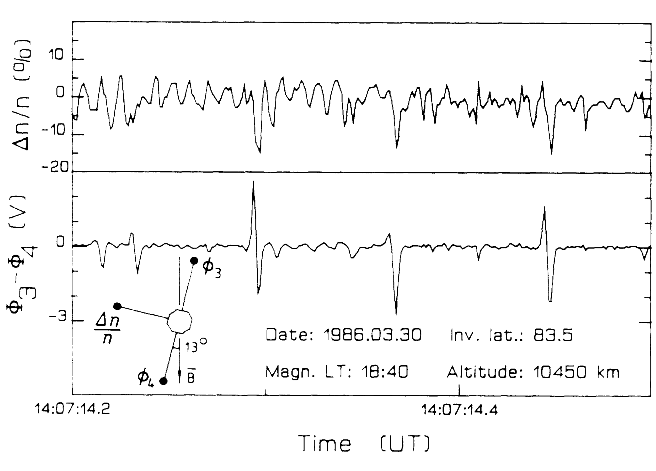

FIG. 3. Simultaneous density and electrostatic potential difference variations during passage of solitary structures.

vation alone could be interpreted either as a positive potential barrier moving downwards passing first the upper and then the lower probe, or as a negative potential well moving upwards passing first the lower and then the upper probe. As our $\Delta n/n$ measurements show that the structures move upwards, the latter alternative must be the correct interpretation. When the positive and negative peaks of the signal differ, the negative peak generally dominates which implies a net potential drop in the upward direction. These structures are classified as WDL's and the net potential drops are up to about 1 V. The polarity is consistent with the one required for acceleration of ions upwards and electrons downwards as observed.

In Fig. 3 we compare the potential-difference variations recorded by the pair of potential probes with simultaneously recorded density rarefactions seen by a third probe operated in $\Delta n/n$ mode. Coincident signatures of solitary structures are seen, and Fig. 4 shows a scatter plot from a larger number of observations of maximum rarefactions versus maximum potential difference between the two probes. Although the variations are not recorded at precisely the same point in space (cf. inset in Fig. 3) they clearly belong to the same structure and exhibit a general correlation.

We have neither precise nor continuous electron temperature measurements, but from intermittent Langmuir-probe sweeps temperatures of the order 1–10 eV are inferred. The two lines of Fig. 4 correspond to Boltzmann relations for 2- and 20-eV electrons, and the plot demonstrates that the quasistatic electric forces may balance the electron pressure gradients of the solitary structures and prevent thermal electrons from entering the holes. Although the solitary holes are depleted also of ions there is no similar static force keeping thermal ions from flowing into the holes and becoming trapped there during the growth. The lifetime of the structure is therefore expected to be governed by ion inertia, which is consistent with the minimum lifetime inferred from our observations.

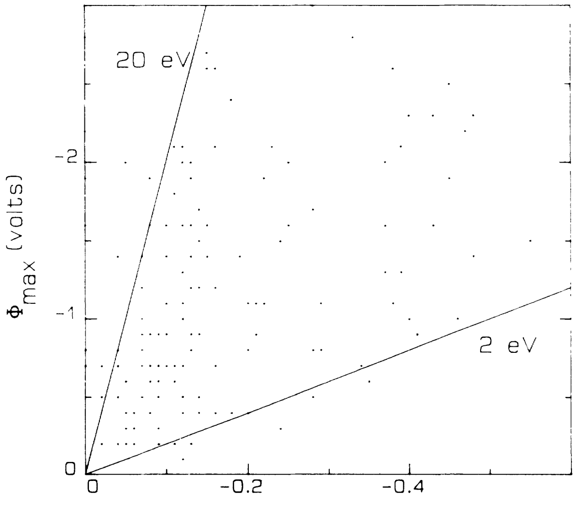

FIG. 4. Scatter plot of maximum recorded potential variations vs maximum density variations for individual solitary structures. The lines correspond to Boltzmann relations for 2- and 20-eV electrons.

Experimentally, probe currents in $\Delta n/n$ mode do not allow a unique interpretation. Solitary decreases could alternatively be increases of electron temperature with $\Delta T_e/T_e$ about twice as large as the quoted $|\Delta n/n|$. We consider this less likely, as we are not aware of any mechanism for maintaining such localized increases of electron temperature, which in particular would be incompatible with the suggested balance between the observed electric fields and the electron pressure.

The observed solitary structures presumably grow out of small-amplitude fluctuations by a microinstability mechanism associated, e.g., with drifting particle populations. The electron-driven ion-acoustic instability has been studied most extensively, but some simulations[3] show growth even for electron drift velocities below the threshold for linear instability suggesting a nonlinear instability. We note that currentless double-layer solutions also exist.[11] The ion beams and frequently observed electrostatic ion cyclotron waves[8,9] may also be crucial for the growth. Wave troughs and crests of large-amplitude ion cyclotron waves may trap or expel particles[4] and form seeds for solitary wave formation.

The evolution into strongly nonlinear solitary structures and WDL's is usually assumed to result from momentum exchange[6] between downward-drifting thermal electrons and the potential wells. The wells then grow to about kT_e/e and develop similar upward-directed net potential drops. The model, however, does not readily explain multiple WDL's along each field line, as indicated by our data and required to produce significant acceleration. In a steady-state 1D model only the uppermost WDL reflects thermal electrons. Electrons in the tail of the velocity distribution, which are not reflected, will become energized and are then not reflected, but further accelerated, by the WDL's below. An adequate time-dependent 3D model is called for where possibly transverse drift or diffusion supplies fresh thermal electrons all along the field lines.[7]

Our Viking experiment has verified and considerably extended the earlier observations[9] of solitary structures in the magnetospheric plasma. The structures are found to have similar characteristics (polarity, spatial scales, amplitudes, lifetimes) as in some laboratory experiments[1,2] and computer simulations.[3,4] Depending on the net potential drop the structures may be classified as SW's and WDL's, or in other words symmetric and asymmetric ion holes. Most likely these represent different phases of the evolution of a type of solitary structure, rather than different phenomena. In general the potential of a WDL is not monotonic, but starts with a minimum on the upper side, and the structure is then really a triple layer in terms of charges.

So far we have only analyzed a limited data set; further work will encompass more extensive statistical studies and should also focus on the relations to geophysical phenomena observed by the full complement of instruments on the Viking spacecraft.

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