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Front cover: Sun-god Papautl of the Mayas.

ION SOUND TURBULENCE IN THE SOLAR WIND

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Abstract: A stability analysis for ion sound is carried out which directly uses detailed measured particle distributions, rather than model distributions. Correlation with measured wave activity is satisfactory. Valuable information about the instability mechanism, transport processes and the accuracy of measured distributions can be obtained by this method.

Recently, electrostatic fluctuations have been measured in the solar wind, over a wide range of radial distances (0.3 - 3 AU) from the sun (Gurnett, 1978). The wave vectors tend to be aligned with the magnetic field (heat flux) and satisfy $k\lambda_D \lesssim 1$ (λ_D Debye length). Waves occur in bursts of a few tenths of a second and activity lasts from several hours to several days. These wave characteristics and the correlation of wave activity with macroscopic parameters such as the electron-ion temperature ratio and the electron heat flux strongly indicate that the modes may be identified with ion sound waves (Gurnett et al., 1978). The stability of unmagnetized electrostatic modes depends on the reduced distribution function in the direction of wave propagation. Accepting that electrons have no net drift with respect to the ions or low energy double peaks, there are basically only two free energy sources for ion sound, a drift of low energy electrons (core) relative to the ions as is characteristic of a skewed distribution carrying a heat flux, and resolved double peaks in the reduced ion distribution (Gary, 1978; Lemons et al., 1978). Nonlinear excitation by coupling to other modes may also be possible. The question regarding the mechanism responsible for the observed fluctuations is still open. An answer to this problem is also important for a stuy of the anomalous transport effects connected with the wave activity (Dum, 1978a, b). We hope to contribute to a resolution of this issue, by a linear stability analysis which directly uses detailed measured particle distributions rather than model distribution functions, and compares the results with measured wave activity.

A numerical code which resolves the measured distribution functions into spherical harmonics,

$$f(\underline{v}) = \sum_{l,m} f_l^m(\underline{v})\, Y_l^m(\hat{\underline{v}}); \qquad \hat{\underline{v}} = \underline{v}/v = (\theta,\phi) \tag{1}$$

in an appropriately chosen coordinate system, and then determines the dispersion relation for arbitrary speed dependence of the f_l^m, can be used most efficiently for our purposes (Dum et al., 1978). One may, for example, isolate a particular free energy source for instability, by arbitrarely turning off various measured anisotropies, corresponding to heat flux ($l = 1$), viscous pressure ($l = 2$) or higher order l terms required to describe the electron anisotropy at high speeds or the strong speed dependent ion anisotropies. We are not biased by the rigid speed dependence and anisotropies of the various model distributions generally used in stability analysis and thus are able to extract the maximum information from data, such as obtained from the Helios space crafts (Rosenbauer et al., 1978).

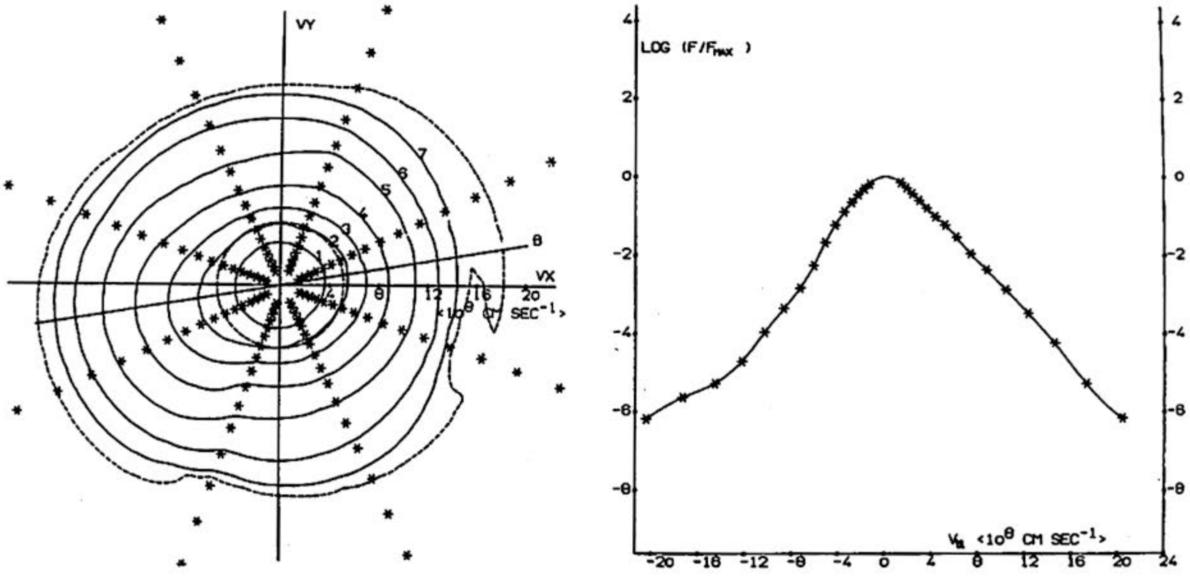

Fig. 1. Electrons: Contour lines (10^{-n}, n = 1,2..) of a cut in the ecliptic plane and reduced distribution function along the magnetic field. (Solar direction: $v_x > 0$, $v_\parallel < 0$).

The intrinsic limitations of the stability analysis imposed by the finite resolution and accuracy of the measurements can be analyzed by our method. We may also find out how the ambiguity in fitting various models to measured distribution functions affects the outcome of conventional stability analysis. The fact that there is an apparently strong positive correlation between observed wave activity and the least square deviation from a Maxwellian fit to the ions (Gurnett et al., 1978) should be noted in this connection. For electrons, more sophisticated core-halo fits by two bi-Maxwellians, also become poor for increased anisotropies, characteristic of heat flux, despite the large number of parameters that need to be determined (Feldman et al., 1976).

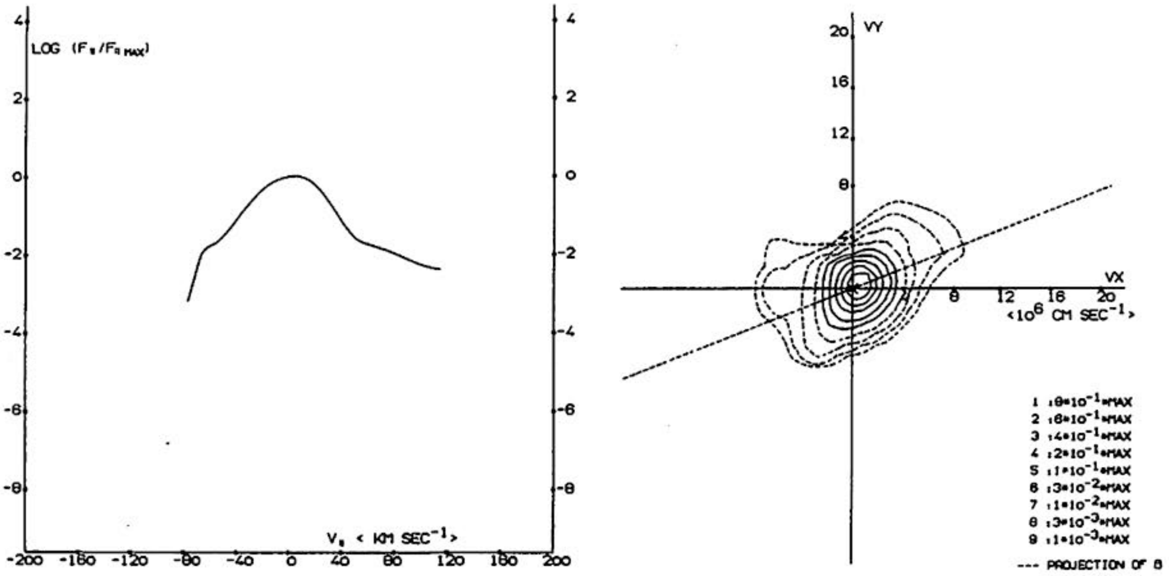

Fig. 2. Ions: Reduced distribution along the magnetic field and contour lines of a cut in the plane formed by magnetic field and bulk speed. (Solar direction: $v_x < 0$, $v_\parallel < 0$). Measurements are by Helios 1 at UT 289:14:12:32 and distance 0.57 AU from the sun.

A stability analysis using a combination of drifting Maxwellians is very instructive (Gary, 1978; Lemons et al., 1978) but appears somewhat artificial for the measured distributions. The features of non-Maxwellian distributions relevant to ion sound have been analyzed in detail (Dum, 1978a, b). The dispersion relation may be written in the form

$$(kv_i/\omega_i)^2 = -\left[(T_i/T_e)\hat{\varepsilon}_e(\underline{k},\omega) + \hat{\varepsilon}_i(\underline{k},\omega)\right] \tag{2}$$

where the dielectric constants are normalized by introducing the plasma frequencies $\omega_j^2 = 4\pi n_j e_j^2/m_j$ and characteristic thermal velocities $v_j^2 = T_j/m_j$, $j = e, i$ defined by the second moments of the distributions in the (common) rest frame $\underline{w} = \underline{v}-\underline{u}$. The quasi-neutrality condition $n_e = n_i = n$ is also used, but not for the fluctuations. For phase velocities $(\omega/k) \ll v_e$ the electron contribution to (2) depends primarily on low speed particles, roughly with the weight factor w^{-2}, although particles of all speeds $w > (\omega/k)$ contribute to the resonance $\omega-\underline{k} \cdot \underline{w} = 0$. The dielectric constant may be written in a form resembling the result for a drifting Maxwellian

$$\hat{\varepsilon}_e(\underline{k},\omega) = a_{-2} + i(\pi/2)^{1/2} a_{-3}\, v_e^{-1}\left[(\omega/k)-u^*(\hat{k})\right] \tag{3}$$

where the form factors $a_{-2} = v_e^2 \int d\,\underline{w}\, f_e(\underline{w}) w^{-2} = T_e/T_e^*$ and $a_{-3} = (2\pi v_e^2)^{3/2} f_e(0)$ define the effective electron temperature and slope respectively, and are equal to unity for a Maxwellian. The effective drift velocity is determined by the odd l anisotropies, also weighted with the factor w^{-2}. Thus, $u^{*}(\underline{\hat{k}})$ is not directly related to the mean-velocity ($\langle w \rangle = 0$ in the rest frame) or the heat flux ($\sim w^{3}$) but rather to the rate of momentum transfer with an effective collision frequency $\nu \sim w^{-3}$, corresponding to electron-ion collisions or ion sound turbulence (Dum, 1978b). A unique relationship between u^{*}, heat flux q_e and temperature gradient ∇T_e exists only for the nearly Maxwellian distributions of classical transport. The dependence on the angle α between wave vector $\underline{\hat{k}}$ and anti-heat flux direction $-\underline{\hat{q}}$ may also differ from a $\cos \alpha$ law. In fact, we find that in the presence of a strong "Strahl", u^{*} generally peaks at substantial angles to $-\underline{\hat{q}}$. In the low temperature approximation $(\omega/kv_i) \gg 1$ for the ions, the real part of the dielectric constant may be expanded in terms of the usual moments, density, pressure tensor, heat flux tensor etc. Each term also yields a dependence on the direction $\underline{\hat{k}}$, corresponding to definite values of l in expansion (1) (Dum et al., 1978). Stability analysis must account for the very different behaviour of electrons and ions, just discussed. If model distributions are used, the fit parameters should at least be determined from measured distributions with appropriate weight factors, rather than from simple least square fits.

For ion sound in the solar wind, the approximation $(\omega/kv_e) \ll 1$ is excellent. The condition $(\omega/kv_i)^2 \gg 1$ is not very well satisfied, however. In fact, the temperature ratio is often not as large as demanded by conventional stability analysis. From Fig. 2 we may guess that the effective ion temperatures for the sound velocity, $c_s^2 = (T_e^{*} + 3\,T_i^{*})/m$, and for Landau damping also differ from the moment T_i. No analytic reduction such as (3) is possbile, however, for finite (ω/kv_i) and the dielectric constant must be computed directly from the measured distribution. For resonant instabilities, the imaginary part of the dielectric constant depends on details of the distribution functions and thus must always be computed by the full numerical code. For small growth rates the range of phase velocities $(\omega/k) + i0$ is determined by the condition that $\mathrm{Re}\hat{\varepsilon}_i$ be sufficiently negative to compensate $(T_i/T_e)\mathrm{Re}\hat{\varepsilon}_e \approx T_i/T_e^{*}$ in (2).
The imaginary part of (2) determines then the rate of dissipation or the growth rate $\gamma_{\underline{k}}$. We introduce the normalization

$$\hat{\gamma}_{\underline{k}} = -(1/2)(\omega/kv_i)^2 \left[(T_i/T_e)\mathrm{Im}\,\hat{\varepsilon}_e + \mathrm{Im}\,\hat{\varepsilon}_i\right] \tag{4}$$

corresponding to $\hat{\gamma}_{\underline{k}} \approx \gamma_{\underline{k}}/\omega_{\underline{k}}$ for low temperature ions. The distributions in Figs. 1, 2 correspond to observed ion sound activity. We find $T_i/T_e^{*} = 0.187$, a maximum phase speed $(\omega/k) = 46$ km/sec corresponding to $k\lambda_D \approx 0$ and $\gamma_{\underline{k}} = -3.8\,10^{-2}\,[-3.8 + 4.8] = -3.8\,10^{-2}$ in the direction $-\underline{\hat{q}}$. The damping is larger in other directions and increases rapidly with decreasing phase speed. Less than three minutes later the electrons are more anisotropic and give the largest destabilizing term at $\alpha \approx 45^{o}$. We also found a few destabilizing double ion peaks. So far, however, we have not found positive net growth rates by either mechanism. For periods of observed wave activity the computed damping rates are very small, whereas for passive periods the damping is large. We consider this correlation satisfactory, since for active periods we only expected to find conditions close to marginal stability. It is well known from laboratory and computer experiments that self-regulatory quasi-linear effects in a collisionless plasma limit ion sound turbulence to short temporal or spatial bursts, with a width and (much longer) repetition period depending on macroscopic conditions (Dum, 1978a, b). High resolution wave observations in the solar wind agree with this picture. The period required for a complete measurement of particle distributions, however, is much longer than the duration of the bursts, hence it should be dominated by the decay and recovery phase, $\gamma_\kappa \lesssim 0$, of the bursts (Lemons et al., 1978). From the very low excitation levels and the short duration of the bursts, we may conclude that during active periods the plasma actually remains extremely close to marginal stability. Rather than looking for unstable distributions, it thus appears to be more promising to study possible modifications of the distributions, consistent with the constraints imposed by the marginal stability condition, quasi-linear effects and particle measurements. Comparing with Coulomb collisions we find for electrons that even for fluctuation levels $<E^2>/8\pi nT$ as low as 10^{-7}, turbulence completely dominates isotropization. Inelastic turbulent scattering is much slower but still dominates for speeds $w \leq w_0 = O(v_e)$ and leads to a flattening of the electron distribution in this range. The form factor a_{-3} decreases very rapidly (Fig. 1; Dum, 1978a) and a_{-2} also decreases for an electron distribution self-consistent with ion sound. Because of contamination by photoelectrons and distortions by the spacecraft potential the electron distribution below the thermal velocity is not measured but extrapolated, using a Maxwellian fit to core electrons. Simply using a flat topped distribution in this range, instead, leads to negligible changes in total temperature and density but reduces the form factors for the core component from unity to $a_{-3} = 0.63$ and $a_{-2} = 0.83$. Varying the space craft potential by ± 2 Volts from the estimated value changes $\mathrm{Im}\hat{\varepsilon}_e$ by a few percent. Cold ions, on the one hand favor ion sound instability, but on the other hand, the measured fluxes are then above the one count level only in relatively few channels of the ion instrument. The spacing of channels in velocity may become comparable or even larger than the ion thermal velocity. These uncertainties affect primarily the imaginary part $\mathrm{Im}\hat{\varepsilon}_i$. The net growth rate, of course, is affected even more strongly, since near marginal stability it is the difference of two comparable terms.

We have demonstrated the feasibility of a stability analysis which directly uses measured distributions. More extensive data surveys are under way, including also electromagnetic instabilities. Stability analysis for periods of observed ion sound activity should give valuable information about the instability mechanism, transport processes and particle distributions.

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