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An Effect of Micro-Instability on the Temperature Anisotropy in the Solar Wind

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Abstract: Recent observations show that the solar wind plasma has a thermal anisotropy in a reference frame moving with the convective velcoity. A rough estimate of anisotropic thermal velocities can be made if the anisotropy is produced by a combination of the collisional redistribution process and the increment of an anisotropy due to the conservation of the first adiabatic invariant. The velocity distribution estimated in this paper is much more anisotropic compared with the observations by space vehicles. This discrepancy suggests that there must be some processes which are more effective in redistributing velocities than the collisional process. In the hydromagnetic analysis, it has been generally considered that the *garden-hose* (*G-H*) instability is caused by the anisotropy of the velocity distribution in the interplanetary plasma. When right-hand polarized waves (*R-mode*) come into resonance with protons in the tail of the anisotropic velocity distribution, R-*mode* instability breaks out due to a perturbation. The quasilinear treatment leads to the conclusion that beside the *G-H* instability, the R-*mode* instability can control the temperature anisotropy. The *G-H* instability can be caused when the pressure ratio β exceeds 2, while the R-*mode* instability takes place when $\beta \geq 0.7$.

1. Introduction

Parker (1963) first described the solar wind as the stationarily expanding solar corona in a frame work of ordinary hydrodynamics, the gross feature of the solar wind observed by space probes can be explained so far by an asymptotic solution of his theory. This fact would confirm the justification of his treatment of the medium as well as his basic idea. However, the situation of the plasma in which hydrodynamic description can be used is that the velocity distribution of plasma particles must have relaxed sufficiently toward equilibrium, suggesting that the redistribution must occur. Parker expected that some plasma instabilities would contribute to the redistribution in the solar wind plasma.

Actually, there would be such redistribution processes in the solar wind, since the solar wind plasma is unstable for some kind of perturbations. Solar wind plasma will be lead to turbulent state through the wave-particle interactions. It can be qualitatively inferred that there are many types of such wave-particle interactions in the solar wind, but, at the present time, direct observations have not be able to offer so sufficient plasma parameters as can be used for quantitative analysis of the process.

However, we have informations on the "temperature" (or thermal spread) T, of the plasma. Wolfe *et al.* (1966) reported that the temperature of the solar wind was considerably anisotropic. According to them the ratio $T_{\parallel}/T_{\perp}$ amounts to where $T_{\parallel}$ and $T_{\perp}$ are the temperature parallel and perpendicular to the local magnetic field, respectively.

This anisotropic feature was confirmed more strictly and rigorously by Hundhausen *et al* (1967). So we shall discuss in this report the plasma instabilities due to anisotropic velocity distribution.

Here we outline the typical parameters in the interplanetary space for the later use. These are observed by many space probes in the vicinity of the earth's orbit.
Average temperature $T=6\times10^4\sim5\times10^{5}$°K
Ion number density $N_i=1\sim2\times10$ protons/cm^3
Magnetic field B_0=several gamma (1 gamma$=10^{-5}$ gauss)

2. Temperature anisotropy

Let us consider a simple theoretical picture that redistribution mechanism only depends on collisions and that there is an isotropy for ions and electrons at some radial distance r_0 from the sun. Parker (1963) and Hundhausen *et al.* (1967) expected that an anisotropy is made from the cooling process of the thermal motions perpendicular to the solar magnetic field through the invariance of magnetic moment, μ, ($v_\perp^2/B$ is constant) and the redistribution process through the self-collision mechanism.

Quiet day interplanetary magnetic field may be written by Parker(1958) as follows;

$$B=B_r r_1^2\sqrt{\frac{1}{r^4}+\left(\frac{\Omega_s}{V_s r}\right)^2}, \tag{1}$$

where r_1= a reference level (1.3 $R_\odot$)
B=a radial field at the reference level
V_S= a solar wind velocity
Ω_S= the solar angular velocity.

As the solar wind flows away from the sun, the magnetic field decreases, and the transverse thermal motions cool down in the absense of redistributions due to a conservation of the first adiabatic invariant μ. While we can suppose that longitudinal thermal motions are essentially maintained. In this way the temperature anisotropy ratio $T_{/\!/}/T_\perp$ grows till redistribution becomes effective.

Now we consider a collisional redistribution process. According to Spitzer (1956) a self collisional time τ_c is expressed by

$$\tau_c=\frac{11.4\,A^{1/2}\,T^{3/2}}{N\,ln\,\Lambda}, \qquad \Lambda=1.24\times10^4\,T^{3/2}\,N^{1/2}, \tag{2}$$

where A is the ratio of the particle mass to the mass of unit atomic weight.

The variation of the self collision time with a temperature is shown in Table 1.

Proton-proton collision will gradually establish an isotropic Maxwell velocity distribution for the protons, and the same process may be said of the electrons. But the self collision time τ_c for electron is less than for proton by the square root of the mass ratio of electron to proton, or by a factor of 1/43. On the other hand proton-

Table 1
Self collision time

Temberature	Proton-Proton Selfcollision	Electron-Electron Selfcollision
1×10^4 °k	5.16×10^4 sec	1.20×10^3 sec
3×10^4	2.50×10^5	5.83×10^3
5×10^4	5.20×10^5	1.21×10^4
7×10^4	8.50×10^5	1.98×10^4
1×10^5	1.41×10^6	3.30×10^4
3×10^5	6.89×10^6	1.61×10^5

electron collisions do not change appreciably the distribution of electron kinetic energies. Therefore, the self collisions are only considered to be the redistribution process.

The interplanetary space is classified here into two regions; A and B. In the region A, the solar wind sweeps before the redistribution occurs, $V_S\tau_c+r_0$ away from the sun, and in the region B the solar wind sweeps after redistribution.

Thus, we may say from Equation (1) and conservation of the first adiabatic invariant that the temperature anisotropy ratio $T_{/\!/}/T_\perp$ is limited to a value of the order of

$$\frac{T_{/\!/}}{T_\perp}=\frac{r^2}{r_0^2}\sqrt{\frac{1+r_0^2\,\Omega_s^2/V_s^2}{1+r^2\,\Omega_s^2/V_s^2}} \qquad r<r_0+V_s\tau_c$$

and

in the region A

$$\frac{T_{/\!/}}{T_\perp}=\frac{r^2}{(r-V_s\tau_c)^2}\sqrt{\frac{1+(r-V_s\tau_c)^2\,\Omega_s^2/V_s^2}{1+r^2\,\Omega_s^2/V_s^2}} \qquad r>r_0+V_s\tau_c$$

in the region B.

The ratio $T_{/\!/}/T_\perp$ reaches its maximum at the boundary between the regions A and B. Based on the equation (3),the proton temperature anisotropy ratio $(T_{/\!/}/T_\perp)_i$ for a particula solar wind velocity is expressed as a function of a radial distance from the sun (Figure 1). In this case a relatively simple situation that the mean kinetic energies of electrons and protons are of the same order of magnitude is taken into consideration. The self collision time becomes longer with increase of the average temperature in both regions. The region A will consequently expand, and the maximum of $(T_{/\!/}/T_\perp)_i$ and $(T_{/\!/}/T_\perp)$e will increase.

In Figure 1, the magnetic field intensity at the photosphere and the solar wind velocity are assumed to be one gauss and 3.5×10^2 km/sec, respectively. Therefore, the average temperature of about 4.2×10^4°K leads to $(T_{/\!/}/T_\perp)_i$ of 2×10^2 at the distance of one astronomical unit. In this case the region A extends just to the earth orbit. After the solar wind passes through the boundary between the regions A and B, $(T_{/\!/}/T_\perp)_i$ radically decreases, as is shown by a special example illustrated in Figure 1. The variations of $(T_{/\!/}/T_\perp)_i$ and $(T_{/\!/}/T_\perp)_e$ at one astronomical unit as a function of the average temperature are shown in Figure 2. On the contrary to the present assumption, many observations reported that $T>4\times10^4$°K.

Thus, even if ambiguity in the values of B_r and r_0 are considered, we conclude that

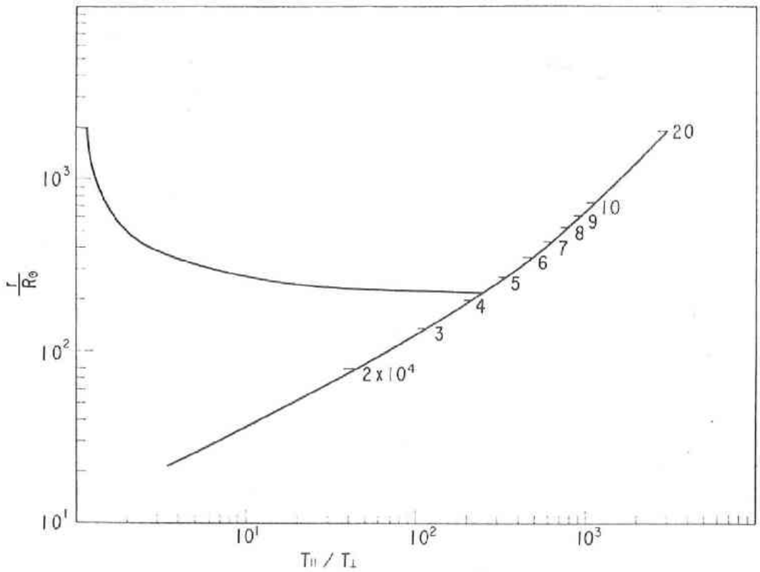

Figure 1 Rate of the temperature anisotropy $T_\parallel/T_\perp$ as a function of distance from the sun for several average temperatures. Several numbers beside the curve multiplied by 10^4 make average temperature. These indicate the position of the boundary between the regions A and B, and $T_\parallel/T_\perp$ there. An example for $T_\parallel/T_\perp$ in the B region is ploted, when average temperature is 4.2×10^{4}°K.

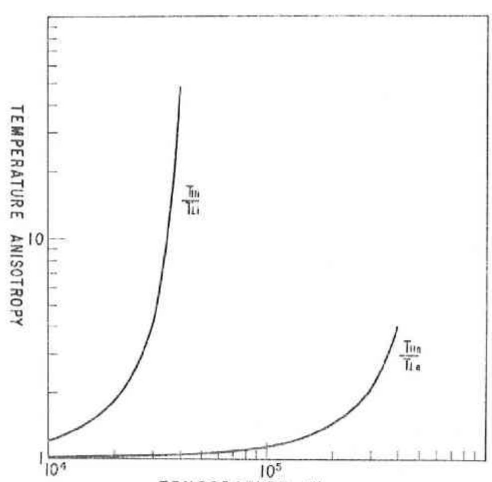

Figure 2 The relationship between the temperature and the temperature anisotropy ratio $T_\parallel/T_\perp$ for ions and electrons at the one astronomical unit apart from the sun.

$(T_\parallel/T_\perp)_i$ at one astronomical unit would be in the order of 10^2.

Recently, Wolfe *et al* (1966) and Hundhausen *et al* (1967) published the observational results in the vicinity of the earth's orbit obtained by the Pioneer VI and the Vela III, respectively.

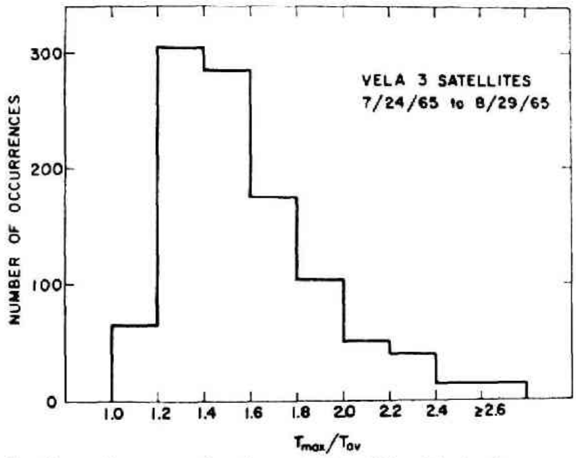

Figure 3 The distribution of measured values of T_{max}/T_{av}, T_{av} is the average temperature over all directions. (see Hundhausen et al 1967)

The distribution of (T_{max}/T_{av}), which is a measure of the degree of anisotropy, obtained by the Vella III satellites is shown in Figure 3, where 1046 measurements are summarized. The ratio T_{max}/T_{av} ranges from 1.0 to 2.5, where T_{av} is the average of temperature over all azimuthal angle. Therefore, it is clear that this observed ratio cannot be explained only by the redistribution mechanisms only due to the collision processes.

Based on this fact, it becomes very important to examine the micro-instabilities as a possible mechanism, which determines the distribution of proton and electron velocity, as suggested by Parker (1963).

In the next section, let us consider what sort of an instability can occur in the interplanetary plasma with the anisotropic temperature, and how large the growth rate of these instabilities are, and how much these instabilities control the temperature anisotropy compared with the collision process.

3. Basic equation

In this section, we shall discuss the instability due to the temperature anisotropy in an Alfvén mode and ion cyclotron mode by treating the linear approximation of Vlasov-Maxwell equations. Such kinetic analyses were carried out previously by Kutsenko and Stepanov (1960), Sagdeev and Shafranov (1961), Shapiro and Shevchenko (1964), and Kennel and Petschek (1966).

We consider that a homogeneous rarefied plasma with no static electric fields has an anisotropic kinetic temperature of electrons and ions, parallel and perpendicular to the static magnetic field $\boldsymbol{B}_0$.

The zeroth order of Vlasov's equation may be writen by

$$\left| \frac{e}{c} \boldsymbol{v} \times \boldsymbol{B}_0 \cdot \frac{\partial F_0}{\partial \boldsymbol{v}} \right| = 0 \qquad \text{or} \qquad \frac{\partial F_0}{\partial \phi} = 0 , \tag{4}$$

where F_0 is the zeroth order distribution function for electrons or ions.

Then we find that the zeroth order distribution function is independent of the Larmor phase angle ϕ. The Vlasov's equation for the distribution function, in which the first order perturbation F' $(\boldsymbol{r}, \boldsymbol{v}, \boldsymbol{t})$ superposes on the equilibrium distribution F_0 $(\boldsymbol{r}, \boldsymbol{v}, \boldsymbol{t})$, can be written by

$$\frac{\partial F_s'}{\partial t} + \boldsymbol{v}\frac{\partial F_s'}{\partial \boldsymbol{r}} + \frac{e_s}{M_s}\left(\boldsymbol{E} + \frac{\boldsymbol{v}\times \boldsymbol{B}}{c}\right)\frac{\partial F_{0s}}{\partial \boldsymbol{v}} + e_s\frac{\boldsymbol{v}\times \boldsymbol{B}_0}{c\,M_s}\frac{\partial F_s'}{\partial \boldsymbol{v}} = 0 \quad (5)$$

where E and B are perturbations of electric and magnetic fields respectively. $\boldsymbol{B}_0$ is the constant external magnetic field, and the subscipt s=e or i for electrons and ions respectively.

Maxwell equations for the electromagnetic field are

$$\nabla\times \boldsymbol{B} = \frac{4\pi}{c}\int d^3v\sum_s e_s F_s' + \frac{1}{c}\frac{\partial \boldsymbol{E}}{\partial t}, \quad (6)$$

$$\nabla\times \boldsymbol{E} = -\frac{1}{c}\frac{\partial \boldsymbol{B}}{\partial t}, \quad (7)$$

$$\nabla\cdot \boldsymbol{B} = 0 \quad (8)$$

and

$$\nabla\cdot \boldsymbol{E} = 4\pi\int d\,v^3\sum_s e_s F_s'. \quad (9)$$

The equations from (5) through (9) give the basic equations of the analysis of plasma instability in a frame work of kinetic treatment. The first order quantities are assumed to vary as $\exp i\,(\boldsymbol{k}\cdot\boldsymbol{r}\text{-}\omega t)$ for space-time coordinates and a wave vector $\boldsymbol{k}$ is real, but an angular frequency ω has the real part ω_r and the imaginary part γ. If $\gamma>0$, the instability occurs, and the energies are transported from particles to waves.

3-1. Garden hose instability

In this section, the following notations will be used:

$\Omega_s = \dfrac{eB}{c\,M_s}$ Gyro-frequency for S type particle,

$\Pi_s = \dfrac{4\pi N_s e^2}{M_s}$ Plasma-frequency,

$u_s = \dfrac{2\kappa T}{M_s}$ Thermal velocity, and

κ Boltzman constant.

The subscipt $\perp$ and $//$ will mean perpendicular and parallel to the external magnetic field, $\boldsymbol{B}_0$ respectively.

The following dispersion relation is obtained by combining the equations from

(5) through (9) when we take k parallel to $\boldsymbol{B}_0$:

$$\frac{k^2 c^2}{\omega^2} = 1 - \pi \sum_s \frac{\Pi_s^2}{\pi} \int_{-\infty}^{\infty} d v_{/\!/} \int_0^{\infty} v_{\perp}^2 d v_{\perp} \frac{\left[\left(1 - \frac{k_{/\!/} v_{/\!/}}{\omega}\right) \frac{\partial F_s}{\partial v_{\perp}} + \frac{v_{/\!/} k_{/\!/}}{\omega} \frac{\partial F_s}{\partial v_{/\!/}}\right]}{(k_{/\!/} v_{/\!/} - \omega \pm \Omega_s)}. \tag{10}$$

Let us now limit our consideration to wave frequency and wave numbers for which $|(\omega_r \pm \Omega_i)/k| > u_s$ The following anisotropic Maxwell distribution is adopted for F_{0s}:

$$F_{0s} = \frac{1}{\sqrt{2\pi^3}} \frac{1}{u_{/\!/} u_{\perp}^2} \exp - \left(\frac{v_{/\!/}^2}{u_{/\!/}^2} + \frac{v_{\perp}^2}{u_{\perp}^2}\right). \tag{11}$$

Let us take a frequency range of hydromagnetic wave for which the following relations hold:

$$|\omega| \ll \Omega_i \qquad \text{and} \qquad k^2 u_{\perp}^2, k^2 u_{/\!/}^2 \ll \Omega_i^2. \tag{12}$$

The dispersion equation for this range can be reduced to

$$\frac{k^2 c^2}{\omega^2} \left(1 + \frac{\beta_{\perp}}{2} - \frac{\beta_{/\!/}}{2}\right) = 1 + \frac{\Pi^2}{\Omega^2} \tag{13}$$

$$\beta_{\perp,\,/\!/s} = \frac{8\pi N_s \kappa T_{/\!/s}}{B^2}$$

where

$$\beta_{\perp,\,/\!/} = \sum_s \beta_{\perp,\,/\!/s} = \frac{Gaspressure}{Magnetic\ pressure} \tag{14}$$

This dispersion relation corresponds to the cold plasma shear Alfven waves a plasma is isotropic distribution.

It follows from equation (13) that the waves are unstable, if

$$\beta_{/\!/} > \beta_{\perp} + 2. \tag{15}$$

This instability was also found by employing hydromagnetic treatment and has sometimes been referred to as the "*Garden Hose*" instability, so it will be called G-H instability. Equation (15) shows that gas-pressure must be more than two times as great as magnetic pressure for the start of the G-H instability.

3-2. R-mode Instability

This section discusses that fast waves in the neighbourhood of the ion gyro-frequency $|\omega| \approx \Omega_i$, correspond to a right-hand polarized wave (R-mode), interact the higher tail of the velocity distribution. Resonant protons on the high energy tail of the distribution may be considered to be small, and to be $\gamma \ll \omega_r$. Therefore, integrating (10) over $v_{\parallel}$, we can use the Plemelj formulas

$$\lim_{\varepsilon \to 0} \frac{1}{x-(x' \pm i\,\epsilon)} = P\,\frac{1}{x-x'} \pm \pi\,i\,\delta\,(x-x')\,, \tag{16}$$

where P means the Cauchy principal value integral.

This method was fully discussed by Montgomery and Tidman (1964) and Stix (1962).

If gas pressure is smaller than magnetic pressure, which corresponds to the case $kv_{\parallel} \ll \omega$. In this case, it is a good approximation that the plasma is assumed to be cold for the principal part of the following intergral

$$F_{0s} = \frac{1}{\pi\,v_{\perp}}\,\delta\,(v_{\parallel})\,\delta\,(v_{\perp})\,. \tag{17}$$

For the sake of simplicity let us restrict ourselves to the case of $T_i \approx T_e$ and $\omega_r \ll \Omega_e$. F_{0s} is given by the Maxwell distribution (11) and the effect of protons on the wave-particle interaction exceeds that of electrons by a factor of

$$\left(\frac{M_i}{M_e}\right)^{3/2} \exp\,\frac{-\,\Omega_e{}^2}{u_{\parallel e}{}^2\,k^2}\,.$$

Therefore, neglecting the effect of electrons, we have the dispersion equation

$$n^2 = \frac{\Pi_i{}^2}{\Omega_i\,(\Omega_i+\omega)} - \pi\,\frac{\Pi_i{}^2}{k\omega}\int_{-\infty}^{\infty} dv_{\parallel}\int_0^{\infty} d\,v_{\perp}\cdot v_{\perp}{}^2$$

$$\times\left[\frac{\partial F_i}{\partial v_{\perp}} - \frac{k}{\omega}\left(v_{\parallel}\,\frac{\partial F_i}{\partial v_{\perp}} - v_{\perp}\,\frac{\partial F_i}{\partial v_{\parallel}}\right)\right] i\,\pi\,\delta\left(v_{\parallel} - \frac{\omega+\Omega_i}{k}\right) \tag{18}$$

Then, using (11), we have the dispersion relation,

$$n^2 = \frac{\Pi_i{}^2}{\Omega_i\,(\Omega_i+\omega)} + i\,\sqrt{\pi}\,\frac{\Pi_i{}^2}{\omega^2}\left[\frac{T_{\perp}-T_{\parallel}}{T_{\parallel}} + \frac{\omega}{\Omega_i+\omega}\right]\frac{(\omega+\Omega_i)}{u_{\parallel}\,k}$$
$$\times\,\exp\,\frac{-\,(\omega+\Omega_i)^2}{k^2\,u_{\parallel}{}^2}\,. \tag{19}$$

The first and second terms of the right of the equation (19) represent, the wave term which corresponds to the R-wave in the cold plasma, and the term which leads to amplitude growing due to a finite anisotropic thermal spread, respectively.

If $n \gg 1$ and $\omega_r \gg \gamma$, the equation (19) has an approximate solution,

$$\frac{k^2\,c^2}{\omega_r{}^2} = \frac{\Pi_i{}^2}{\Omega_i\,(\Omega_i+\omega_r)}\,, \tag{20}$$

$$\gamma = -\sqrt{\frac{\pi_i\,\Omega_i}{\beta_{\parallel i}}}\,\frac{(\Omega_i+\omega)^{7/2}}{\omega^2(2\,\Omega_i+\omega)}\left[\frac{T_{\perp}-T_{\parallel}}{T_{\parallel}} + \frac{\omega}{\omega+\Omega_i}\right]\exp\,\frac{-\,(\omega+\Omega_i)^3}{\Omega_i\,\omega^2\,\beta_{\parallel i}}\,, \tag{21}$$

therefore instability occurs when

$$\frac{T_{\parallel}}{T_{\perp}} - 1 > \frac{\omega_r}{\Omega_i}. \tag{22}$$

This instability is called "*R-mode*" instability hereafter.

Existing a limiting velocity V_{lim} ($<c$=light velocity) in a actual velocity distribution, there is the minimum resonance frequency $\omega_{min} = \left(\frac{v_{lim}\,k}{\omega} - 1\right)^{-1}$ and minimum criterion of instability becomes $\frac{T_{\parallel} - T_{\perp}}{T_{\perp}} > \left(\frac{v_{lim}\,k}{\omega} - 1\right)^{-1}$. It is because the frequency corresponding to the maximum growth rate occurs at $\Omega_i \left|\frac{T_{\parallel} - T_{\perp}}{T_{\perp}}\right|$ (Sagdeev and Shafranov, 1961) in the case of $T_{\perp} \approx T_{\parallel}$.

In the actual interplanetary condition, v_{lim} is far greater than the wave phase velocity (order of Alfven velocity, V_A), then, R-mode instability can occur for almost all the conditions if $T_{\parallel} > T_{\perp}$.

This type of instability, which is unable to be obtained from the hydromagnetic analysis, has not been known yet in the interplanetary space.

4. Discussion and Conclusion

Let us consider the growth rate of micro-instabilities of G-H and R-mode and compare with the collisional redistribution process. The variation of $\gamma^2 / k^2 c^2 \left(= \frac{\omega^2}{-k_2 c_2}\right)$ with T_i^2/Ω_i^2 for different values of $T_{\parallel} - T_{\perp}$ is shown in Figure 4.

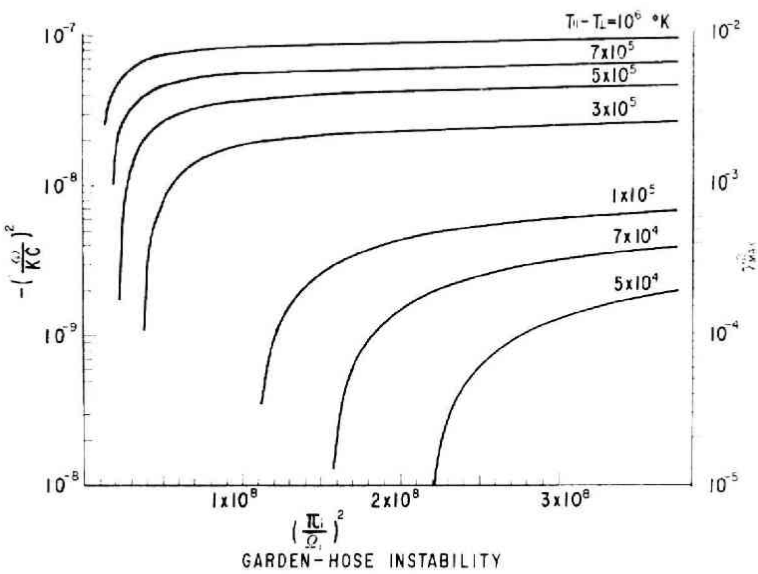

Figure 4 The refractive index of the garden hose instability for several $T_{\parallel}/T_{\perp}$. The maximum growth rate γ_m (2π/sec) scale at right is valid when $\mathbf{B}_0 = 5$ gamma and $T = 5\times10^5$K°.

Here, electron effect is neglected, because $(T_{\parallel}/T_{\perp})_i \gg (T_{\parallel}/T_{\perp})_e$ is expected at the initial stage of instability as mentioned in Figure 2. It seems that γ can increase infinite when k reaches infinite for garden hose instability. But we must consider the limitation

$$|(\omega_r + \Omega_i) / k| > u_s . \tag{23}$$

Put in another way

$$\lambda > \rho_L \quad \text{or} \quad 2\pi / \rho_L > \kappa , \tag{24}$$

where λ= wave length,
and ρ_L= gyro-frequency.

The characteristic length of wave potential variation must be much longer than gyro-radius. Value of $2\pi/\rho_L$, which depends on the temperature T, is given in Table 2. Since $2\pi/\rho_L$ can decrease to 10^{-7}cm^{-1} for the reasonable model of interplanetary temperature (Table 2), $k \leqslant 10^{-7}$,cm^{-1} must be satisfied. We need to consider the G-H instability in the condition which the maximum wave number k_m is 10^{-8}cm^{-1}. Then, γ/kc (in Figure 4) multiplied by $k_m c$ (about $\sqrt{10^5}$) makes the maximum growth rate γ_m. The variation of γ_m with $(T_i/\Omega_i)^2$ is shown in Figure 4.

Table 2
Thermal Velocity & Gyro-radius (B_0= 5 gamma)

Temberature	Thermal Velocity	Gyro-radius	$2\pi/\rho_L$
(K°)	(km/sec)	(km)	(1/cm)
1.0 E+4	12.9	26.6	2.36×10^{-6}
5.0 E+4	28.7	59.2	1.06×10^{-6}
1.0 E+5	40.7	84.1	7.56×10^{-7}
5.0 E+5	91.0	188.0	3.34×10^{-7}

Table 3
Alfvén Velocity (B_0= 5 gamma)

Number Density	Alfvén Velocity	$(\pi_i/\Omega_i)^2$
(Proton/cm³)	(km/sec)	
2	77.43	1.501×10^{7}
4	54.75	3.002×10^{7}
6	44.70	4.504×10^{7}
8	38.71	6.006×10^{7}
10	34.63	7.505×10^{7}
12	31.61	9.007×10^{7}
14	29.26	1.051×10^{8}
16	27.38	1.201×10^{8}
18	25.81	1.351×10^{8}
20	24.49	1.501×10^{8}

Based on the data obtained by IMP-1 satellite, T_i/Ω_i is calculated for the position within the quasi-stationary corotating 2/7 sectors (Willcox and Ness, 1965) of the interplanetary space, (see Figure 5). Values of the pressure raito β and Alfvén velocity are given in Table 3. A very important feauture of the G-H instability in the vicinity of the earth is the fact that γ_m can become 10^{-2} sec^{-1}, and this value of γ_m

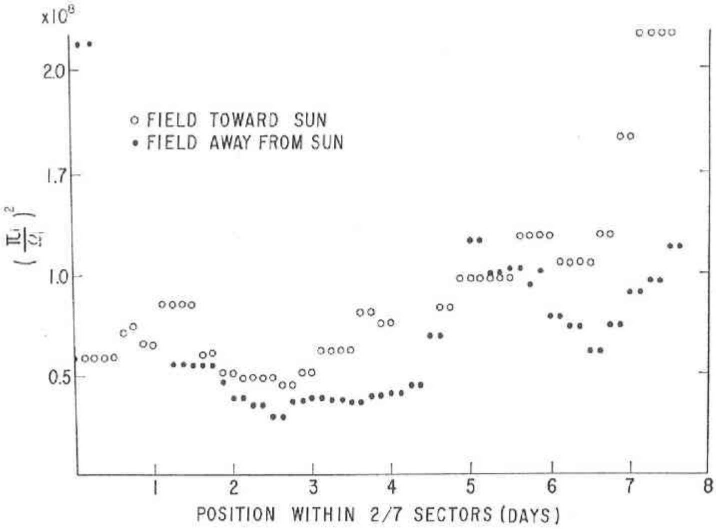

Figure 5 The magnitude of the pressure ratio β $(=u^2/V_A)^2$ as a function of position with the 2/7 sectors. β is calculated from the data obtained of the IMP-1 sattelite during 3 solar rotation (see Wilcox and Ness 1965).

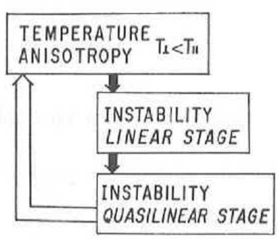

Figure 6

is much shorter than the self collision time.

In the nonlinear wave-particle interaction, perturbations connected with the first order velocity distribution grow to cause a change of the form in the zeroth order velocity distribution, until the plasma reaches a condition which is stable to the collective interaction.

An analysis of quasilinear theory of the G-H instability was carried by Shapiro and Shevchenko (1964). We now consider the redistributional action by th G-H instability of the interplanetary plasma after reffering the above-mentioned paper. When $T_{\parallel}/T_{\perp}$ increases to satisfy the condition (15) [see Figure 1], the G-H instability in the linear stage will set in by a small disturbance, [see Figure 6]. This phenomena will develop into the quasilinear stage under which the nonlinear interaction between the different harmonics of the collective motions can be neglected. In the quasilinear stage, the energies of motion perpendicular to a magnetic field-line are transferred to the energies of longitudinal motion through the wave-particle interaction of G-H instability. Therefore $T_{\parallel}/T_{\perp}$ is on the decrease. Finaly this action reaches the equilibrium state and satisfies the condition.

$$\frac{T_{\parallel}}{T_{\perp}}=\frac{\beta_{\parallel}}{\beta_{\parallel}-2}\,. \tag{25}$$

In conclusion, we will discuss the meaning of feature of $T_{\parallel}/T_{\perp}$. If $\beta_{\parallel}$ is given, the restrained $T_{\parallel}/T_{\perp}$ can be expected in the interplanetary space where growth time of G-H instability is exceedingly short time compared with the solarwind travel time for one astronomical unit ($V_S=350$ km, Travel time$=4.5\times10^5$ sec). In order to estimate $\beta_{\parallel}$ we may use the theoretical value of N_i, and T(r) which is given by Noble and Scarf (1963), and value of $\boldsymbol{B}_0(r)$ that is given by equation (1) and assume one gauss radial magnetic field at the solar photosphere. Pressure ratio $\beta_{\parallel}$ plotted in Figure 7 reads $T_{\parallel}/T_{\perp}$ to be about 10^0 to 10^1 in the interplanetary space among the inner three planets. Thus, the G-H instability is effective to control $T_{\parallel}/T_{\perp}$. But the rough estimation of $\beta_{\parallel}$ may give a possibility that a practical, $T_{\parallel}/T_{\perp}$ restrained by G-H instability, is higher than the values shown in Figure 7. Furthermore, we must expect the interplanetary plasma condition which $\beta_{\parallel}$ is less than 2.

Therefore, next, the R-mode instability which occur in almost magnitude of $T_{\parallel}/T_{\perp}$ and $\beta_{\parallel}$ will be considered. Growth rate γ of R-mode instability becomes large with increasing of $\beta_{\parallel}$ as shown in Figures 8 and 9. The R-mode wave frequency ω_r corresponding to the maximum growth rate γ_m is about ion gyrofrequency for the most case. Figure 10 yields the γ_m for various $\beta_{\parallel}$, and shows that γ_m, is about 10^{-3} to 10^{-2} for $\beta_{\parallel}\approx1$. Comparing with the travel time of the solar wind for one AU (4.5×10^5

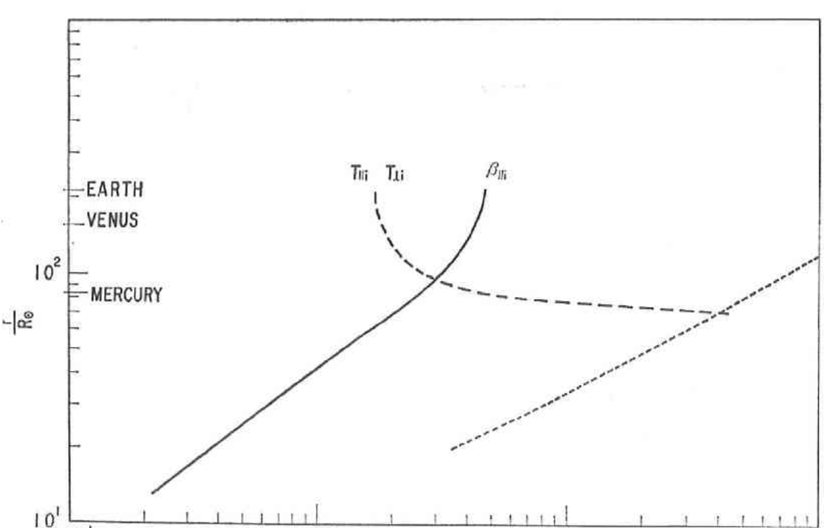

Figure 7 Estimation of controlled $(T_{\parallel}/T_{\perp})$ by grarden hose instability as a function of distance from the sun. The dashed line represents $(T_{\parallel}/T_{\perp})$ for redistribution process due to the garden hose instability. The dotted line shows $(T_{\parallel}/T_{\perp})_i$ for collisional redistribution process (see Figure 1). The solid line indicates the pressure ratio. β. which is calculated from a paper produced by Noble and Scarf (1963).

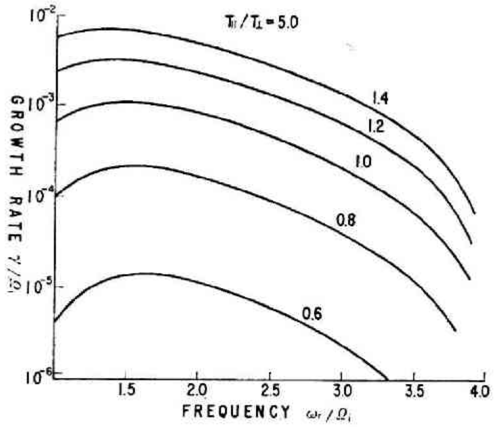

Figure 8 The growth rates for R-mode instability for $T_{/\!/}/T_{\perp}=5.0$. The ratio of the growth rates. γ, to the ion gyrfofrequency. Ω_i. is ploted as a function of normalized frequency ω_r/Ω_i. for several. pressure ratio $\beta_{\parallel i}$.

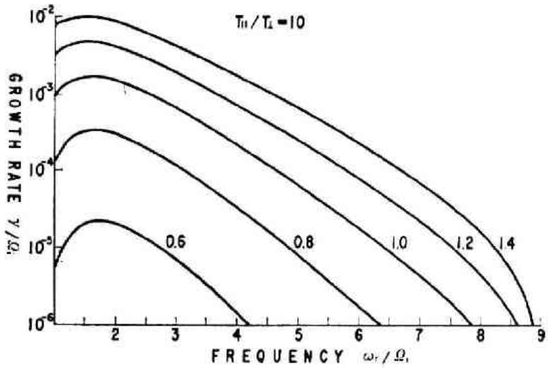

Figure 9 The growth rates for R-mode instability for $T_{/\!/}/T_{\perp}=10$.

sec) and the self collision time ($10^5 \sim 10^7$ sec for $T=10^4 \sim 4\times10^5$ °k), R-mode instability is effective to control $T_{/\!/}/T_{\perp}$, too. Especially, it should be noted that R-mode instability can occur for all the conditions of the interplanetary temperature anisotropy plasma. That is, even if G-H instability reachs equilibrium state and stops, R-mode instability can decrease $T_{/\!/}/T_{\perp}$ further.

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Scarf et al (1967) have obtained in their study of the interplanetary magnetic field the same expression for the growth rate of the R-mode instability as equation (21) in this paper, when this paper was in preparation. It is noted here, however, that the main subject of this paper is to discuss the anisotropy of the temperature of the solar wind.

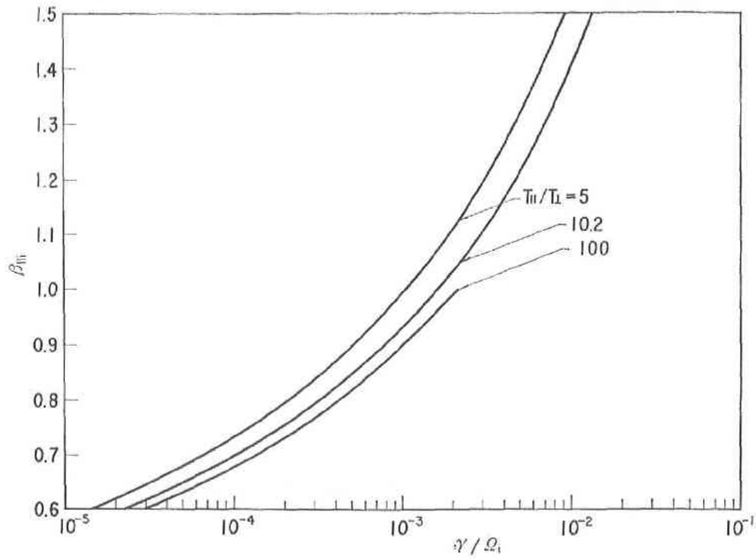

Figure 10 The maximum growth rate for R-mode instability. The variation γ/Ω_i with pressure ratio, $\beta_{\parallel i}$ is shown for several $T_\parallel/T_\perp$.

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