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LANC-R-5

A STUDY OF COUPLING IN STARFISH

BY:
CONRAD LONGMIRE
LOS ALAMOS NUCLEAR CORPORATION

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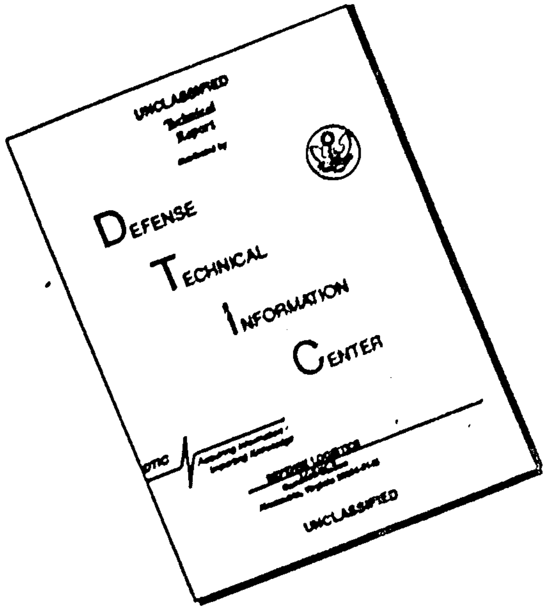

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Conrad L. Longmire

Los Alamos Nuclear Corporation

Box 1020, Los Alamos, N. Mex. 87544

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ABSTRACT

Several pieces of data from Starfish are examined with the goal of trying to discover the type of coupling that was effective between moving and stationary ions. It appears that Larmor radius coupling is required, although there are some discrepancies, connected with the ambient air density or ionization cross sections, to be resolved.

ACKNOWLEDGEMENT

I wish to express my gratitude to Herman Hoerlin, Dale Sappenfield, Milt Peek, John Zinn, Bill Maier, John Kodis, and the secretaries of LASL Group J-10, to Col. Don Flood of DASA Field Command, to a group of engineers at McDonnell-Douglas, to Dick Patrick and Joe Workman of Avco, to Bill Drummond and associates of ARA, to Ralph Kilb of TEMPO, and to Dan Hamlin, Bob Lowen and Dave Sowle of San Diego, for helpful discussions of the problems treated herein and for other assistance; and to DASA Headquarters for patient support.

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1. Introduction

At the altitude (400 km) of the Starfish nuclear burst, the mean free path for momentum transfer in ordinary atomic collisions is so long that such collisions play a negligible role in transferring momentum from bomb debris to the ambient atmosphere. Whatever interaction takes place must be of a plasma nature. The geomagnetic field provides one such interaction mechanism. The Larmor radii of debris ions is a few km to a few tens of km. Therefore in distances no longer than this, the moving debris ions will pick up the magnetic field and carry it with them. In turn, the moving magnetic field picks up ambient air ions, thus completing the transfer of momentum from debris to air. Numerous other possible transfer mechanisms exist, with shorter lengths than the Larmor radius, based on various types of instability that may occur when two plasmas stream through each other. The question is whether they do occur in high altitude bursts, or whether the interaction length is the longest possible one--the Larmor radius.

A consequence of Larmor radius coupling is the guidance of substantial amounts of the debris kinetic energy to the "conjugate" regions--the regions near the points where the burst magnetic field line enters the atmosphere at altitudes between 100 and 150 km. (This is the altitude range where fast moving atoms or ions are stopped by ordinary collisional energy loss.) In Starfish, this "debris patch" was very prominent. It had been predicted by Longmire, Petschek, and Wendroff (reference 1) prior to the event; the prediction was based on our belief that the debris would remain ionized (which was contrary to popular opinion at that time), and on our assumption that the debris would move freely along the magnetic lines. The latter assumption was based on our belief that the presence of many low-energy electrons would prevent ion streaming instabilities from developing effectively. The predictions turned out to be roughly correct in overall effect, although some "details" were wrong. For example, we had not predicted the early beta column or the hot electron patch.

However, it may be possible to get the debris patch with coupling on a shorter length than the Larmor radius. In Starfish, where dimensions are large compared with even Larmor radii, one has to look carefully at the data to distinguish between Larmor radius and short length coupling. This is the task undertaken in this report.

At lower altitudes, where the radius, corresponding to a mass of air equal to the bomb mass, is less than the Larmor radius but greater than possible short coupling lengths, it is believed that considerable differences in energy deposition would ensue, depending on the coupling.

The altitude range in question is from about 150 km to 300 km, and the importance of the question of coupling relates to the possible use of bursts in this altitude range in ABM activities.

II. Properties of the Explosion

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Fig. 1. Sketch of Starfish as seen from Maui.

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Hoerlin (reference 5) has made an analysis of the masses in the three parts, up, down, and horizontal. He used observed velocities of the three parts, and used the facts that the total mass is known, the total kinetic energy is known, and the total momentum parallel to axis is zero, to write three equations for the three unknown masses. I have repeated Hoerlin's analysis using currently accepted values for the (average) velocities, and find results differing somewhat from his.

The properties of the three parts are listed in Table I. It should be noted that the axis was not exactly vertical, but the upper end was tipped southward by about 12°. In addition, the central angle of the part called horizontal was not exactly perpendicular to the axis, but corresponds to a "downward" velocity about 1/8 of the "horizontal" velocity.

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Based on what is now known about the atmosphere, the air atom density at the Starfish altitude of 400 km is believed to have been about 3×10^7 atoms/cc, and the atoms were mostly atomic oxygen. The accuracy of this density is uncertain. I assume that a factor of two error is possible.

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III. Data: Stationary Atom Spectra

In this section and the next several we examine various pieces of data, mostly for their implications concerning coupling of debris and air.

Group J-10 of LASL obtained several spectra of the burst region in Starfish, which are presented and discussed in reference 6. The spectra show clearly that some of the emitting atoms are moving, while others appear to be stationary. We shall consider a few cases here.

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Fig. 2. Sketch of some features from N4GS streak spectrogram.

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Fig. 3. Sketch of the C^{++} 4650 feature in E & L time integrated spectrogram.

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The values of cross sections in the proceeding paragraph are inferred from the experimental values for atoms of similar ionization potential in reference 7.

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IV. Data: The Beta Column

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Some pictures and data on this beta streamer have been presented by Leonard and Buckner in reference 8, and Buckner has supplied some further information by private communication.

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These numbers were obtained from radiance profiles measured from the films, and are larger than earlier numbers based on visual inspection of the photographs.

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Because of such arguments, I proposed the model of Larmor radius coupling, several years ago, in reference 10. In this model, it is assumed that debris and air ions can interpenetrate each other up to the extent of their respective Larmor radii, with respect to the moving magnetic field. Thermal electrons in the debris and air have short Larmor radii (~1 meter), so air electrons are stuck to the magnetic field lines, and do not interpenetrate with debris electrons. The electrons move with the net ion flow, to maintain charge neutrality, and in doing so they carry the magnetic field with them. It might appear, then that debris ions could not get into the magnetic field. However, a debris ion can move outwards in the magnetic field if, at the same time, an air ion is moving inwards (relative to the moving field). Since the air ions are all stationary initially, they are all moving inwards with respect to the outward moving field lines. The debris ions can then enter the magnetic field by "swapping electrons" with these air ions.

Those air ions that are less than two Larmor radii from the central field line will "fall" into the magnetic bubble. Those that are farther away will be picked up by the magnetic field, forming a shock wave. The Larmor radius of O^+ is about 12 km. Therefore all O^+ within 24 km from the burst point will fall into the bubble.

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It should be noted that C or H atoms which are neutral until the debris arrives, and which are therefore ionized inside the bubble, do not help the debris enter the magnetic field. Thus the neutral atoms needed in Section III and the ionized atoms needed here have to come separately from the

It appears to me that the two requirements fit rather comfortably in the latter figure, being neither too large or too small.

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This effect may be seen more clearly in one frame, of the sequence of photographs of the northern conjugate region, taken at about 30 milliseconds after the burst. Due to favorable level of background, the beta streamer is seen again at this time. In this picture the hot electron patch is also visible at this time.

Deleted Based on visual inspection of the photographs, and projecting along the field lines from the hot electron patch to the beta streamer,

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John Buckner (private communication) has stressed that visual determination of diameters, as used in the foregoing paragraph, is often unreliable, and believes that the true ratio of radii mentioned is somewhat closer to unity.

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If some of the fission fragments are neutral, then they should make a beta streamer whose radius expands with the original debris velocity. One cannot say with certainty, from the beta streamer data, that there are none of these.

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V. Data: The Hot Electron Patch

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For several years we thought this patch was due to beta rays. It was at the wrong altitude for betas, but we conjectured that the betas were being stopped at higher altitude by streaming instabilities. Finally, about two years ago, the total optical power of this patch was measured from the films, in the LASL-EG&G data reduction program. This power is shown as a function of time in Fig. 4, which is taken from Hoerlin and Buckner, reference 9.

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We also looked at other possibilities for explaining this patch. John Zinn and I considered the hypothesis that it was an electric discharge,(reference 11).

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Fig. 4 Optical power of various phenomena in northern conjugate region.

The debris-air shock wave might generate an electric potential from front to back across itself. This potential could be discharged by a flow of electrons down the outer magnetic field lines to the atmosphere, across to the inner field lines, and back up to the inside of the shock (or in the opposite direction).

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In the summer of 1958 I reached the conclusion that the patch must be due to energetic electrons that are heated by the debris-air interaction or shock, and this has given rise to the name "hot electron patch."

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Fig. 5 Radius of hot electron patch as function of time, and radius and velocity of shock inferred from it.

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Hasti and Drummond (reference 13) have applied to Starfish a shock model which has two steps.* In the first step, the magnetic field changes and the electrons are joule heated as by Eq. (13). In the second step, the ions are shocked, and the electrons heated adiabatically. (Ion streaming instability is proposed as the mechanism of the ion shock.) The power put into electrons in this model is more than the amount given in Eq. (7), but the power escaping is reduced by a potential barrier which allows only the more energetic electrons to escape. The agreement with the patch power curve is reasonably good. The joule heating of the electrons is not explained in detail, in particular it is not resolved whether anomalous resistivity should apply.

* T. Coffee has also worked out a similar model.

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VI. Data: Shock Radius Versus Time

In the previous section we have argued that the shock radius can be deduced from the radius of the hot electron patch, by correcting for the travel time of 50 keV electrons. The radius of the shock, so determined, was given in Fig. 5. The same figure also shows the shock velocity obtained from the shock radius curve. This shock velocity is plotted as a function of shock radius in Fig. 6. This curve gives evidence on the pick-up of mass by the expanding debris and shocked air.

In order to understand the implications of this curve, we first make the assumption of Larmor radius coupling. Let us see how the total moving mass increases with radius.

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Fig. 6 Shock velocity as a function of radius, various models.

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Let us now find the mean free path for creating additional O^+, contributing to N_2. Guided by the data in reference 7, I take the cross section for any of the moving atoms to induce $O \rightarrow O^+$ to be

$$\sigma_O = 8 \times 10^{-16}\ cm^2 \qquad (16)$$

To get this number, I have divided molecular cross sections by two. The number includes the charge transfer cross section, since this process leads to the pick up of an additional atom; the ultimate fate of the fast neutrals will be discussed later. Finally, I have increased the number slightly on the grounds that the impacting atoms are predominantly charged rather than neutral.

In addition to the directed radial velocity, the picked-up ions also have a Larmor velocity roughly equal to the former. This causes an increase by a factor $4/\pi$ in the effective cross section σ_i to be used with the radial ion velocity. Thus

$$\sigma_i = 1.0 \times 10^{-15} \text{ cm}^2 \qquad (17)$$

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The data discussed in earlier sections favored Larmor radius coupling at early times. It is possible that the coupling of all ions does not begin immediately, but develops later. Such a combination of coupling mechanisms could give a better fit to the velocity at large radii. To adequately explain the deceleration at smaller radii one would have to take into account the velocity distribution of the debris mass, rather than assuming that it all moves with the average velocity. I hope to do this analysis at a later date.

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We shall return to this point in a later section. The importance of charge exchange has been stressed by Workman and by Hamlin, Lowen, and Sowle.

Summarizing, from the "observed" shock velocity versus radius, it appears that Larmor radius coupling alone is insufficient to explain the shock deceleration. A combination of Larmor radius coupling at early times, with coupling of all ions at later times appears to be consistent with the data. Coupling of all ions at all times is not badly inconsistent with this data, but disagrees with results of previous sections of this report. These conclusions are modified in the following section.

VII Data: Burst Region Optical Power

Epstein et al. (reference 3) have recently published results of measurements of the optical power from the films of the burst region, including the debris-air shock. Their results are transcribed in Fig. 7.

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Fig. 7 Optical power in burst region.

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VIII. Data: The Debris Energy Patch

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We may note that a potential barrier also occurs in the front of shocks in the Larmor radius coupling model, as is seen from the numerical calculations of Hilb (reference 14). The origin of this potential barrier is quite simple. As the outward moving ions begin to be deflected by the magnetic field, they make a transverse current, which is such as to reduce the magnetic field behind and increase it in front of the ions. In other words, magnetic flux is moved from behind to in front of these ions. Electrons go with the magnetic field, so that electrons are pushed ahead of the ions. This charge separation produces an outwardly directed electrostatic field, which builds up until the resulting E x B drift velocity of the electrons cancels the transverse ion current (approximately). The electric field E is therefore given by

$$E \approx \frac{v}{c} B \tag{30}$$

where v is the transverse ion velocity, which is equal to the total ion velocity at one-quarter of a Larmor period. This field exists over a radial interval of about one ion Larmor radius L_i. Therefore the height of the potential barrier is

$$e E L_i \approx e \frac{v}{c} B \frac{1}{2} \frac{Mvc}{eB} \approx \frac{1}{2} M v^2 \tag{31}$$

where M is the ion mass.

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Fig. 8 Optical power, assumed efficiency, and total power in the northern conjugate region as functions of time.

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The simple theory above becomes invalid for elements of mass at large radii where the shock becomes sonic. The sonic wave carries away . certain fraction of the energy.

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It would be useful to try to determine the energy carried away by the sonic Alfven wave, by examining the various ionospheric data collected in connection with Starfish.

The spatial distribution of power in the debris patch has been measured from the films, but not yet published (Hoerlin and Buckner, private communication). The shape of the power density (brightness) of course depends on time. The shape at early times, when the first debris is arriving, has been discussed by John Zinn (to be published). After about 0.5 second, when the radius stops

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I know of no simple argument explaining the exponential shape of the debris patch brightness. While it does not seem unreasonable, a detailed explanation may be complicated. One would have to look further at the mechamism of the final stopping of the transverse expansion.

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The proper analysis of these ideas may require some numerical computations; but I may try some further analytical calculations later.

I believe we are close to an understanding of Starfish in terms of Larmor radius coupling. There are some discrepancies to clear up, for example the effective ionization mean free path in Sections VI and VII. If these are cleared up, I think we could produce a simple model of the debris patch for RANC.

Appendix A -- TWX Longmire et al, at Honolulu to Moerlin et al. at Johnston Island, June 15, 1962

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Appendix B -- A Trip to McDonnell-Douglas

The origin of the "gas" cloud has been an enigma to the bomb physicists since 1962. Recently, H. Hoerlin and I had an opportunity to discuss the matter simultaneously with Dr. Wm. Ogle and Dr. John Northrop, and to impress on them the need to get what information was possible on its constituents and mass. Dr. Northrop later asked Col. John Kodis (DASA HQ) to see what could be learned, and the latter enlisted the aid of Col. Donald Flood (DASA Field Com.), who was acquainted with the engineers at McDonnell-Douglas who are familiar with the Thor booster. Col. Flood relayed the question and put me in touch with these engineers. On Sept. 12, 1969, I visited the McDonnell-Douglas plant in Culver City, California. Specifically, I discussed our problem with K. B. Duke, D. Fazio, R. P. Kellogg, R. J. Mack, R. E. Mitchell, J. R. Reider, and W. F. Weltner. This meeting was most fruitful, and my only regret is that it did not happen several years ago.

I explained that we were looking for something containing C and H, perhaps rocket fuel, in amounts of the order of tens of kilograms; that if it were released below about 250 km altitude it had to be liquid or solid droplets, not molecules, in order to penetrate the residual atmosphere; but that if released above 250 km altitude it could be molecules; and finally that fuel in the booster tanks at burst time was not of interest, because of insufficient time for dispersal.

The McDonnell-Douglas people then gave the following description of what they believed to be the likely source of the material. At main engine cut-off (MECO) the valves in the lines from the engine to the fuel (RP1) tank and to the LOX tank are caused to close. However, in the fuel lines between valve and burning chamber there are approximately 112 lb. (50 kg) of RP1 at this time, and in the LOX lines there are 39 lb (18 kg). While some of this might burn, they felt it was quite likely that a good deal of it would simply leak into space. The normal ratio of weights of RP1 to LOX is about 1/2.5.

We agreed on the following rough picture of what was likely to happen. When burning stops in the chamber, the pressure there drops essentially to zero. The vapor pressures in the LOX and RP1 lines will then eventually drive the liquids out of those lines. The RP1 lines are used to cool the nozzle, and since the throat of the nozzle is still hot, there may be a high pressure there that holds up the purging of the RP1 above that point until the nozzle cools down. Because the LOX lines are more direct and because of the low boiling point of LOX, it was felt that the LOX would probably purge first.

Some indication of the altitude at which the RP1 was purged is provided by the following facts. MECO occurred at an altitude of about 117 km. Fifteen seconds later, at an altitude of about 155 km (and after booster-payload separation), the booster is kicked down and sideways and induced to tumble at a rate of about one revolution per 24 seconds. Fuel leaking at this time would form a spiral vapor or droplet trail. Since two or three loops of such a spiral are visible in the burst photographs, we conclude that fuel was leaking at this time and altitude. Droplets released at this altitude would have very nearly the same ballistic trajectory as the booster.

With regard to droplet size we offer the following considerations. The holes in the fuel injector plate had radii about 0.1 cm; let us try this size for the droplets. With a surface tension of about 25 dyne/cm, the pressure in a droplet of this radius would be

$$p = \frac{2 \times 25}{0.1} = 500 \text{ dyne/cm}^2$$

The vapor pressure of RP1 falls below this value when it temperature falls below about 0°F. At 100°F the vapor pressure is ten times higher. Since the latter is a more likely initial temperature, partial boiling would have to cool the residual liquid by 100°F. In order to achieve this much cooling, about 30% of the RP1 would have to evaporate (heat capacity - 0.4 BTU/lb °F, heat of vaporization = 100 BTU/lb). It appears that droplet radii somewhat smaller, say 0.03 cm, are more likely.

Thermodynamic data for RP1 were supplied by McDonnell-Douglas. RP1 is essentially a kerosene, chemical formula approximately $C_{10}H_{22}$.

The mass in the atmosphere above 155 km altitude is about 10^{-6} gram/cm^2. The mass in a droplet of radius 0.03 cm is about 0.03 gram/cm^2 of its cross sectional area. Therefore, as stated above, the residual atmosphere has little effect on the droplets. The heat acquired by the droplets in colliding with the air molecules above them is about 3×10^4 erg/cm^2 → 10^6 erg/gm ≈ 1/40 calorie/gm, which is also negligible. (The velocity of the booster was about 2.5 km/sec).

I wish to express here my gratitude to the individuals mentioned above, who have helped to clear up substantially the enigma of the "gas" cloud.

Appendix C -- Effect of X-Rays on Droplets

Consider a droplet of RPI ($\sim C_{10}H_{22}$), of radius 0.03 cm, subjected to the Starfish x-rays at a typical distance of 3 km from the burst.

The x-ray spectrum from Starfish has been given in reference 2.

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I realize that the considerations above may not be very accurate. However, the conclusions are not unreasonable.

Appendix D. Ion Streaming Instability

Consider two interpenetrating beams of singly charged ions of mass M in the presence of a neutralizing background of electrons with temperature T_e and density N. The beams need not have delta-function velocity distributions, but let the total ion velocity distribution be $f(\vec{v})$, and let $f(\vec{v})$ be normalized.

$$\int f(\vec{v})\, d^3v = 1 \qquad \text{(D-1)}$$

The dispersion relation for electrostatic waves of the form $\exp\left[i(\vec{k}\cdot\vec{r} - \omega t)\right]$ is

$$\frac{k^2 + k_d^2}{\omega_{pi}^2} = \int \frac{f(\vec{v})\, d^3v}{(\frac{\omega}{k} - v_p)^2} \qquad \text{(D-2)}$$

Here k_d is the Debye k

$$k_d^2 = \frac{4\pi N e^2}{T_e} \qquad \text{(D-3)}$$

and ω_{pi} is the ion plasma frequency

$$\omega_{pi}^2 = \frac{4\pi N e^2}{M} \qquad \text{(D-4)}$$

and v_p is the component of $\vec{v}$ parallel to $\vec{k}$.

In general unstable solutions (complex ω) most easily occur for $k^2 \ll k_d^2$. In this limit, and for symmetrical $f(\vec{v})$, $f(\vec{v}) = f(-\vec{v})$, it can be shown that a necessary and sufficient condition for instability is

$$2\int_0^\infty \frac{1}{v}\, \frac{df_p(v)}{dv}\, dv \geq \frac{M}{T_e} \qquad \text{(D-5)}$$

Here $f_p(v)$ is the projection of the velocity distribution on the $\vec{k}$ direction, and v is the former v_p.

Let $f(\vec{v})$ be composed of two displaced Gaussians, characterized by ion temperature T_i and centered about $\pm\vec{V}$. Define a parameter

$$\alpha = \sqrt{\frac{M}{2T_i}}\; V \cos\theta \qquad \text{(B-6)}$$

where θ is the angle between $\vec{k}$ and $\vec{V}$. Then the condition (B-5) becomes

$$\left(2\,\alpha\, e^{-\alpha^2} \int_0^{\alpha} e^{x^2}\, dx\right) - 1 \;\geq\; \frac{T_i}{T_e} \qquad \text{(B-7)}$$

The left hand side of this equation, as a function of α, starts at -1 for α=o, becomes positive for $\alpha > 0.92$, and approaches zero as $\alpha \to \infty$. The maximum value is 0.285, and occurs at $\alpha = 1.50$ (approximately). Thus in this case a necessary and sufficient condition for instability is that

$$T_i \;\leq\; 0.285\; T_e\,. \qquad \text{(B-8)}$$

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13. ABSTRACT

Several pieces of data from the Starfish event are examined from the standpoint of the coupling mechanism between debris and air.

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