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LA-UR--87-40

DE87 005121

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SUBMITTED TO Submitted by Smith to Proceedings of the 20th ESLAB Symposium

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Los Alamos, New Mexico 87545

FORM NO 836 R4
ST NO 2629 5/81

In the Proceedings of the 20th
ESLAB Symposium, ESA SP-250

ANALYSIS OF THE GIACOBINI-ZINNER BOW WAVE

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ABSTRACT

The cometary bow wave of P/Giacobini-Zinner has been analyzed using the complete set of ICE field and particle observations to determine if it is a shock. Changes in the magnetic field and plasma flow velocities from upstream to downstream have been analyzed to determine the direction of the normal and the propagation velocity of the bow wave. The velocity has then been compared with the fast magnetosonic wave speed upstream to derive the Mach number and establish whether it is "supersonic", i.e., a shock, or "subsonic," i.e., a large amplitude wave. The various measurements have also been compared with values derived from a Rankine-Hugoniot analysis. The results indicate that, inbound, the bow wave is a shock with M = 1.5. Outbound, a subsonic mach number is obtained, however, arguments are presented that the bow wave is also likely to be a shock at this location.

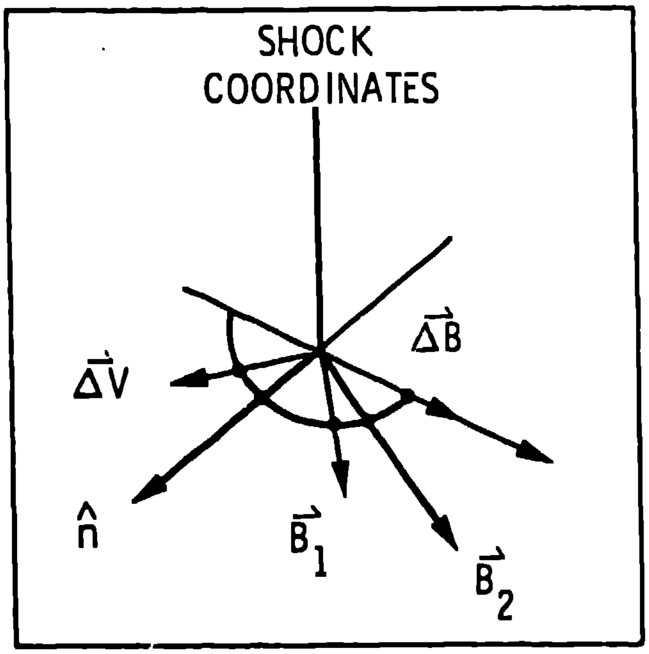


Figure 1. Shock coordinates. The X axis is the shock normal and the Y axis is in the direction of the jump in the vector magnetic field. The other parameters, which lie in the X-Y plane, are defined in the text.

1. INTRODUCTION

The analysis referred to in the title addresses two basic questions: (1) is the bow wave a shock? (2) can the observed properties up-and downstream of the bow wave be reconciled with the Rankine-Hugoniot relations?

The basic approach to answering the first of these questions is to derive the velocity of the bow wave in the upstream solar wind and determine whether the Mach number is > 1 or < 1, i.e., supersonic or subsonic. At this stage of the analysis, the reconciliation with the Rankine-Hugoniot relations is principally restricted to comparisons between observed and calculated jumps in the particle density and magnetic field strength. We use the mathematical formulation to be found in Tidman and Krall (Ref. 1, p. 11) which is basically a single fluid description.

2. ANALYSIS PROCEDURE

The analysis procedure that has been followed is based upon experience obtained in studying interplanetary shocks and planetary bow shocks (Ref. 2, 3). The first step is to determine the normal to the shock surface. As is customary, we make use of the coplanarity of the velocity vectors, $\vec{V}_1$, $\vec{V}_2$, the magnetic field vectors $\vec{B}_1$, $\vec{B}_2$, and the normal, $\hat{n}$. A representation of these vectors appears in Figure 1 in coordinates aligned with, and moving with, the shock. The principal axes are (1) the normal, $\hat{n}$, where the symbol, ^, indicates a unit vector, (2) the vector change in the field from upstream to downstream, $\vec{\Delta B} = \vec{B}_2 - \vec{B}_1$, and (3) the orthogonal direction parallel to the shock, also the direction of the electric field. The analysis is based on three dimensional velocity vectors obtained by the Energetic Particle Anisotropy Spectrometer (EPAS) (Ref. 4). Three dimensional measurements of anisotropies in the pick up ions are used to find a reference system moving with velocity, $\overline{V}$, which renders the distributions isotropic (Ref. 5).

We use the formulation first introduced by Abraham-Schrauner (Ref. 6) which involves the cross products of $\overline{\Delta V}$ and $\overline{\Delta B}$ as shown in the figure. Our experience with other shocks indicates that this approach is generally reliable even in the case of perpendicular shocks, i.e., when the angle, θ_{Bn}, between n and the upstream magnetic field, B_1, is ≈ 90°. The computation of θ_{Bn} is the second step in our analysis.

The speed of the bow wave in the solar wind frame, V_s, is calculated using two complementary methods. The more conventional approach is based on the conservation of mass and can be expressed as $V_S = [N_2/(N_2 - N_1)]\, \Delta V \cdot n$ where N_1, N_2 are the fluid densities up-and downstream. The other method, which we developed as an alternative and which depends on the magnetic field rather than the particle density, is a condition satisfied by all kinds of electromagnetic waves. Basically, the wave velocity equals the ratio of the wave electric field, in this instance simply $\overline{\Delta V} \times \overline{B_2}$, to the transverse magnetic field change associated with the wave, $|\overline{\Delta B}|$. An alternative derivation of this relation is based on recognizing that, in the shock frame, the wave is non-propagating and the electric field is conserved ($\overline{\Delta E} = 0$) across the shock. The shock speed in inertial space, V_I, is also calculated by finding the component of the upstream solar wind velocity along $\hat{n}$, i.e., $V_I = V_S + \overline{V_1} \cdot \hat{n}$.

Before obtaining the Mach number, it is necessary to derive the phase velocity for the fast mode of propagation upstream of the bow wave. The conventional equations were used for the Alfven speed, $C_A = B/(4\pi\rho)^{1/2}$, the ion sound speed, $C_s = (\gamma p/\rho)^{1/2}$, and the fast mode speed, C_f, which depends on C_A, C_s and the angle of propagation with respect to the magnetic field, θ_{Bn} (Ref. 1, p. 15). The pressure, p, is the sum of the partial pressures associated with the solar wind electrons, the solar wind protons and the heavy cometary ions. The electron and heavy ion properties were measured or inferred from the ICE measurements (Ref. 7,8). Since no proton measurements are available, the wave speeds depend on reasonable assumptions for the proton densities and temperature. We have followed the policy of varying all the densities and temperatures over reasonable limits in order to carry out a formal error analysis and ensure that uncertainties in these quantities would not change our conclusions. The density, ρ, is the sum of the density-mass products for the same three constituents. In the expression for C_f, γ is, of course, the ratio of specific heats for which we assume the conventional value of 5/3.

Finally, the Mach number is calculated from $M = V_s/C_f$. This quantity essentially provides our definition of a shock, i.e., it is a large amplitude wave propagating at supersonic speeds.

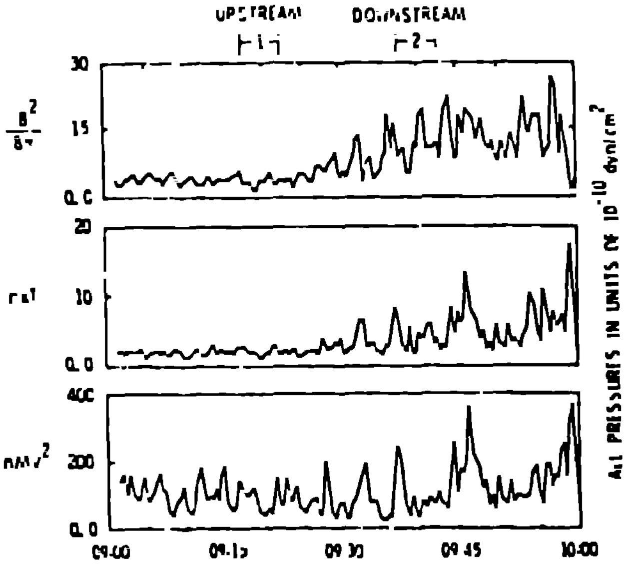


Figure 2. Observations of the inbound bow wave. Three of the principal pressures (magnetic, solar wind electron and solar wind convective pressures) are shown. The horizontal bars above the data show the analysis intervals corresponding to the results in Table I.

An example of the data used in the analysis is shown in Figure 2. The quantities plotted are actually three of the principal pressures: the magnetic pressure, $B^2/8\pi$, the electron pressure, n_ekT_e, and the convective pressure of the solar wind, $n_eM_pV^2$, where M_p is the proton mass. The changes in these quantities across the inbound bow wave are shown with the analysis intervals used to obtain the results presented below indicated at the top of the figure. Overall, the decrease in convective pressure and the accompanying increases in magnetic and internal pressure are evident in spite of the intense hydromagnetic turbulence (Ref. 9) that is present.

The large irregularities introduced by the turbulence pose a significant problem by making it difficult to determine accurately the parameters needed in the analysis. In fact, we have found that a variety of solutions can be generated by varying the location and/or duration of the analysis intervals. Other analysis procedures can also lead to alternative solutions for the same analysis intervals, e.g., we have compared the analysis described above with the output of the program recently developed by Vinas and Scudder (Ref. 10). It is, therefore, important to establish criteria to be met by an acceptable solution (or solutions). These criteria will be described below as we consider the results obtained so far.

TABLE I.

- $\hat{n}$: 0.1210, -0.7089, -0.6948
- θ_{Bn}: 80.1^{0} PERPENDICULAR
- $V_s = |\Delta V X B_2| / |\Delta B| = 189$ km/s
- $V_s = (N_2/N_2 - N_1)\Delta V \cdot \hat{n} = 189$ km/s
- $V_1 \cdot \hat{n} = -102$, $V_I = 86$ km/s
- $C_A = 68$, $C_S = 106$ km/s
  $C_f = 125$ km/s
- $M \cong \frac{189}{125} = 1.5 > 1.0$
- A SHOCK

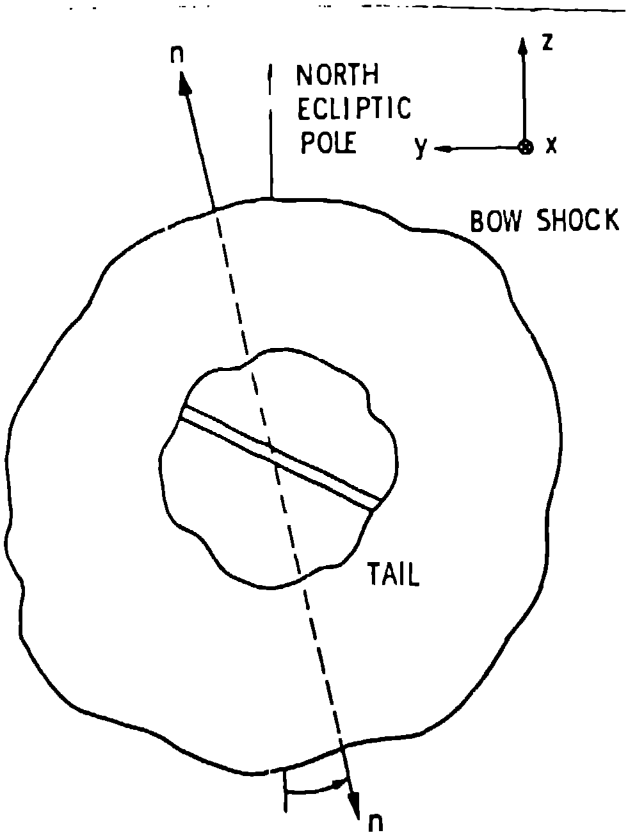


Figure 3. Encounter Trajectory Looking Sunward. Contours corresponding to a bow shock and plasma tail are shown schematically along with the coordinate system used in the analysis (upper right). The normals for the inbound and outbound crossings of the bow wave or shock are indicated.

3. ANALYSIS RESULTS

Table 1 contains the parameters appropriate to the inbound crossing of the bow wave. The first row contains the components of $\hat{n}$ in solar-ecliptic coordinates (X toward the sun, Y parallel to the ecliptic and positive to the East, and Z parallel to the north ecliptic pole). One of our acceptability criteria is that the normal should have a physically reasonable orientation. Figure 3 shows the encounter geometry as seen looking toward the sun along the tail of Giacobini-Zinner. It can be seen that the intercept was basically from south to north so that a reasonable shock normal should have $n_y < 0$, $n_z < 0$ inbound and $n_y > 0$, $n_z > 0$ outbound. In both cases, n should have a component pointing into the upstream solar wind, so that $n_x > 0$.

The angle, θ_{Bn}, is ≈ 80° so that the wave or shock is nearly perpendicular as anticipated from the geometry of the trajectory and the orientation of the interplanetary magnetic field at the time of the crossing.

The two methods of computing V_s lead to identical results of 189 km/s. Although this exact agreement is undoubtedly a coincidence in this case, we generally require acceptable solutions to yield approximately equal values of V_s. The inertial speed, $V_I \approx 86$ km/s, is not zero as would be expected for a bow wave or standing shock in an ideal situation. From the analysis of planetary bow shocks, however, it has been found that the inertial speed is rarely zero but that the shocks are non-stationary with instantaneous speeds of tens of km/s up to values of ≈ 100 km/s. This realization forms the basis of another of our criteria, i.e., V_I need not be zero but should be small (much less than the solar wind speed).

The values of C_A and C_s show that the ion sound speed is dominant. Their ratio implies an upstream $\beta = 8\pi p/B^2$ of 2.9. This value, which is larger than the value near 1.0 that is typically observed in the solar wind, demonstrates the influence of the cometary pick-up ions which have come to dominate the energy density of the plasma upstream of the bow wave. For this quasi-perpendicular orientation, the fast mode speed is essentially $C_f = (C_A^2 + C_i^2)^{1/2}$, leading to a value of 125 km/s.

Hence, the Mach number, $M = 189/125 = 1.5 > 1.0$. The conclusion to be drawn is that the inbound crossing is, in fact, a shock. Further support for this conclusion is provided by the Rankine-Hugoniot solutions, (with $\beta = 2.9$ and $\theta = 80°$) which show that the ratios N_2/N_1, B_2/B_1 as observed are consistent with $M = 1.6 \pm 0.1$.

The outbound crossing is considered next, the results showing that it is not easy to obtain unambiguous results in this case. Table 2 contains the results for an acceptable solution. As above, we have insisted that $\hat{n}$ have a reasonable orientation ($n_x > 0$, $n_y > 0$, $n_z > 0$ and demonstrating a reasonable quantitative rela-

TABLE II.

- $\hat{n}$: 0.4236, 0.1822, 0.8873
- θ_{Bn}: 87.7° PERPENDICULAR
- $V_s = |\Delta V \times B_2| / |\Delta B| = 60$ km/s $\Big\}$ 73 ± 13
- $V_s = (N_2/N_2 - N_1)\Delta V \cdot \hat{n} = 86$ km/s
- $V_1 \cdot \hat{n} \cong 0$, $V_1 = 60\text{-}86$ km/s
- $C_A \cong 32$ km/s, $C_S = 94$ km/s

  $C_f = 99$ km/s
- $M_f \cong \frac{73}{99} = 0.73 \pm 0.13 < 1.0$
- SUBSONIC - A WAVE?

tionship). The wave turns out again to be nearly perpendicular with $\theta_{Bn} = 88°$. The two values of the shock speed are slightly different with $V_s = 73 \pm 13$ km/s, the average value being low compared to that obtained inbound. Again, the inertial speed of 60-86 km/s appears within an acceptable range. In the solar wind upstream of the outbound crossing, C_A has decreased to 32 km/s principally as a result of a decrease in the field magnitude by a factor of approximately 2. The sound speed is also reduced slightly so that $C_f = 99$ km/s. However, even this reduction is not adequate to yield a Mach number greater than one. Thus, $M = 73/99 = 0.73 \pm 0.13 < 1.0$.

Taken at face value, this result implies that the wave is subsonic and not a shock. However, we have applied an additional criterion, not discussed above, which is not fulfilled by this otherwise acceptable solution.

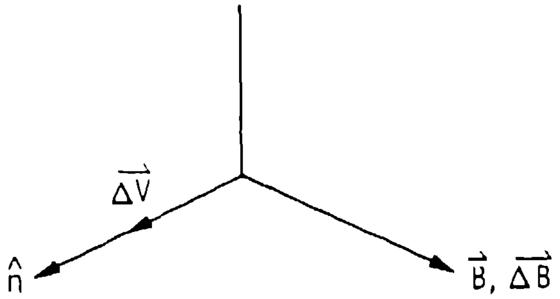
For both waves and shocks, certain geometric relations between $\overline{\Delta V}$ and $\overline{\Delta B}$ must be satisfied (Ref.11, p. 98). In particular, for a perpendicular shock or wave, $\overline{\Delta V}$ should be parallel to $\hat{n}$ (and perpendicular to $\overline{\Delta B}$) as indicated in the upper half of Figure 4. The actual relation is presented in the lower half figure which shows that $\overline{\Delta V}$ makes a large angle of ~ 72° with respect to $\hat{n}$. As a consequence, the numerators in V_s, i.e., $\overline{\Delta V} \cdot \hat{n}$ and $\overline{\Delta V} \times \overline{B}_2$, are small for a given $\overline{\Delta V}$. This misorientation is presumably the reason why V_s is low.

The Rankine-Hugoniot solutions (with $\beta = 10$ and $\theta = 88°$) lead to jumps in density and field consistent with $M = 1.6 \pm 0.3$, i.e., a mean value similar to that obtained for the inbound crossing.

A PROBLEM OUTBOUND:

FOR PERPENDICULAR SHOCK OR WAVE

$\vec{\Delta V} \parallel \hat{n}$, $\vec{\Delta V} \perp \vec{\Delta B}$



HOWEVER, RELATIONS ARE:

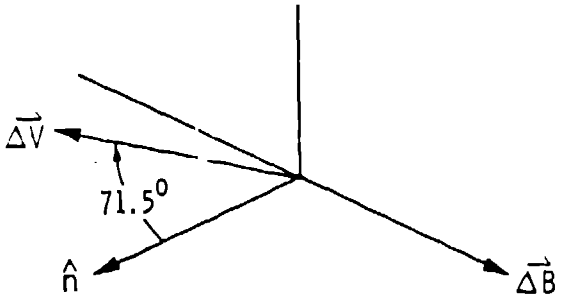


Figure 4. Relative orientations of the velocity and magnetic field jumps. The upper panel shows the orientation anticipated for a quasi-perpendicular shock or wave. The bottom panel shows the actual orientations of the vectors used in the analysis presented in Table 2 and which differ drastically from expectation.

We are continuing to analyze the outbound crossing in the hope of identifying the origin of this misorientation of $\overline{\Delta V}$ and $\overline{\Delta B}$. It may be that time variations are responsible for producing this apparent discrepancy. The variability of the outbound crossing, which may be the result of multiple crossings of the bow wave or a consequence of the high value of $\beta = 10$, leads to a relatively long interval of ~ 20 minutes between stable upstream and downstream conditions. It may be that the solar wind, specifically the orientation of B, has changed significantly during this interval. Continued analysis should show whether or not it is possible to obtain an unambiguous result for the outbound crossing.

4. ACKNOWLEDGEMENT

Arrangements for this analysis, and the concomittant data exchange, were carried out at an ICE workshop held at the U. of Maryland and hosted by M. Coplan with the assistance of K. Ogilvie and T. von Rosenvinge. Other investigators who participated in the workshop and contributed to the study are R. Zwickl, J. Gosling, and B. Tsurutani. The shock analysis at JPL was ably carried through by J. Wolf. The research described in this paper was carried out, in part, by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Work at Los Alamos was performed under the auspices of the U.S. Department of Energy and supported by the NASA ISEE program through S-04039-D.

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