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An East-West Asymmetry in the Solar Wind Velocity

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Abstract

An east-west asymmetry may exist in the solar wind velocity due to the action of a well known mechanism, namely, the influence of the solar rotation on the interaction between fast and slow streams. The mechanism predicts fast streams tend to come from the west and slow ones from the east with respect to the average solar wind direction. It is noted that if there is a correlation between density and velocity, a measurement of the average azimuthal wind component is not sufficient to determine the angular momentum flux. Experimental evidence from Pioneer 6 indicates that about 50% of the east-west variations in flow direction with periods around 4 days (the largest period studied) may be due to the fast stream-slow stream interaction. The percentage decreases for shorter periods.

Physical principle. The solar wind speed is known to be highly variable, for example, it has been observed to double in less than one day [Snyder and Neugebaurer (1966)]. Dessler (1967) has pointed out that one effect of the solar rotation on the interaction of adjacent streams of different velocity is to produce east-west deflections of the flow. Other aspects of the interaction have been described by Parker (1965), Neugebauer and Snyder (1967), and Sarabhai (1963). We would like briefly to describe the interaction in the framework of fluid mechanics since this framework allows calculation of the size of the expected effects (Corovillano and Siscoe, 1969). The main purpose of this section is to point out that the interaction should produce a prevailing east-west asymmetry in the solar wind velocity.

The asymmetry is introduced by the sun's rotation acting on different velocity streams through the physical mechanism illustrated in Figure 1. The figure shows schematically the interaction between fast and slow streams. The sun's rotation imposes a spiral pattern on each stream in the manner familiar from rotating lawn sprinklers: the slower the stream, the tighter the spiral. Thus, adjacent streams with different speeds will interact along their interface. For simplicity, the figure shows a thin interface, however, the same argument holds for a gradual transition between streams. In Figure 1(a), the slow stream precedes, and an increased thermal and magnetic pressure occurs along the interface due to compression by the overtaking fast stream. The associated pressure gradient can be resolved into radial and azimuthal components; only the latter is shown in the figure. It is clear that the radial stress must act to radially speed up the slow stream and slow down the fast stream. The azimuthal stress acts to deflect the slow stream to the west and the fast stream to the east. In Figure 1(b), the fast stream precedes, and the thermal and magnetic pressures are reduced along the interface due to the separation of the two streams. Again the associated pressure gradient can be decomposed into radial and azimuthal components. The radial component again acts to equalize the radial velocity of the two streams. The azimuthal stress pulls the fast stream toward the east and the other toward the west. Thus, in both cases, the fast stream is accelerated toward the east and the slow stream toward the west which should result in the asymmetry claimed in the first paragraph.

In the final section the expected asymmetry is shown to be present in that portion of the Pioneer 6 plasma data for which the east-west angles have been computed. Future comparison is planned for Pioneer 7 and IMP 1 data. The solar wind velocity asymmetry has been shown to be consistent with an observed prevailing east-west asymmetry in the orientation of tangential discontinuities (Siscoe, Turner and Lazarus, 1969).

North-south component. The correlation between solar wind speed and east-west direction will be degraded to some extent by the north-south component of the pressure gradient. To recognize the importance of the north-south component, consider the case in which it is zero. This case occurs only in the special circumstance where the interface between the two streams intersects the solar equatorial plane at right angles. Projected back onto the solar surface, the situation requires that the regions generating the fast and slow streams interface along a line of constant solar longitude. However, it is probable that such interfaces are arbitrarily oriented on the solar surface and the special situation required for zero north-south component is unlikely. Thus, a substantial amount of the non radial motion induced by the solar rotation may occur in the north-south direction. A fast stream may find it easier to flow north or south of a preceding slow stream than to deflect to the east. All though the east-west effect competes with the north-south motion, it should be measurably present.

A contribution to the average azimuthal velocity. Several authors have considered the possibility of a non-zero average azimuthal component of the solar wind velocity (Weber and Davis, 1967, see also the review by Dessler, 1967). Magnetic and viscous stresses have been invoked to transfer some of the sun's angular momentum to the solar wind. There results a net loss of angular momentum from the sun and an average azimuthal velocity in the same direction the sun rotates.

There is, therefore, a tendency to believe that a measurement of average azimuthal velocity gives direct information about the angular momentum flux. We point out in this section that correlations in the longitudinal structure in the solar wind can also produce an average azimuthal component but with no angular momentum flux, thus, the assumed association need not be valid. It would avoid all ambiguity if the observed average of the product $\rho V_\varphi V_r$ were computed by experimenters.

since this is directly proportional to the angular momentum flux at a fixed solar distance.

A non-zero average azimuthal velocity will occur as a result of the interaction of fast and slow streams if there is a correlation between speed and density. The resulting average velocity can be either from the east or from the west, and it produces no loss of angular momentum from the sun. Since this mechanism is independent from those mentioned above, we may isolate it and assume zero net flux of angular momentum away from the sun. For the purpose of illustrating the mechanisms, consider the following idealized situation: fast streams alternate with slow streams; all north-south velocity components are zero, all fast streams have the same velocity and density (V_r^f, V_φ^f, ρ^f) and the slow streams all have velocity and density (V_r^s, V_φ^s, ρ^s); let the total azimuthal angle occupied by the fast streams be Φ^f and that of the slow streams be Φ^s. Recall from the discussion about the interaction of fast and slow streams that V_φ^f and V_φ^s have opposite signs. If we choose the angle φ to decrease in the direction the sun rotates, V_φ^f is positive and V_φ^s is negative. The net flux of angular momentum carried away in the solar equatorial plane per unit north-south distance is

$$\rho^f V_\varphi^f V_r^f r^2 \Phi^f + \rho^s V_\varphi^s V_r r^2 \Phi^s = 0 \qquad (1)$$

The average azimuthal velocity is

$$\bar{V}_\varphi = \frac{\Phi^f V_\varphi^f + \Phi^s V_\varphi^s}{2\pi} \qquad (2)$$

Eliminating V_φ^s between equations (1) and (2), we find

$$\overline{V}_\varphi = \left(1 - \frac{\rho^f V_r^f}{\rho^s V_r^s}\right) \frac{\Phi^f V_\varphi^f}{2\pi} \tag{3}$$

Thus, the sign of $\overline{V}_\varphi$ depends on the mass flux ratio of the fast and slow streams. For example, in the case of equal densities, $\rho^f = \rho^s$, $\frac{\rho^f V_r^f}{\rho^s V_r^s} > 1$ since $V_r^f > V_r^s$. In this case $\overline{V}_\varphi$ is negative, that is, the wind would appear to come from east of the sun on average. However, there is experimental evidence that the solar wind speed and density tend to be anticorrelated, that is $\rho^f < \rho^s$ [see, for example, Snyder and Neugebauer, 1966]. Hence, it might be that the mass flux ratio is less than one, which would produce a positive $\overline{V}_\varphi$. If this is the case, the wind might appear to come from west of the sun on average.

Experimental evidence. Data from the M.I.T. plasma experiment on Pioneer 6 have been examined for evidence of the predicted asymmetry. The instrument measures the flow direction in the spacecraft equatorial plane (essentially the ecliptic plane) with a relative error probably less than $\pm 1^\circ$. The accuracy of the absolute angle with respect to the sun-spacecraft line is not yet determined; hence, we will not consider the average direction of flow.

Three hour averages of the solar wind speed were correlated against the flow angle in the ecliptic plane for a 27 day stretch of data. The aberation of the wind due to spacecraft motion was removed. Also the troublesome effects of long term trends were reduced by subtracting three day sliding averages.

The angle was taken positive for flows from the west; thus, there should be a positive correlation between angle and speed.

The correlation coefficient as a function of lag is shown in Figure 2 for lags up to 30 hours. There is a conspicuous peak of +0.45 at zero lag, which implies an in phase positive correlation as predicted.

That the peak value is considerably less than 1 implies an appreciable uncorrelated component to the variations, or another correlation with a different phase. To decide which, the cross spectrum shown in Figure 3, was made. The coherence falls off with increasing frequency beginning with 0.49 at 0.29×10^{-5} cps or a period of 4 days. However, the phase stays essentially at zero until the coherence falls to 0.1, and then begins to deviate randomly. Thus, the departure from perfrect coherence must be due to uncorrelated fluctuations. Whatever coherence is present is caused by a mechanism that produces zero phase such as that described here. The uncorrelated part of the fluctuations, becomes relatively more important for higher frequencies or for smaller scale lengths. In addition to the reduction in correlation due to the north-south velocity component which was mentioned earlier, part of the uncorrelated component might be Alfven waves, which would be unlikely to remain coherent over a 27 day period.

The experimental evidence suggests that part of the variations in angle are due to the mechanism described here. In fact for variations with periods around 4 days about 50% may be so generated.

Acknowledgements

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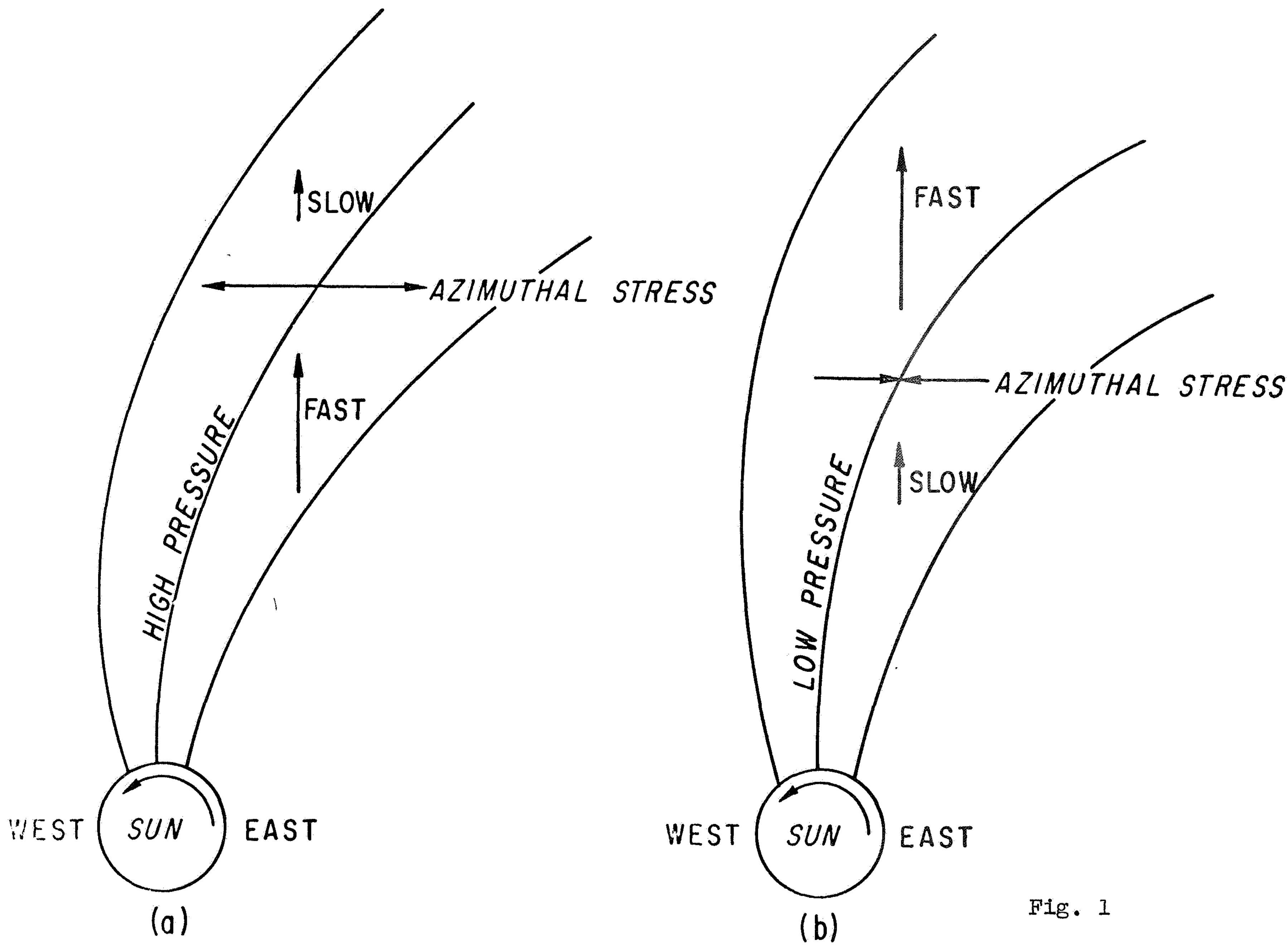
Figure Captions

Figure 1: A schematic representation of the interaction between fast and slow streams. (a) Slow stream preceding. (b) Fast stream preceding.

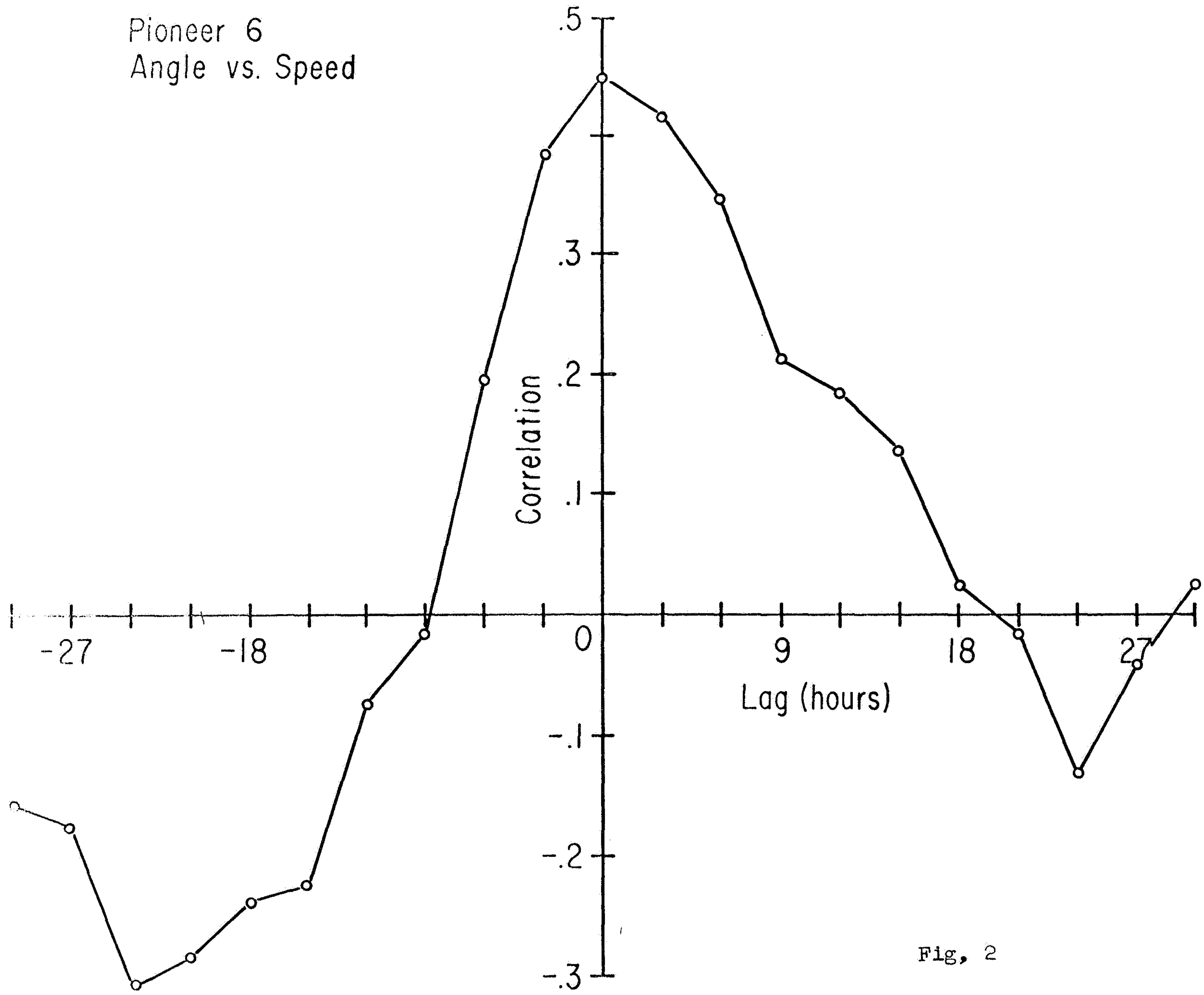
Figure 2: Correlation between Pioneer 6 measurements of solar wind speed and angle in the ecliptic plane as a function of lag time.

Figure 3: Cross spectrum between data used in Figure 2.

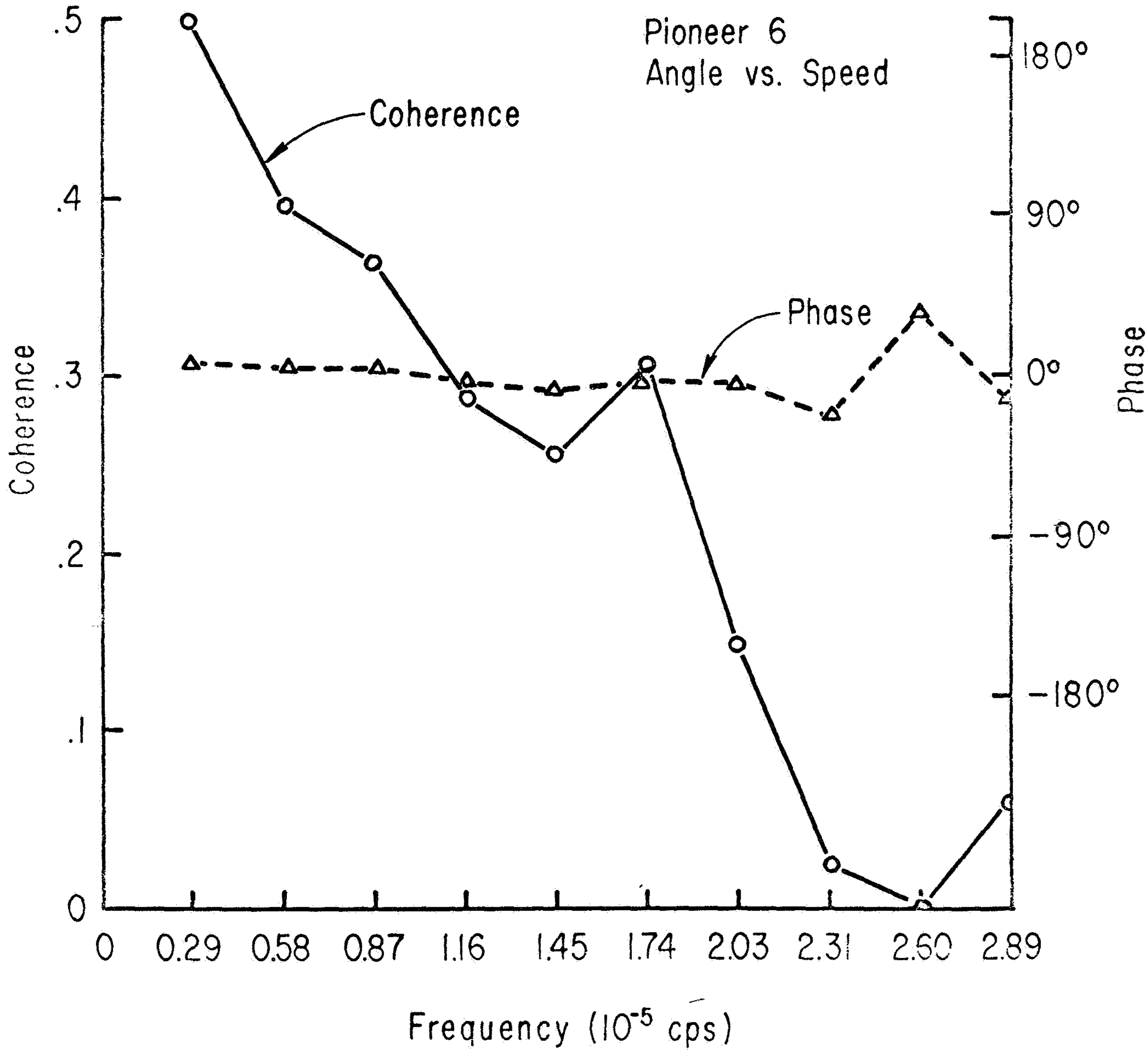


SLOW
AZIMUTHAL STRESS
FAST
HIGH PRESSURE
WEST
SUN
EAST
(a)
FAST
AZIMUTHAL STRESS
SLOW
LOW PRESSURE
WEST
SUN
EAST
(b)

Fig. 1


Pioneer 6
Angle vs. Speed
.5
.3
.2
.1
0
-.1
-.2
-.3
Correlation
-27
-18
9
18
27
Lag (hours)

Fig, 2


Pioneer 6
Angle vs. Speed
Coherence
Phase
.5
.4
.3
.2
.1
0
180°
90°
0°
−90°
−180°
0
0.29
0.58
0.87
1.16
1.45
1.74
2.03
2.31
2.60
2.89
Frequency (10^{-5} cps)