mean-square timing error of 400 μsec derived from the scatter of the data about curve B in Fig. 1.

The results of the observations are shown in Fig. 1, where the difference between the measured pulse arrival times and the predicted arrival times are plotted against the date of observation. The predicted arrival times are based on a pulse period of 0.253 065 030 second U.T. $\pm 1 \times 10^{-9}$ second U.T. (*3*), and all times are referred to the solar system barycenter (*4*). Corrections for the position of the observer included all rotational and orbital effects according to Newtonian physics; Jet Propulsion Laboratory ephemeris data DE-19 was used as a basic source. The open circles are observations at 404.8 Mhz, and the crosses are measurements at 445.8 Mhz with a delay of 13.2 msec added to correct for interstellar dispersion. The measured average delay between the two observing frequencies of 13.2 ± 0.2 msec is in agreement with that predicted from the measurements of other observers of 13.24 ± 0.18 msec (*5*). Curve A is the predicted differential arrival time based on a period of 0.253 065 030 70 second U.T. and on the mass-on-frequency effect suggested in (*1*) using a value for the constant K of 3×10^{-30} cm/g. Curve B is a least-squares straight line fit to the data. It is clear that the observations do not fit curve A and are not in accordance with the speculated relation between mass and frequency presented in reference (*1*). The present observations can only be reconciled with the experimental results of reference (*1*), if there is a fundamental difference between this experiment and the previous two experiments. In the Taurus A experiment, the shift of a spectral line was measured; in the cesium clock experiment, the accumulated phase difference of two monochromatic waves was measured; whereas in this experiment, the arrival time of a pulse envelope was measured. It is not clear whether these differences in experimental procedure involve any fundamental difference in the experiments.

In the absence of the mass-on-frequency effect, curve B can be interpreted as resulting from a slight error in the adopted pulsar period or, alternatively, in the adopted pulsar position (*6*). An error in the adopted pulsar period would generate a linear slope with time in the residual arrival time plot. An error in the adopted pulsar position would lead to a sinusoidal error with a period of 1 year in the time corrections used to refer the observations to the solar system barycenter; because of the limited observing period in this experiment it was not possible to distinguish this effect from that of a period error. On the assumption of no error in the position of the pulsar, curve B indicates a period for CP 0950 of 0.253 065 032 54 second U.T. The error based only on the internal consistency of the data is $\pm 3 \times 10^{-11}$ second. A new and more precise position for CP 0950 than the one adopted has just become available (*7*). If we use this position of $9^h50^m30.76^s \pm 0.15^s$ right ascension and $+8°09'48'' \pm 5''$ declination epoch 1950.0, the data is best fit by a period of 0.253 065 032 0 second U.T. $\pm 4 \times 10^{-10}$ second U.T., where the error is completely determined by the positional uncertainty. Observations over a period of 1 year will allow a distinction between the effects of a period error and a position error, enabling a determination of both quantities.

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30 September 1968

Earth's Bow Shock: Elapsed-Time Observations by Two Closely Spaced Satellites

Abstract. *Coordinated observations of the earth's bow shock were made as Vela 3A and Explorer 33 passed within 6 earth radii of each other. Elapsed time measurements of shock motion give directly determined velocities in the range 1 to 10 kilometers per second and establish the existence of two regions, one of large amplitude magnetic "shock" oscillations and another of smaller, sunward, upstream oscillations. Each region is as thick as 1 earth radius, or more.*

The collisionless plasma shock that forms sunward of the earth as the super-Alfvénic solar wind streams from the sun toward the obstacle presented by the geomagnetic field (*1*) varies in momentary location and appearance, as witnessed by numerous satellite measurements (*2–4*) and emphasized by multiple shock crossings during individual satellite passes (*3–5*). Some experimenters have succeeded in estimating parameters characterizing the shock, such as velocity, range of movement, and thickness, by applying models of periodic shock motion to sequences of multiple crossings seen by single satellites (*4–6*). An obvious refinement of this approach is to compare measurements by two or more satellites near the shock at the same time. One such comparison has been made in which shock velocity was measured by using concurrent observations on opposite sides of the earth by two satellites separated from each other by 26 earth radii (R_E) (*7*), but no information was obtained on local shock structure. The first opportunity to secure simultaneous dual satellite observations of shock at relatively close spacing came during the flights of Explorer 33 and Vela 3A.

On 12 to 13 July 1966, during the inbound portion of its first orbit, Explorer 33 passed close to Vela 3A near the earth's shock below the ecliptic, in the dawn-to-noon quadrisphere. The two satellites spent 6 hours within 6 R_E of each other, coming as close as 5.2 R_E in straight-line distance. Concurrent observations by magnetometers aboard the two vehicles occurred as Explorer 33, entering the transition region inbound, was encountering the shock, while Vela 3A, exiting the transition region outbound, was also encountering the shock. Both satellites passed through or into the shock and its upstream magnetic oscillations several times, allowing mutual observation of a variety of shock-related phenomena, including apparent shock motion between the spacecraft, from which shock velocity and dimension can be estimated by measurements of elapsed time. These parameters of shock motion and profile are obtainable from a portion of the conjunction interval toward the end of the joint observation period, when a sequence of comparatively isolated events permitted straightforward shock identifications at both vehicles.

Figure 1 illustrates the relative positions of the two satellites during that part of the observation interval described here. Figure 1a shows the vehicle trajectories rotated around the solar ecliptic X-axis and projected onto a common X-ρ plane, where ρ is perpendicular distance to the X-axis; Fig. 1b shows a projection of the vehicle trajectories on the solar ecliptic Y-Z plane, looking from the sun toward the earth. Gaps within the range of interest of the trajectory curves represent intervals during which data were not acquired. The numbered circles and lettered curves denote events to be discussed; times corresponding to these points are given in Table 1.

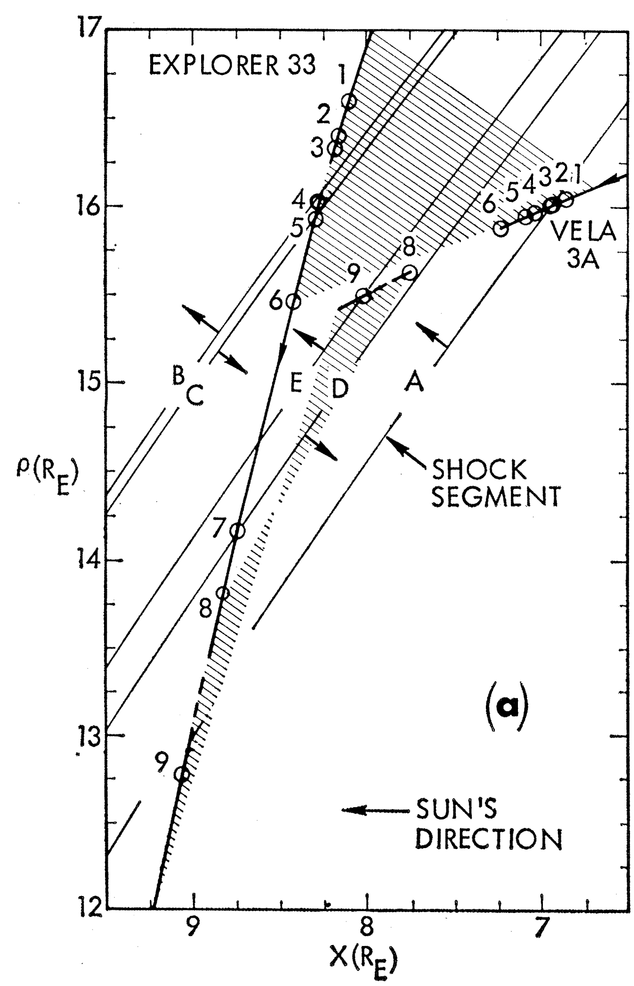
Table 1. Times of events marked in Figs. 1 and 2.

Event No.	Time (UT)
1	0018
2	0028.5
3	0031
4	0047.1
5	0050.5
6	0112
7	0209.5
8	0235.4
9	0316

The Los Alamos plasma spectrum analyzer on Vela 3A was not in operation at the time of these observations. Assignment of solar wind, shock, or transition region status to sections of the Vela data were therefore made on the basis of similarity of waveforms to those identified in an earlier study in which concurrent magnetic waveforms and ion spectra were compared (*8*). Assignment of regime at Explorer 33 was made on the basis of ambient field magnitude, which was under 5 gammas in the solar wind and characteristically two or three times higher in the transition region, but which occasionally oscillated between two levels. The assignments were confirmed by the Explorer 33 plasma probe (*9*).

It was assumed that the shock was cylindrically symmetric around an axis, in the ecliptic plane, oriented 3° west of the sun to simulate an average angle of solar wind aberration. It was further assumed that the portion of the shock subtending the illustrated satellite positions expanded and contracted uniformly so as to move along its own normal from one observation to the next. The lettered curves of Fig. 1a depict various positions of the shock as determined by the paired satellite observations. The shock segments are taken from a figure of Spreiter *et al.* (*10*) for $\gamma = 2$, $M_\infty = 8$, where γ is the ratio of specific heats, and M_∞ the Mach number of solar wind.

Figure 2 shows a condensation of the data from the two satellites. We have plotted the highest and lowest readings, each half-minute, of field magnitude at Explorer 33 and magnitude of the spin-normal field projection at Vela 3A (*3*). The numbers in Fig. 2 refer to the times of Table 1. The following description of the timed events in the data requires



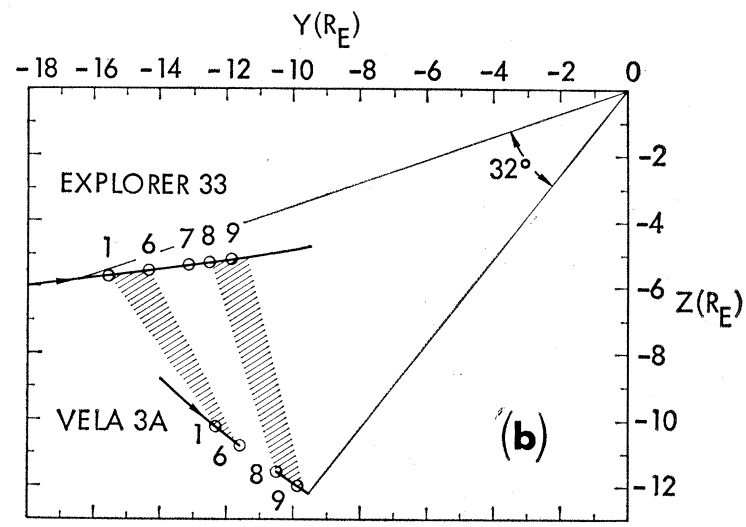


Fig. 1. Relative positions of Vela 3A, Explorer 33, and the earth's bow shock during data-acquisition portions of the reported time interval. Shading and number sequences indicate time-correspondence of trajectory segments. Scales represent earth-centered solar ecliptic coordinates, with X toward the sun, Y opposite the earth's orbital velocity, and Z completing the system. In (a) the loci of both spacecraft appear rotated onto a common plane; the rotation is always less than 32° for the illustrated orbital segments, as shown in Y-Z projection, looking from the sun, in (b). The ρ coordinate in (a) represents the perpendicular distance from spacecraft to X-axis. Some numbered points are omitted from (b) because the smaller scale would crowd them undesirably. Arrows normal to shock curves in (a) represent apparent direction of shock motion at instants of observation.

alternating attention to Figs. 1a and 2. Actual details of the waveform and times mentioned derive from the original records.

Before time 1, both spacecraft were in the solar wind. At time 1, small-amplitude, low-frequency waves appeared at Vela and persisted until time 2, when the Vela magnetometer saw the beginning of a d-c shift in the field projection, which was followed at once by a burst of large-amplitude oscillations similar to those identified in an earlier study as shock pulses, on the basis of correlated irregular ion spectra (*8*). We interpret this shift (downward in the figure) as the initial appearance of the shock, *A*, as it overtook Vela on its way outward. Explorer began to observe upstream waves at time 3, until a gap in its record 8 minutes later. Its data resumed at the end of the gap with a continuation of the upstream waves, until Explorer 33 saw a large field increase 4½ minutes later at time 4. This increase is interpreted as the arrival of the outward-moving shock, *B*, at Explorer. Vela continued to observe isolated bursts of large field oscillations and pulses sporadically until the last pulse 2 minutes before time 4, after which Vela recorded some d-c field shifts followed by typical behavior of the transition region field from 0055 until the end of its transmission at time 6. The elapsed time of 18.6 minutes and apparent normal distance of 1.1 R_E between shock positions *A* and *B* at times 2 and 4 correspond to an equivalent mean normal velocity of 6.25 km/sec. If the shock or shock oscillations arrived unobserved at Explorer before time 4, as early as the beginning of the data gap, their equivalent normal velocity could have been as high as 11 km/sec, an upper bound.

By time 5 the shock was receding, and Explorer 33 emerged from a brief residence behind it into a relatively steady field in the solar wind, which it continued to observe until time 7, when it reentered the transition region through an abrupt field jump. Equivalent normal velocity of the shock from *C*, at 5, to *D*, at 7, must have averaged at least 0.9 km/sec to keep it ahead of the vehicle. Occasional appearance of

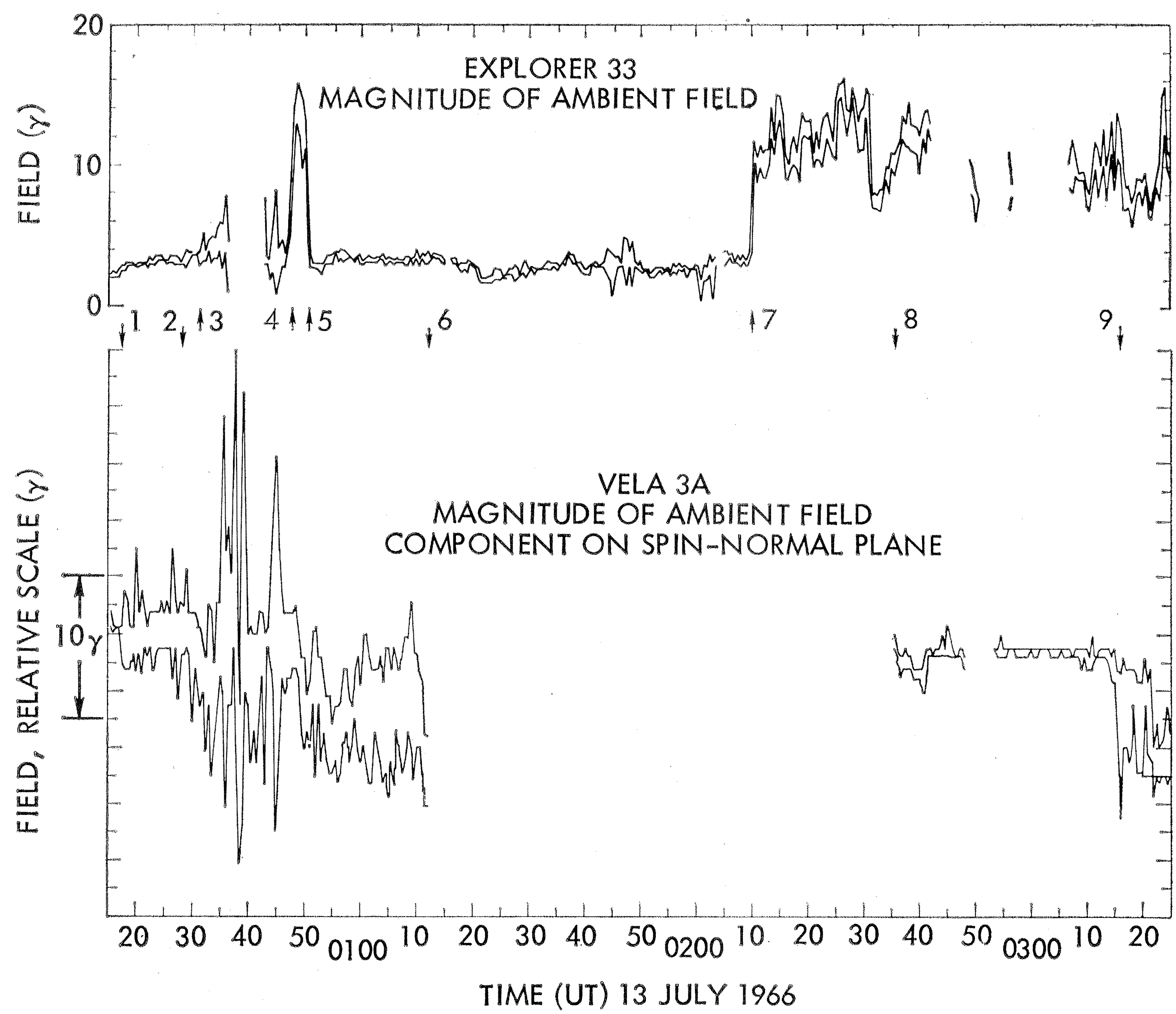


Fig. 2. Concurrent data from Vela 3A and Explorer 33 magnetometers for the reported interval. Numbers correspond to the numbered positions of Fig. 1a; arrows indicate features described in the text for the designated vehicle. Each double curve represents a plot of the highest and lowest value every half minute.

upstream waves at Explorer between 0140 and 0205 suggest that the shock remained not too far ahead of the satellite, so that its velocity must have been fairly low. This inference is supported by the failure of the retreating shock to appear at Vela before the suspension of its data transmission at time 6. The shock's average equivalent normal velocity could not, therefore, have exceeded 4.4 km/sec from time 5 to time 6, and, since it must have been between the Explorer and Vela positions at time 6, its average velocity of contraction must have been bounded by 0.9 and 4.4 km/sec during the interval from time 5 to 6. The lower value is the same as the 0.9 km/sec minimal average velocity necessary for the much longer interval from time 5 to 7 and is probably just under a true, sustained shock velocity.

After time 7, Explorer 33 remained in the transition region beyond the end of the interval depicted, with some gaps in the record resulting from a calibration sequence. At time 8, Vela data resumed in the solar wind. A final observation of shock motion occurred when, an hour after the shock was last seen by Explorer at time 7, it again expanded past Vela, causing the latter to record a reentrance of the transition region from the solar wind through an abrupt shock crossing at time 9. Vela remained behind the shock for the rest of the illustrated interval of data acquisition.

It seems likely that Explorer's shock crossing at time 7 was caused by the vehicle overtaking the contracting shock, rather than the shock expanding past the satellite. Continued contraction of the transition region boundary behind Explorer after time 7 is implied by failure of the shock, had it moved outward instead, to expand the short distance to Vela by time 8, when transmission resumed in typical solar wind field. This reasoning makes it impossible to fix a time or position at which the shock reached its innermost location before again expanding. However, the elapsed time and distance from shock *D*, at 7, to *E*, at 9, provide a minimal mean velocity of 0.3 km/sec, about a third of the lower estimate given above for the earlier section of the same observation interval, when the shock led the Explorer satellite inward. The shock velocities and limits found above are consistent with, or bound, the majority of velocities inferred less directly from single satellite measurements (see *4–6*).

The most important new result of this report is contained in the time interval from 1 to 5. For the first time there is definite evidence for upwind magnetic waves being part of the shock structure, for they appear at the outer satellite (Explorer) after they appear at the inner one; that is, the low-frequency ($f < 0.25$ hz) wave components seen in the solar wind by Vela after time 1 and by Explorer after time 3 appeared at Vela 13 minutes before they appeared at Explorer. The normal distance applicable at that time yields a normal velocity of 9.9 km/sec. This figure is 44 percent higher than the 6.25 km/sec found above for the shock between *A* and *B*, and suggests that the upwind oscillations, or "halo," may have been expanding more rapidly than the shock. The three-dimensional relative positions of the two spacecraft, Fig. 1, a and b, together, also imply that the shock-halo structure extended tangentially over a region at least several earth radii in diameter, encompassing both vehicles.

Estimates of shock velocity can be used to obtain other parameters of shock profile, if the velocity with which the wave train passed each vehicle is assumed to be the same as the average velocities with which events moved from one vehicle to the other. The normal distance between the vehicles when the forward side of the halo reached Explorer at time 3 was 1.2 R_E. The beginning of the d-c shift identified as the shock in the lower curve of Fig. 2 passed Vela 2.5 minutes earlier, traveling, we assume, at 6.25 km/sec, and would therefore have gone 0.15 R_E toward Explorer from Vela by time 3, which would leave 1.2 minus 0.15, or 1.05 R_E, as the instantaneous thickness of the halo at time 3.

The 6.25 km/sec figure also yields an estimate of the thickness of the shock oscillation zone itself. The large peak-to-peak fluctuations of tens of gammas and the changes in mean field level lasted many minutes after time 2 at Vela. The exact duration assigned to passage of the zone depends on the somewhat arbitrary way in which it is defined, but a duration of 7.5 minutes for the central group of pulses, or a separation of 21 minutes between the first and last major d-c shifts, gives a thickness from just under half an earth radius to 1.25 R_E. A large thickness is consistent with the appearance of a large pulse at Vela 2 minutes before time 4, when the shock was almost at Explorer; with the occurrence of mean level changes at Vela between times 4 and 5, when the shock was beyond Explorer; and with prolonged occurrences of apparent shock oscillations simultaneously at both vehicles during the preceding hours, not covered in this report, when both satellites were separated by a shock-normal distance of more than an earth radius. A wide, thick shock pulsation zone, moving with a gross velocity comparable to the slower satellite velocities around 1 km/sec obtained between times 5 and 9, would easily explain the occasional prolonged residence of Vela in regions of violent field fluctuation reported earlier (*3*, *8*).

Gross shock motion appeared more erratic than periodic during the present interval. However, structural magnetic oscillations within the shock, upwind, and transition region often exhibited an underlying periodicity of several tens of seconds at both spacecraft. Solar wind velocities and spectral analysis of the magnetic signals will be necessary to remove Doppler effects and obtain estimates of true wave velocities, frequencies, wavelengths, and gradient scales in the plasma reference frame.

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11. We are grateful for the encouragement of Dr. C. P. Sonett, principal investigator for the NASA/Ames Explorer 33 magnetometer.

22 July 1968