RADIO DETECTION OF SOLAR-WIND DISCONTINUITIES *Jeremy A. Landt*

ABSTRACT Geomagnetic field sudden increases or storm sudden commencements are compared with measurements of electron content of the solar wind. The latter data are obtained by a radio propagation experiment, which measures the electron content along a radio path between transmitters on the Stanford campus and several spacecraft in solar orbit. Measurements were examined during time periods that included 40 of the geomagnetic disturbances (gmd) reported between January 1, 1966, and June 30, 1969.

These studies indicate that some widely reported solar wind discontinuities have been detected by the radio propagation experiment. Eleven of the 40 gmd were classified as storm sudden commencements (ssc), which usually result when a shock in the solar wind strikes the magnetosphere. The relative timings of these 11 events are consistent with conclusions drawn from comparisons of experiment geometry to prevailing shock models. Compared to the nature of these 11 events, the characteristics of the solar-wind disturbances corresponding to the remaining 29 gmd were generally found to have been less favorable for detection by the radio propagation experiment, but sharp changes in the content were clearly evident at the time of several minor gmd.

INTRODUCTION

Recent experimental and theoretical studies of blast waves in the solar wind have led to a general consensus about an average disturbance shape [*Hirshberg,* 1968; *Taylor,* 1969; *DeYoung and Hundhausen,* 1969]. The experimental studies have usually assumed a knowledge of the location of the disturbance near the sun (e.g., a solar flare site), and measurements were necessarily confined to the locale of spacecraft. This spatial limitation in the study of the structure of individual events can be partially overcome by combining such localized measurements with other measurements of the average density between the earth and a deep space probe. Spatially averaged electron number density data have been obtained since December 1965 by the radio propagation experiment using radio waves transmitted between powerful transmitters on the Stanford campus and several specially equipped spacecraft in orbit around the sun. These data have been determined from radio delay measurements of electron content along the path connecting earth and the spacecraft. The trajectories of the spacecraft are shown in figure 1.

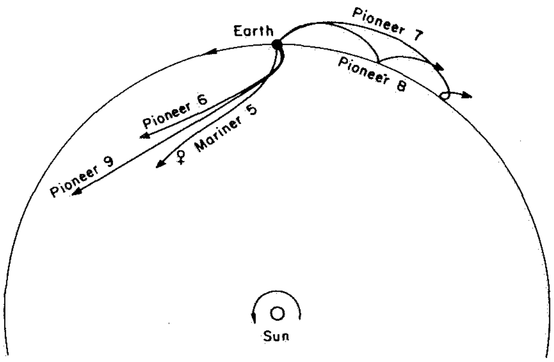

Figure 1. *The paths of the five spacecraft used in this study, projected onto the ecliptic plane and shown in the frame that rotates with the earth.*

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Records of the horizontal component of the earth's magnetic field provide one of the most complete data sets indicating solar-wind conditions near the earth. Some worldwide fluctuations in the earth's field are the result of compressions or expansions of the magnetosphere due to fluctuations in the streaming pressure of the solar wind. Before turning to individual events, we have attempted to determine whether solar wind discontinuities that cause sudden impulses (si) and storm sudden commencements (ssc) have been detected by the radio propagation experiment. This was done by comparing the timings of ssc and si to the times of sharp changes in the average electron density for the period from January 1, 1966, to June 30, 1969. During this period, 257 geomagnetic events were reported by ten or more stations and summarized in *Solar Geophysical Data.* We have also deduced the approximate orientations of some of these solar wind disturbances by comparing the relative timings of the events with the locations of the radio path.

THE EXPERIMENT

Coherent radio signals are sent from Stanford to receivers on several spacecraft in solar orbit. The differential group delay and phase advance of these signals are measured at the spacecraft and relayed to earth via the deep space network maintained by NASA. These measurements are related to the electron content between earth and the spacecraft. The content is the number of free electrons in a unit area column between the transmitter and receiver. The content can also be expressed as the product of the average electron number density along the path, and the length of the radio path.

Measurement of the content using phase advance data is quantized in steps of about 0.04×10^6 electrons/m^2, but this measurement contains an unknown additive constant, which is supplied by group delay data which has larger quantization increments. Here, we have relied mainly on the fine density versus time structure provided by the phase advance data.

The electron content from Stanford to the altitude of synchronous orbit is measured by monitoring the polarization plane of radio signals from geostationary satellites, mainly ATS 1. Using these measurements, the ionospheric contribution is calculated along the Pioneer line of sight and is subtracted from the total Pioneer measurement, yielding the interplanetary content. The error in this calculated ionospheric contribution is normally about $\pm 4 \times 10^{16}$ electrons/m^2, but can be larger when the radio path passes obliquely through the ionosphere during mid-day. Since the average density is found by dividing the interplanetary content by the distance to the spacecraft, the accuracy of the average density improves as the spacecraft recedes from earth.

The experiment can be performed only while the desired spacecraft is visible from Stanford and within range of our transmitter. Thus, the maximum length of a single continuous data record is about 14 hr.

THE NATURE OF LARGE SOLAR-WIND DISCONTINUITIES

Colburn and Sonett [1966], *Spreiter et al.* [1968], and *Burlaga* [1970] have reviewed the five types of hydromagnetic discontinuities that can occur in an isotropic plasma. In the comparisons of this paper, we have relied on the fact that the number density may change across four of these: The fast and slow shocks, contact surfaces, and tangential discontinuities. The density does not change across a rotational discontinuity.

The existence of hydromagnetic shock waves and tangential discontinuities in the solar wind has been inferred from direct solar-wind plasma observations. *Chapman and Ferraro* [1931] and *Gold* [1955] have suggested that ssc are the result of interplanetary shock waves propagating in the vicinity of the earth. *Burlaga and Ogilvie* [1969] have confirmed the correspondence between ssc and solar wind shocks for several events in 1967. They also found that some si have resulted from tangential discontinuities in the solar wind. Here, the term *geomagnetic disturbance* (gmd), refers to any geomagnetic event reported as an ssc or si. *Siscoe et al.* [1968] and *Ogilvie et al.* [1968] have found that the change in the horizontal component of the geomagnetic field varies as the change in the square root of the solar-wind streaming pressure [$\alpha \rho v^2$], although the constant of proportionality was roughly half of that predicted by the magnetospheric model of *Mead* [1964]. The present knowledge of interactions between the geomagnetic field and solar-wind discontinuities has been reviewed recently by *Burlaga* [1970].

The propagation of shocks originating near the sun has been studied theoretically by *Parker* [1963], *Lee and Chen* [1968], and *Hundhausen and Gentry* [1969]; for a review, see *Hundhausen* [1970]. Heliocentric symmetry was assumed in these studies, but this assumption was relaxed by *DeYoung and Hundhausen* [1969], who predicted a roughly spherical shock shape with a radius of curvature of ~0.6 AU by the time the shock reaches the earth's orbit (for a blast wave that initially subtended 30° in solar longitude at 0.1 AU). *Hirshberg* [1968] studied the strength of geomagnetic storms and found an average shock shape in the ecliptic plane. This shape agreed with the theoretical shape predicted later by *DeYoung and Hundhausen* [1969]. *Taylor* [1969] found similar shock orientations derived from measurements of the magnetic field in the solar wind near the earth. In the direction normal to the ecliptic. the extent of the shocks may be more limited, resulting in a pancake-like shape [*Hirshberg et al.,* 1970; *Greenstadt et al.,* 1970], but this deduction from experimental observation has not yet been theoretically explained.

Tangential discontinuities and contact surfaces may be accompanied by abrupt changes in density. *Burlaga* [1969*a, b*] has found small changes in density at many tangential discontinuities and the radio propagation experiment is probably insensitive to these events. Discontinuities with large changes in density have been observed less often. It is thought that some tangential discontinuities or contact surfaces may separate the driver gas of a blast wave from the rest of the wind. The orientation of such a discontinuity may be similar to the orientation of the shock at the leading edge of the disturbance. It is also possible for a tangential discontinuity or contact surface to occur along the interaction surface between colliding solar wind streams, and these discontinuities are expected to be alined roughly along an Archimedean spiral. Such orientations were found by *Burlaga and Ness* [1969].

DETECTION OF SOLAR-WIND DISCONTINUITIES IN ELECTRON CONTENT MEASUREMENTS

A worldwide geomagnetic event signals the arrival of a solar-wind disturbance at the earth. If a change in density accompanies the disturbance, a change in the content must result, since the earth is at one end of the path along which the content is measured. Figure 2 shows results for a hypothetical disturbance corresponding to three different orientations of the radio path. In these examples, the disturbance is a heliocentric symmetric shell passing by the earth in 3 hr (~0.03 AU thick at 400 km/sec) with a density of 20 cm^{-3} in an ambient wind of 10 cm^{-3}. (Both densities are normalized to 1 AU and falling off as $1/R^2$.)

In these simple cases, each jump in the slope of the content versus time curve marks the time when a discontinuity first intersects the path, or when a discontinuity passes either end of the path. At the time a broad disturbance is tangent to the radio path, a large change in slope of the content versus time curve occurs. This orientation is the most favorable for detection of a discontinuity by the radio propagation experiment.

Changes in content corresponding to path A are likely to be overlooked because fluctuations in the ionospheric content tend to mask small interplanetary changes. Thus, some events may not be noticed even though the density changes by more than a factor of 2 at the discontinuity.

Commonly, increases in density of 1.5 to 3 times have been measured by other experimenters for shocks that are related to ssc [*Ogilvie and Burlaga,* 1969; *Gosling et*

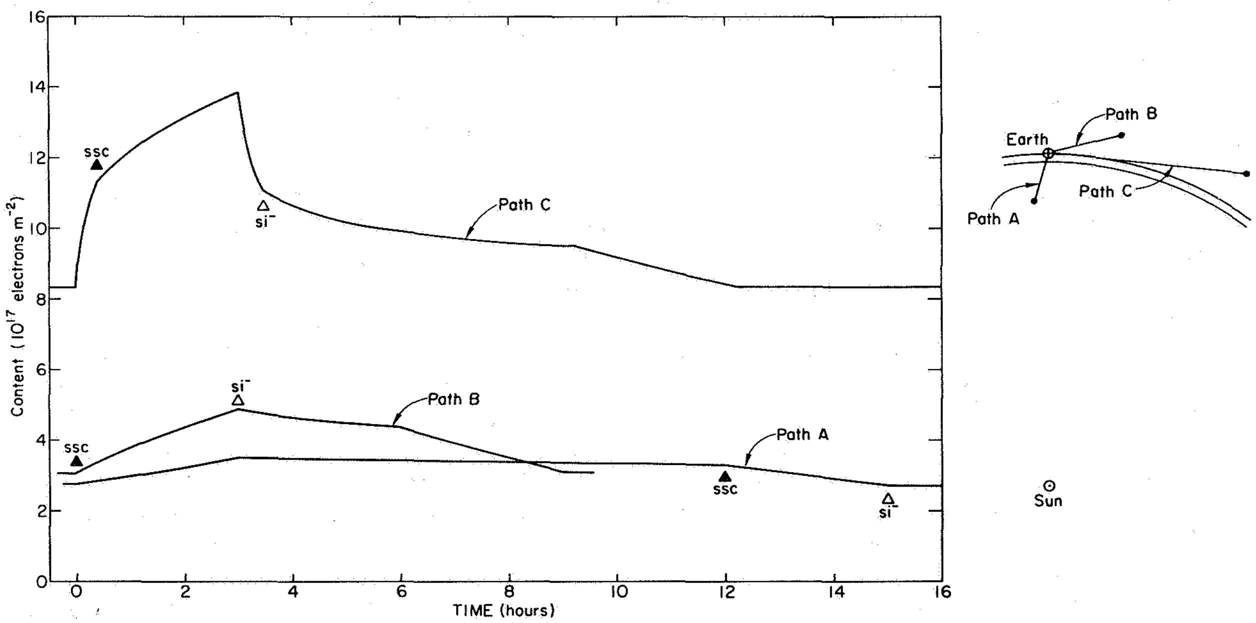

Figure 2. *The electron content that results when a 10 cm^{-3} spherically symmetric pulse of electrons passes the earth in 3 hr, corresponding to the three orientations of the radio path shown. The solid triangle and ssc denote the time the shell reaches the earth. Hour 0 is the time the shell first intersects the radio path.*

al., 1968]. Changes in content due to passages of weak shocks may go unnoticed, but the detection of some shock fronts in the solar wind is expected.

OBSERVATIONS

Approximately 8000 hr of data were obtained between January 1, 1967, and June 30, 1969. Two lists were made for this interval. The first was a list of measurements that were abnormally high and contained fine scale fluctuations, or clearly indicated the passage of an unusual solar wind through the radio path. The decision to include or exclude some records from this list was subjective; to obtain unbiased statistics, this was done before comparison to the geomagnetic storm data. A clear onset of an event occurred in 22 percent of these records. The second list contained all coincidences between gmd and times when the radio propagation experiment was in operation. The 40 coincidences used in this study are summarized in tables 1, 2, and 3.

Tables 1 and 2 contain events for which the content measurements were "disturbed"; the remainder are in table 3. Some coincidences were not included in this study because of the poor quality of content data, or classification of the content event was not made because the gmd occurred near gaps in the content data.

The number of stations reporting a gmd is given in the tables, along with the date and time of the event and the variable A, which was introduced by *Burlaga and Ogilvie* [1969]:

$$A = \frac{N(\mathrm{ssc}) - N(\mathrm{si})}{N(\mathrm{ssc}) + N(\mathrm{si})}$$

where N(ssc) is the number of stations that reported an scc and N(si) is the number that reported an si. Thus $A = 1$ if all stations called the gmd and ssc, and -1 if all called it an si. Burlaga and Ogilvie found that if $A \gtrsim 0.8$, the solar-wind discontinuity was usually a shock, and if $A \lesssim -0.8$, it was usually a tangential discontinuity.

Since the content is proportional to the length of the radio path, and since irregularities in the ionosphere tend to dominate our measurements at close ranges, the range to the spacecraft is given in the tables. An event that appeared to be undisturbed is not included in table 3 unless the range to the spacecraft was larger than 15 million km (0.1 AU). At this range, the content of the nighttime ionosphere is nearly that of the solar wind if it has a density of 7 cm^{-3}. For radio paths that pass through the daytime ionosphere, a 15-million km range may be insufficient to permit accurate measurement of the interplanetary content, but at this range, changes in the content of the solar wind should be evident. The decision to place a given record in table 3 was subjective. Future careful examination may reveal that some of these records were slightly disturbed, but they did not contain any noticeable changes in content at the time of the gmd.

CORRELATION BETWEEN GMD AND CONTENT EVENTS

It was calculated that if the 257 gmd were randomly distributed over the interval from January 1967 to June 1969, there should be about 67 coincidences of gmd with times when the radio propagation experiment was in operation; there were 69.

If gmd were not related to content events, then approximately 8 gmd should have randomly occurred during a content record that we previously had considered to be disturbed. In fact, 27 such occurrences took place. Consequently, it appears that at least some gmd and content disturbances were related, as expected.

There were 24 clear onsets of content events during the period of this study. Ten of these events are in table 1. Since the time intervals in which measurements can be made depend on the trajectories of the spacecraft, availability of spacecraft tracking for telemetry, and similar factors, and are unrelated to the solar wind, these 24 onsets should be good samples of this type of event. If gmd were not related to the onsets of content events, the calculated probability is 0.1 that a gmd would have randomly occurred within 15 minutes of an onset, but table 1 contains 6 such occurrences. The most plausible explanation is that solar-wind discontinuities corresponding to these six gmd intersected the radio path at the earth and were accompanied by appreciable changes in density.

FEATURES OF DISCONTINUITIES CAUSED BY STRONG SSC EVENTS

Figures 3, 4, and 5 show data for selected strong ssc events ($A \geq 0.8$, with the number of stations reporting a gmd ≥ 30) of tables 1, 2, and 3, respectively. Four-minute averages of interplanetary average electron density are displayed along with the horizontal component of the earth's magnetic field recorded at San Juan, Puerto Rico. For each event, the geometry of the experiment is shown, and a circle of 1 AU radius is included for reference.

Four ssc occurred close to the time when a change in the average density was evident (events 1, 7, 8, and 10; call these events type A). Five of the ssc (events 6, 14, 15, 16, and 17; type B events) occurred several hours after the average density had become disturbed, and the two remaining ssc corresponded to low fluctuating average density levels (events 29 and 30; type C events).

Table 1. *Geomagnetic events that occurred within several hours of sharp changes in the electron content. In the spacecraft column, number 5 denotes Mariner 5, and numbers 6 through 9 denote Pioneers 6 through 9, respectively. These gmd's were found to occur within several minutes (a), before (b), or after (c) the first sharp change in content; or within several minutes of some other sharp change in content (d). The content corresponding to event 12 decreased, all others were increases.*

	Geomagnetic event					Content event		
	Event	Date	Time, UT	Stations reporting a gmd	A	Spacecraft	Range, million km	Time of change, UT
(a)								
	1	10 Jun 68	2154	48	0.96	8	33.8	2200
	2	1 Jun 68	0109	13	0.54	8	31.0	0108
	3	22 Dec 66	0441	34	0.35	7	36.3	0442
	4	25 Jan 67	0001	10	0.20	7	54.3	0005
(b)								
	5*	19 Sep 66	0251	43	0.49	7	4.7	$\sim$0400
(c)								
	6	14 May 69	1929	68	0.97	9	119.3	1410
	7	4 Apr 67	0304	57	0.96	7	88.0	0230 to 0300
	8	7 May 68	0030	42	0.95	8	24.0	2320
	9	14 Jun 69	0422	8	0.00	8	84.4	0222
(d)								
	10	7 Jan 67	0800	51	0.88	7	45.1	0752
	11	16 Feb 67	0835	19	0.47	7	66.0	0823
	12	3 Nov 67	1338	9	−0.33	5	95.6	1342
	13	4 Aug 68	0252	24	−0.92	8	47.3	0100 to 0400

**This event was noticed after comparison to the geomagnetic data. The timing is not accurate because of insufficient range to the spacecraft.*

If the change in density was larger than ~ 10 cm^{-3} at the shock fronts corresponding to the type B and C events, these shock fronts must have been oblique to the radio path at the earth. The shocks first encountered the radio path at the earth for type C events, but were oblique to the path so that the passage of the shocks were not apparent in the average density. The shocks corresponding to type A events intersected the radio path at or near the earth because of the agreement in timing of event onsets. These shocks were accompanied by changes in density of ~ 10 cm^{-3} or larger, or the shock fronts were favorably oriented for detection (or both). The shocks of type B events intersected the radio path first, but at some distance from the earth. Since the average density was disturbed before the time of these ssc, it is thought that a limited radius of curvature for the shock fronts (less than 1 AU) would allow the shocks to be oblique to the radio path at the earth. This accounts for the lack of noticeable changes in the average density at the time of the ssc.

Hopefully, a better estimate of the size of individual shocks will emerge when details of the content data and local number density data are compared, but a spherical shock with a radius of curvature of ~ 0.6 AU [*DeYoung and Hundhausen,* 1969] is consistent with these events.

RESULTS

The number of gmd that occurred within minutes of sharp changes in the content was found to be far greater than the random prediction. This indicates that the two types of events are probably related. In turn, it is thought that these events were the result of disturbances in the solar wind. Some other gmd and disturbed content measurements were probably related, although exact coincidences in the timings of events were not apparent.

Several minor events were found to be associated with sharp changes in the content of the solar wind. Among the gmd reported by less than 30 stations with $0 < A < 0.8$, 50 percent coincided with sharp changes in

Table 2. *Geomagnetic events that did not coincide with sharp changes in the content, but during disturbed content measurements.*

	Geomagnetic event				Current event	
Event	Date	Time, UT	Stations reporting a gmd	A	Spacecraft	Range, million km
14*	10 Feb 69	2024	64	1.00	9	22.6
15	9 Jul 68	2155	46	1.00	8	41.6
16	12 Apr 69	2046	69	0.86	8	67.9
17	8 Jun 69	0509	64	0.81	8	82.7
18	27 Feb 69	0307	14	0.71	8	60.0
19	27 Apr 69	1831	39	0.69	9	100.3
20	28 Oct 67	1637	47	0.45	5	89.0
21	3 Nov 67	1628	10	-0.20	5	95.6
22	23 Mar 66	0012	29	-0.52	6	21.1
23*	13 Mar 67	0835	11	-0.64	7	78.1
24	31 Oct 67	1114	12	-0.67	5	92.4
25*	20 Sept 67	1736	18	-0.78	5	44.9
26	31 Oct 67	1449	33	-0.88	5	92.4
27	29 Oct 67	1324	12	-1.00	5	90.2

**These content events were small and went unnoticed until the content data were compared to the geomagnetic storm data.*

Table 3. *Geomagnetic events that occurred during content measurements that appeared to be undisturbed, where the range to the spacecraft is greater than 15 million km.*

	Geomagnetic event				Content event	
Event	Date	Time, UT	Stations reporting a gmd	A	Spacecraft	Range, million km
28	17 Oct 68	0031	6	1.00	8	56.8
29	2 Oct 68	0018	33	0.94	8	55.9
30	26 Feb 69	0158	68	0.92	8	60.0
31	2 May 69	1322	59	0.73	9	106.2
32	25 Jan 69	0036	13	0.69	8	57.6
33	6 Jan 67	0714	40	0.60	7	44.1
34	28 Feb 69	0423	68	0.44	8	60.2
35	27 Mar 66	1935	37	0.41	6	23.8
36	29 Aug 67	1738	32	0.19	5	26.6
37	7 Mar 69	2336	9	-0.33	8	61.2
38	2 Oct 68	0348	21	-0.52	8	55.9
39	19 May 66	2004	9	-0.56	6	65.7
40	2 May 69	1811	19	-0.90	9	106.2

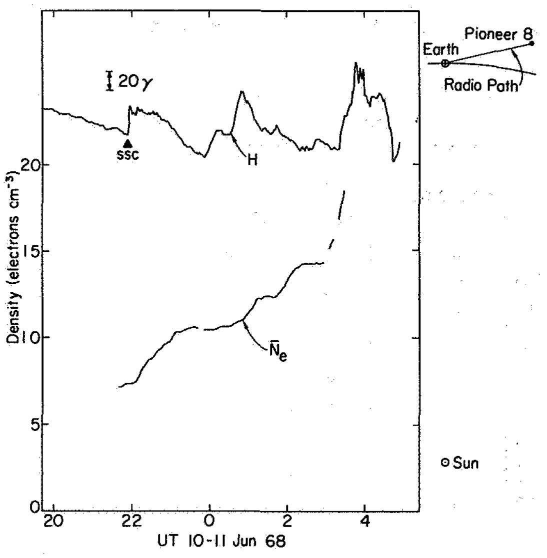

Figure 3. *An example of near coincidence between a change in the average interplanetary electron density and a sudden change in the horizontal component of the earth's magnetic field recorded at San Juan. The location of the radio path is shown at the right in a frame of reference similar to that of figure 1. This is event 1 (type A) of table 1.*

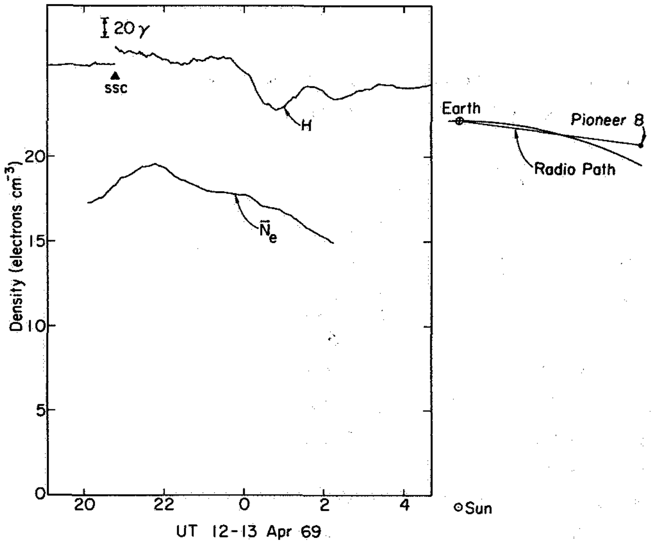

Figure 4. *An example where the average interplanetary electron density is disturbed at the time of a sudden change in the horizontal component of the earth's magnetic field recorded at San Juan. This is an example of a type B event.*

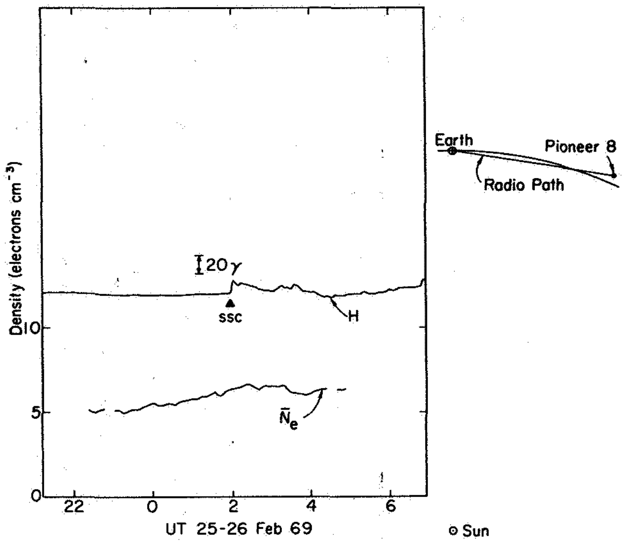

Figure 5. *An example of a sudden change in the horizontal component of the earth's magnetic field recorded at San Juan with no corresponding event in the average interplanetary electron density. This is a type c event.*

the content. Similar coincidences in timings of events occurred in 11 percent of the gmd with the same range of *A* reported by more than 30 stations, and in 36 percent of the strong ssc. These numbers may indicate that larger changes in solar-wind density have accompanied some of these less widely reported gmd than have accompanied the strong ssc.

For a blast wave with inital kinetic energy of 2.8×10^{30} ergs and initial velocity of 100 km/sec near the sun, *DeYoung and Hundhausen* [1969] predict a shock with a radius of curvature of about 0.6 AU and a change in density of about three times at the shock front when the shock reaches 1 AU. This model was found to be consistent with the relationships observed between ssc and sharp changes in electron content and the orientation of the radio path relative to the earth-sun line. However, this evidence is not so conclusive that we can rule out other models.

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DISCUSSION

A. Lazarus Just a very brief comment. It's going pretty far to say that each one of these ssc is due to a shock. Secondly, I think it's encouraging that you don't see a big change because you should be able to integrate out the small local changes that have been shown to cause these changes in magnetic field. There have been studies on how much the density should change for a given magnetic field change by Siscoe *et al.* And you should be able to integrate that out and see that it has very little effect on your measurements.

J. A. Landt I've done a study like that. These events were classified, if you use the quantization of Burlaga and Ogilvie, larger than eight-tenths; because of the lack of time I did not include what you would expect in the content measurement from a given disturbance. Now you notice most of the shocks that have been displayed have an increase in density by a factor of at least two at the shock front, and this does make it very sensitive to the orientation of the shock front with respect to the orientation of the radio path. So I agree with you that we will not expect to see many coincidences unless the radio path is oriented just right with respect to the disturbance front and if the changes are large at the disturbance front.