COROTATING SHOCK STRUCTURES *K. W. Ogilvie*

ABSTRACT Consideration of observed interplanetary shocks leads to the conclusion that a corotating forward shock has not been unambiguously identified at 1 AU. A reverse shock identified in September 1967 is a likely candidate for a corotating structure.

When the speed of the solar wind increases, the plasma in the high speed stream overtakes the slower plasma in front (fig. 1). Along the line A-A there is a velocity discontinuity, in the limit, but in fact as we have seen the speed change may take place in a thin region where the pressure is raised above that of the surrounding. *Dessler and Fejer* [1963] suggested that a pair of shock waves would be formed along the positions of the dotted lines. *Razdan et al.* [1965] investigated this configuration also and proposed that the structure would include shocks which were oppositely directed, that is, a forward shock (2) propagating generally in the direction of convection, and a backward propagating, but outwardly convected, shock (1). Thus, a spacecraft at the point X would see, in sequence, a forward shock, followed by a rapidly rising bulk speed and density, then probably one or more discontinuities, and lastly a reverse shock in the high speed stream characterized by an increase in the speed in the fixed frame. If the increase in speed is due to a stream of material more or less continuously emitted by the sun, then when the solar wind speed drops again at the other edge of the stream no collision takes place, and presumably no shocks form. Rather there is a rarefaction region of low pressure, which is the analog of the high pressure region A. Thus since the structure corotates counterclockwise, it is quite different from a flare-associated disturbance when the shock travels outward in a more or less radial direction.

The reverse shock (1) is propagating in the plasma toward the sun, while being convected away from it by the solar wind flow. Since its net motion is outward, a solar origin for it cannot be ruled out *a priori*, but this seems unlikely since the Alfvén speed is higher nearer the sun and observations of these shocks would make it likely that disturbances can give rise to shocks in the interplanetary medium. *Hundhausen and Gentry* [1969]

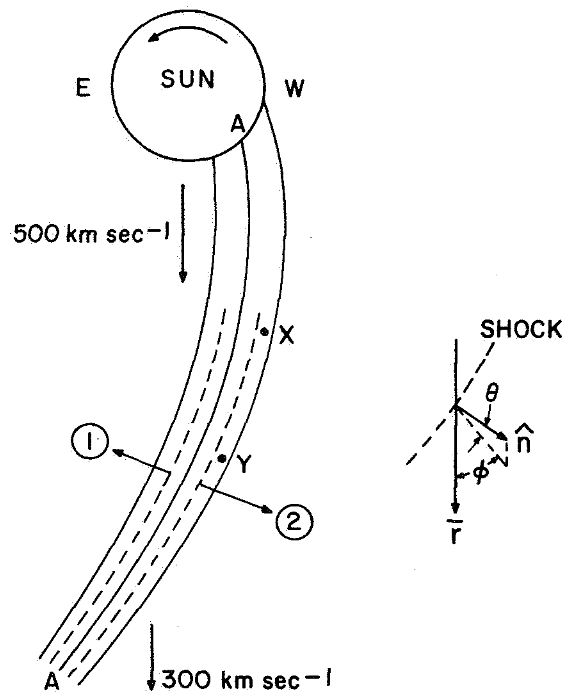

Figure 1. *Schematic representation of corotating stream with forward and reverse shocks 1, 2. The angles θ and φ made by the shock normal with respect to the radial direction and the ecliptic plane are shown inset.*

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on the basis of quite realistic model calculations conclude that flare-associated forward-reverse shock pairs are not likely; they would require solar flares of too long duration.

Thus if we observe with a plasma detector, we expect corotating streams to give rise to a signature such as that shown in figure 2. A rather general theoretical treatment

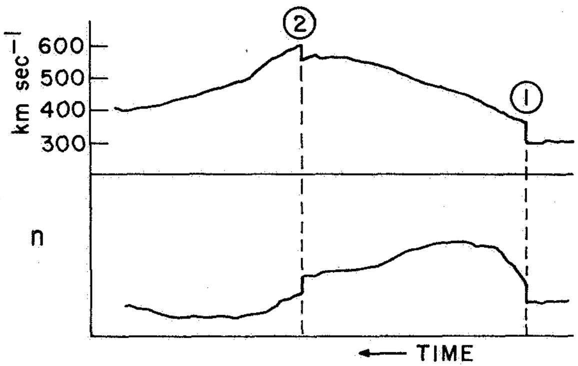

Figure 2. *Hypothetical observations of a corotating shock event as observed by a spacecraft at point X in figure 1.*

by *Carovillano and Siscoe* [1969] and *Siscoe and Finlay* [1970] shows that the density and azimuthal velocity perturbations increase with radial distance for large colliding corotating structures; $\Delta n/n$ increases and eventually becomes ~ 1. Thus, there is probably a critical heliocentric distance inside which no shocks will form. In the absence of (2) the profiles look quite like the predictions of *Hundhausen and Gentry* [1968 and 1969] for the driven shock case, and quite like the observed postshock flows observed by Explorer 34, for example, and shown in figure 3.

Razdan et al. [1965] have linked SI^+–SI^- pairs observed in terrestrial magnetograms with corotating M region beams and suggested that the SI^+–SI^- pair be associated with the two shocks (1) and (2) above. However, *Gosling et al.* [1967] and *Burlaga and Ogilvie* [1969], among others have shown that geomagnetic impulses, though closely associated with interplanetary structures, do not necessarily indicate the passage of shocks. Ssc's are usually associated with shocks, and *SIs* with discontinuities, but the classification scheme is not

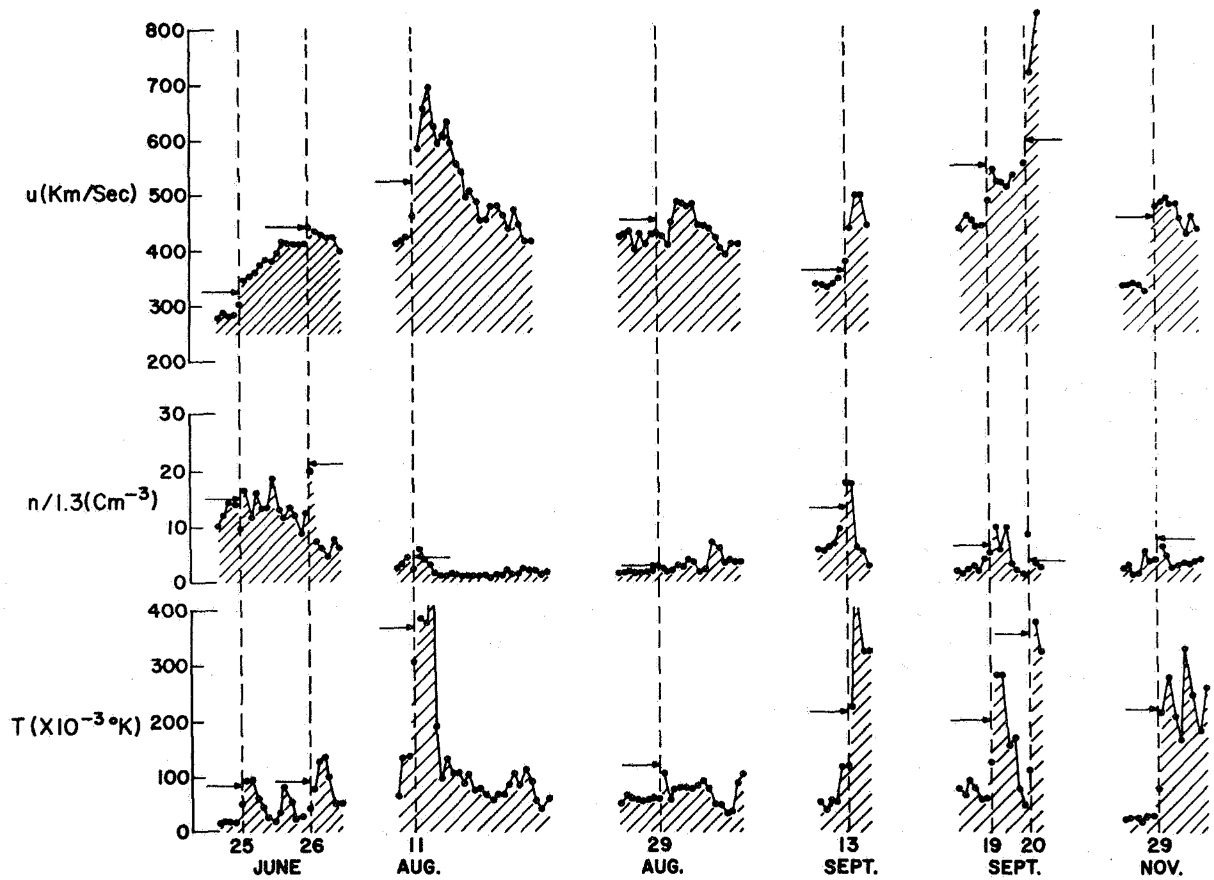

Figure 3. *Profiles for bulk speed u, density n, and temperature T observed by Explorer 34 at the times of interplanetary shocks in 1967.*

very precise. The structure causing one SI^+–SI^- pair has been observed by *Ogilvie et al.* [1968]. The positive impulse was due to a shock and the negative one to an apparent convected discontinuity. The shock was observed by Explorer 34 on 26 June 1967, and was apparently not flare associated. The normal direction [*Chao,* 1970] had values of θ and ϕ of -23° and $+24.9^\circ$, respectively. The angles θ and ϕ are defined in figure 1, and the event illustrated in figure 4. Examination of the

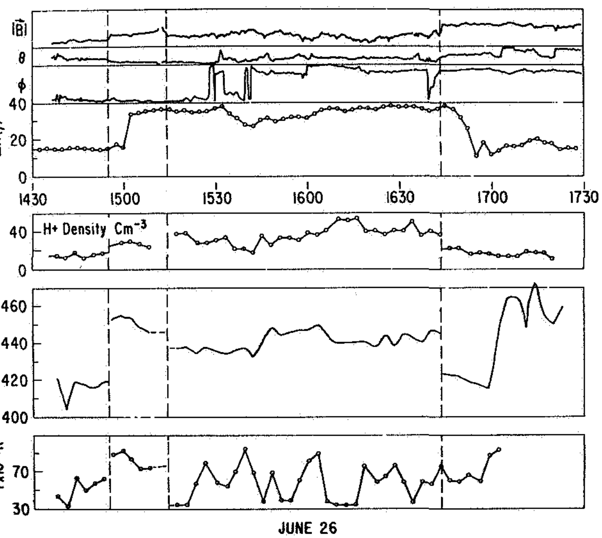

Figure 4. *Geomagnetic (upper) and spacecraft (lower) observations of the SI^+–SI^- event described in the text. Note that the SI^- impulse at about 1640 does not have the correct signature for a reverse shock. Compare with figure 6.*

Kp diagram shows increased geomagnetic activity both 27 and 54 days previously, and a shock 27 days before, on 30 May 1967. Information about the normal direction is not available for this previous shock, and it could be a fortuitous time association, since a large flare (3B) occurred at 0530 on the 28th, although there seems to have been a corotating region. At any rate, since the nature of this event is not certain, we can say that an SI^+–SI^- pair does not *always* arise in the way envisioned by *Razdan et al.* [1965]. Such a pair does not *necessarily* have two shocks associated with it.

Distinguishing between flare-associated shocks and corotating shocks is difficult. There are differences, however; the normal to the shock (2) makes a large azimuthal angle to the radial direction ($\phi \simeq 45^\circ$). This is not an exclusive property of the corotating case if one adopts the *Hirshberg* [1968] idea of a flare-associated shock "standing off" from projected material, the shock having a radius ~0.6 AU. If the axis of this projected material is in a direction making a large heliocentric angle with the line on which the observer is situated, the angle ϕ could be large. We would then be encountering the "side" of the shock; furthermore, in this case flare association might be even harder to establish than usual, because of the large angle between the angular coordinate of the point of observation and the heliocentric coordinate of the flare. Such an event might easily be mistaken for a corotating structure.

A corotating shock should be associated with a structure that appears at 27-day intervals, or at corresponding times at other heliographic longitudes. Such corotating structures are not infrequently observed, an example being one seen at earth at May 28, 1968, and Pioneer 6 on June 10, Pioneer 7 on June 20, and Pioneer 8 on June 23 before reaching the earth again on June 25, where it caused an *SC*, figure 5.

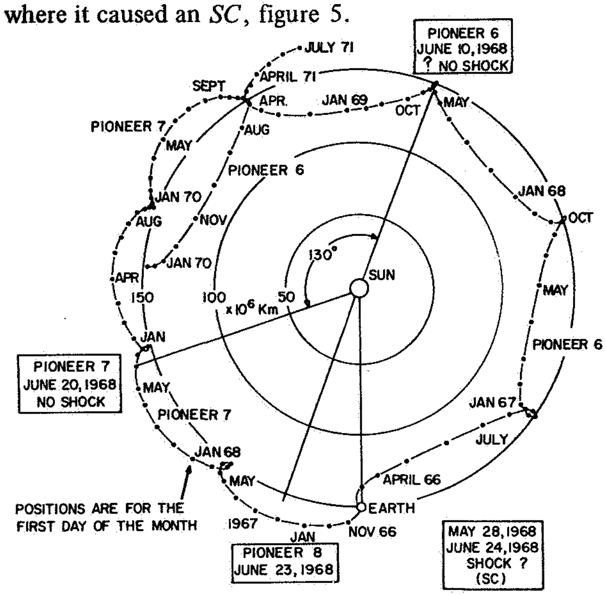

Figure 5. *Positions of Pioneer spacecraft during the May-June 1968 corotating stream.*

Examination of the data from these sources within ±1 day of the appropriate times does not confirm a corotating shock; the data are incomplete. Thus, although the corotating nature of the disturbance is confirmed from radio observations of interplanetary scintillation [*Dennison and Wiseman,* 1968], a corotating shock was not observed.

A corotating shock should have a normal with $\phi \simeq 45^\circ$ or 215°. For our present purposes we disregard values of ϕ between 0 and 20°, to remove those characteristic of radial shocks, so our criterion becomes $20^\circ < \phi < 90^\circ$. The value of θ is apparently not significant for this classification.

There should be no plausible flare association, and we use this criterion to rule out shocks from the list given by *Hundhausen* [1970]. Table 1 lists the remaining examples; where there is a conflict between two values of ϕ, as for June 26 and August 29, 1967, the largest published values are given. The shock of August 11, 1967 [*Lazarus et al.,* 1970] can be eliminated at once since it is impossible to decide on the basis of evidence whether it was flare associated or not; thus, it is a possible example of a corotator, with low reliability. The event of August 29, 1967, occurred at a time when a sector boundary crossed the earth's heliocentric longitude, at the beginning of the life of the sector. At the

Table 1. *Shock normals for four events*

Date	ϕ	
March 23, 1966	43°	Evidence of corotating structure poor. Close to sector boundary. Transit time to earth consistent with ϕ
June 26, 1967	25°	
August 11, 1967	large	Insufficient data. [*Lazarus et al.,* 1970]
August 29, 1967	43°	Close to sector boundary.

next rotation of the sector, on September 28, 1968, the rise in bulk speed was preceded by a number of discontinuities, but none of them appears to have been a shock. The evidence for this event being a corotator is thus not very good. The evidence for the March 23, 1966 event as a corotating structure is not very convincing either.

This leaves the June 26, 1967 shock as perhaps the most likely example from this list, as discussed above, and the low probability we can assign to this case is indicative of the uncertainty in the existence of corotating shocks.

An observed shock perhaps more likely to be associated with a corotating event, and not included in Hundhausen's list, is the reverse shock reported by *Burlaga* [1970] which took place on 28 September 1967. It was not associated with a solar event, and the shock surface was perpendicular to the ecliptic plane and alined along the spiral direction ($\phi = 225.6°$). The direction of the normal was determined by time-of-passage observations from Explorers 33, 34 and 35, and can thus be regarded as determined to an accuracy of ~10°. The direction of propagation was towards the sun, and the "signature" of the event unequivocal, figure 6. There is evidence for a high speed stream with a

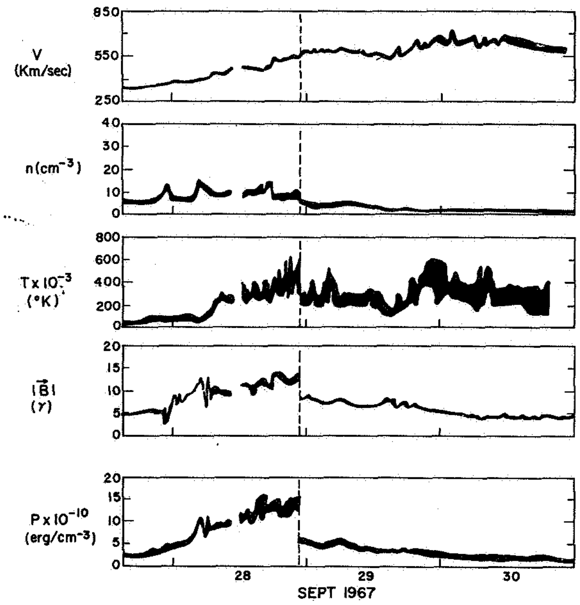

Figure 6. *Explorer 34 observations of reverse hydromagnetic shock, from Burlaga [1970].*

maximum 29 days after the time of the shock. It was close to the boundary of a sector of rotation period 27.5 days persisting for the rest of 1967 [*Wilcox and Colburn,* 1970]. It thus appears that a good method to detect the existence, at this time uncertain, of corotating shocks, might be to search for reverse shocks, a procedure which avoids the problem of flare association. It has been clear for a long time that many corotating streams do not have shocks, forward or reverse, associated with them. It may be that observation of such shocks will become more common at greater heliocentric distances, where the relative perturbations have grown larger, especially around solar minimum when confusion by the effects of flare associated shocks will be less.

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