

## Mass Ejections From the Sun: A View From Skylab

J. T. GOSLING, E. HILDNER, R. M. MACQUEEN, R. H. MUNRO, A. I. POLAND, AND C. L. ROSS

*High Altitude Observatory, National Center for Atmospheric Research, Boulder, Colorado 80303*

More than 30 instances of sudden mass ejections from the sun were observed with the white light coronagraph experiment aboard Skylab during the first 118 days of the mission. Typically, these ejections appear as large magnetic loops rooted at the sun, yet expanding outward through the solar corona at speeds of the order of  $400 \text{ km s}^{-1}$ . The loops always appear to retain their magnetic connection to the sun. Eighteen of these ejections were associated with active and eruptive prominences and surges; only three ejections appear to have been flare initiated. Associations with ground-detected metric wavelength type 2 and 4 radio bursts occur for about 30% of these events; however, ground-detected type 2 and 4 radio bursts originating near the limb are almost invariably accompanied by coronagraph-observed ejections. Pressure or MHD waves run out ahead of the transient material ejecta; at times these waves can be detected by their effects on nearby coronal structures. For one event, that of August 10, 1973, we make the following estimates: (1) mass content,  $4 \times 10^{15}$  grams; (2) mass flow rate,  $1.1 \times 10^{12}$  grams  $\text{s}^{-1}$ ; (3) energy content,  $8.4 \times 10^{30}$  ergs; and (4) energy flow rate,  $7.7 \times 10^{26}$  ergs  $\text{s}^{-1}$ . Locally, this represents a significant mass and energy input to the solar wind; we suggest that the ejections are the coronal counterparts of non-recurrent (including shocks) solar wind disturbances detected near the orbit of the earth.

*Chapman and Ferraro* [1931] proposed many years ago that the observed correlation between solar activity and geomagnetic and auroral activity could be explained if solar activity sometimes resulted in the ejection of ionized material from the sun. In subsequent years, models of sporadic mass ejections from the sun and their 'frozen-in' magnetic fields have been invoked with varying degrees of success to explain such things as the modulation in interplanetary space of galactic and solar cosmic rays [e.g., *McCracken*, 1962; *Gosling*, 1964], the excess mass and helium abundance of major solar wind disturbances [e.g., *Hundhausen et al.*, 1970; *Hirshberg et al.*, 1972], and the outward motion of type 4 radio bursts [e.g., *Smerd and Dulk*, 1971]. Recent observations [e.g., *Stewart et al.*, 1974; *Pinter*, 1973; *DeMastus et al.*, 1973; *Riddle*, 1970; *Tousey*, 1973] of the sun have confirmed the existence of these outbursts of material and have established some of their characteristic features. In this paper we present some observations of mass ejections from the sun taken with the High Altitude Observatory's white light coronagraph experiment aboard Skylab. (At least 39 transient events were detected during the first 118 days of the Skylab mission. Here the term transient is used to describe changes in the corona easily discernible on a time scale of tens of minutes. However, some types of transients are undoubtedly rearrangements of material within the corona. Here we concentrate on those events that obviously represent the ejection of material from the sun.)

The coronagraph was externally occulted, had a band pass from 3700 to 7000 Å, and daily for a period of 8 months provided many pictures of the solar corona from 1.5 to 6  $R_s$  from sun center. The pictures, taken in both polarized and unpolarized light, are of a quality comparable to that of the best obtained at solar eclipses. Instrumental parameters as well as some preliminary results have been described by *MacQueen et al.* [1974].

### AUGUST 10, 1973, EVENT

There are a number of features common to most of the mass ejecta detected by the Skylab coronagraph. Here we illustrate

these features with a discussion of one event, the mass ejection of August 10, 1973. This particular event is one of the brightest and best observed out of approximately 30 generically similar ones detected during the first 118 days of the Skylab mission. Eight frames from a sequence of more than 300 exposed during the ejection are displayed in Figure 1. The event is first evident at 1332 UT on August 10 as a very bright overexposed loop of material extending slightly above the occulting disk on the west limb of the sun (Figure 1, frame A). Examination of pictures taken in polarized light indicates that Thomson scattering of photospheric light is responsible for most of the radiance detected; however, particularly bright knots of material are perhaps seen also in  $H\alpha$  emission. The initial detection of the loop is preceded by the ground detection of an eruptive prominence on the west limb at north 13 at 1255 UT. The prominence was visible to ground observers in both wings of  $H\alpha$  and disappeared from their view at approximately 1355 UT, some 12 min after frame B was taken. However, no unusual motions or changes in the coronal structure above the west limb are apparent in the hours prior to the time of frame A. In the succeeding minutes the leading loop progresses outward through the corona at an apparent radial speed of  $400 \text{ km s}^{-1}$ ; it also expands during this outward progression, ultimately achieving a width exceeding  $3.8 R_s$  as the front edge passes beyond the field of view of the coronagraph. (The measured speed of the leading loop may not be the same as the speed of the center of mass of the structure, since material may flow undetected along the loops and because the apparent motion is probably a superposition of an expansion and outward motion.) The structure's general appearance at the time of frame C is that of one or more loops rooted in the sun, the loops presumably outlining the distended magnetic field in the structure. At this stage of the development the event appears similar to the June 10, 1973, event [*MacQueen et al.*, 1974], which also follows an eruptive prominence seen at the limb.

Retarding the outward motion of the structure are solar gravity, magnetic tension, the back pressure of the ambient corona (which decreases with increasing height as the density decreases), and the transfer of momentum to the ambient corona. These forces are insufficient to slow the motion of the August 10 event as it traverses the coronagraph field of view.

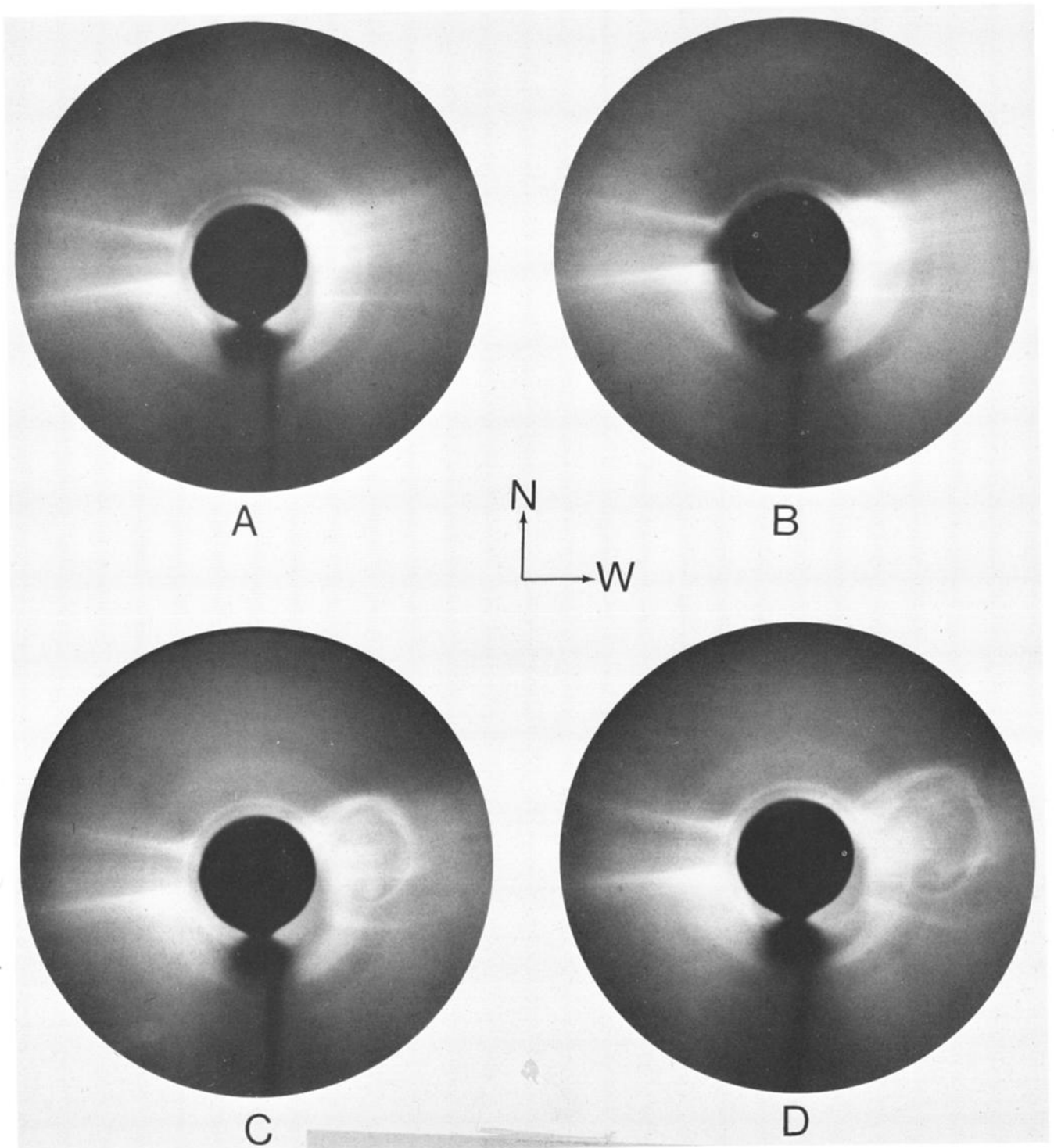


Fig. 1a

Fig. 1. A mass ejection from the sun photographed at 1332, 1343, 1424, 1448, 1512, 1637, 1918, and 0138 UT (frames A–H, respectively) on August 10 and 11, 1973. The field of view of each frame is six solar diameters. The sun is obscured by the occulting disk at the center, whose effective radius is  $1.5 R_s$ . Diffraction rings appear around the periphery of this disk, and the shadow extending downward from the disk is caused by a pylon supporting the occulter. The faint annulus of about three solar diameters is an instrumental artifact. The very strong radial gradient of coronal radiance has been attenuated by vignetting within the instrument and by dodging of the final prints. The faint spot near the bottom of frame C is caused by spacecraft contamination.

Indeed, preliminary measurements (Figure 2) indicate that the loop speeds increase with increasing height; thus the material is continually being driven outward by forces from below. About 2 hours after it first appears, the leading edges of the loop pass beyond the field of view of the instrument (frame F),

yet the structure retains its magnetic connection to the sun. This connection remains intact for the duration of the event, ultimately, the lower ends of the loops become rays projecting almost radially (frame H). (Compare this with the finding of *MacQueen et al.* [1974, Figure 1, frame D] for the June 10,

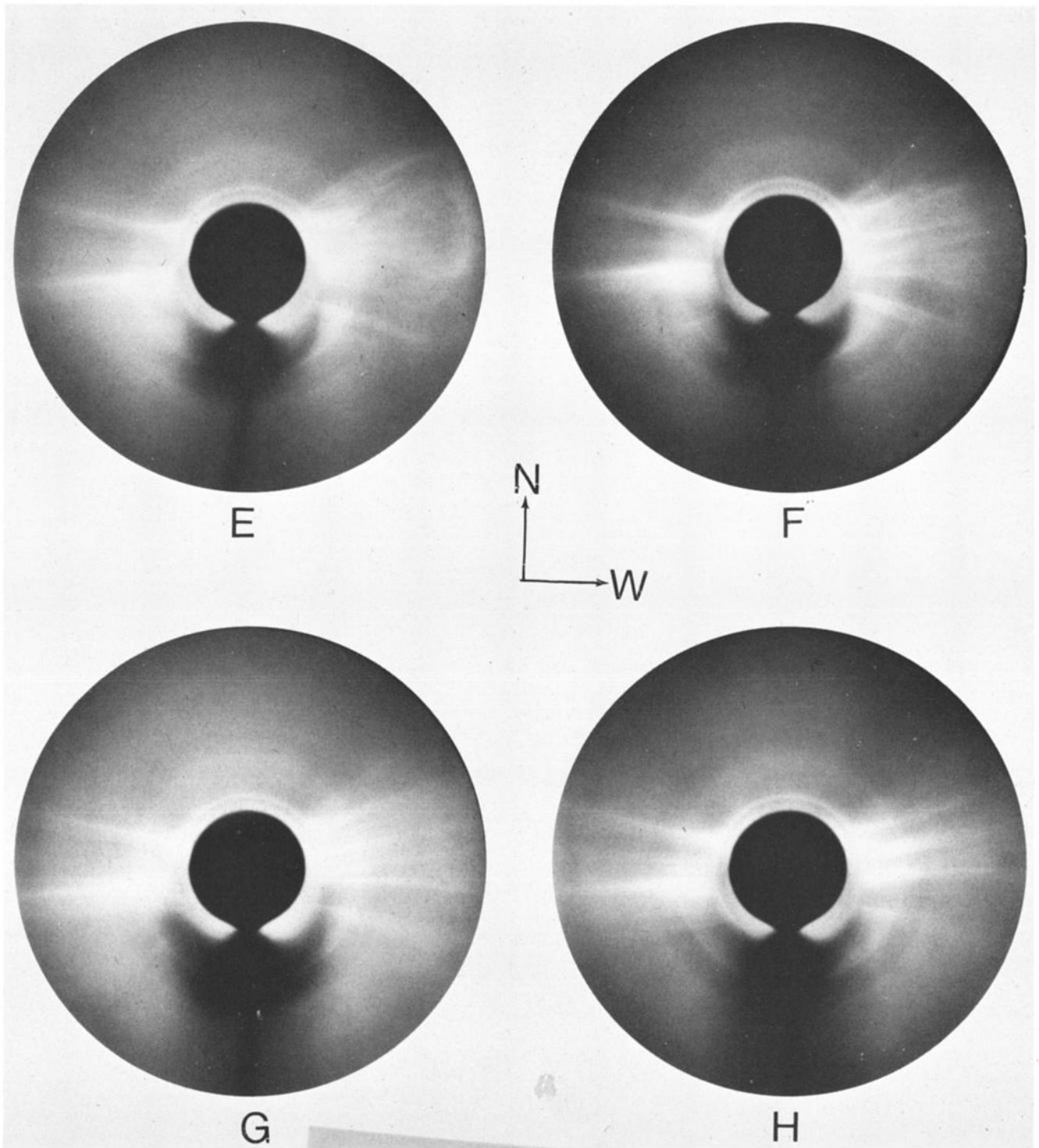


Fig. 1b

1973, event.) The magnetic field lines in these rays are stretched to connect with the portion of the ejection beyond the field of view of the coronagraph.

In the late stages of development the structure of the August 10 event must be that of a large magnetic bottle extending far into interplanetary space and rooted to the sun, similar in many respects to the magnetic bottles first envisioned by *Gold* [1959]. In the days following the time of frame H the rays gradually merge into other structures and disappear as recognizable entities. It is not possible to identify them at their east limb passage 12–14 days later. Solar rotation, the cessa-

tion of mass flow, and the dispersion of field lines are three possible causes for this gradual fading of the rays. There is no evidence that any of the material that enters the coronagraph field of view ever returns to the sun, although without inhomogeneities, it is difficult to ascertain in which direction the material is moving along the loops. Certainly, the outward speed of the outermost loop exceeds the escape velocity ( $250 \text{ km s}^{-1}$ ) at  $6 R_s$ .

There is a large net increase in the overall brightness of the corona associated with the August 10 ejection. The percentage change in intensity at 1424 UT above the equator on the west

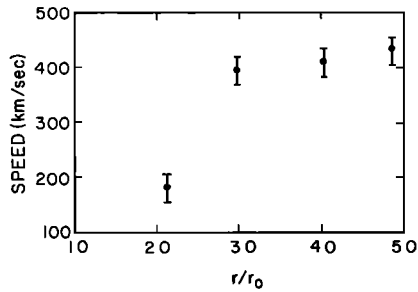


Fig. 2. Speed of the center of the outermost loop during the August 10, 1973, mass ejection. The figure assumes that the motion is in the plane of the sky.

limb relative to that measured at 1140 UT (before the prominence eruption) is shown in Figure 3. Similar results are obtained at other times during the event and for other latitudes on the west limb. Thus the motions described above represent true material and field motions and are not, for example, merely a series of compression and rarefaction waves running outward from the sun. The amount of additional material present in the corona at 1424 UT as well as at other times can be derived from the data. Here we provide an estimate of the number of additional electrons present at 1424 UT by assuming that the material is concentrated in the plane of the sky. The derived estimate, which should be accurate to within 20%, is  $2 \times 10^{39}$  electrons. A nearly equal number of positively charged particles should be present. If we assume that the mean mass per ion is  $2 \times 10^{-24}$  gram (1.2 times that per proton), then the additional mass present in the corona at 1424 UT is  $4 \times 10^{15}$  grams. If we assume that all this material is moving at  $400 \text{ km s}^{-1}$ , then its kinetic energy is  $3.2 \times 10^{30}$  ergs. The gravitational energy at  $4 R_{\odot}$  is  $-1.9 \times 10^{30}$  erg; if we assume a temperature of  $10^6 \text{ }^{\circ}\text{K}$ , then the enthalpy, which is the sum of the internal energy plus the work done in expanding the gas, is  $1.4 \times 10^{30}$  ergs. The mass flow rate is approximately  $1.1 \times 10^{12}$  grams  $\text{s}^{-1}$ . Rates of energy flow are  $9.2 \times 10^{26}$  ergs  $\text{s}^{-1}$  (kinetic) and  $4.0 \times 10^{26}$  ergs  $\text{s}^{-1}$  (enthalpy), whereas work is being done against gravity at the rate of  $5.4 \times 10^{26}$  ergs  $\text{s}^{-1}$ . Later in this paper we compare these numbers with estimates of the mass and energy content of high-speed solar wind streams and flare-produced shock wave disturbances at 1 AU.

The outward progress of the August 10, 1973, mass ejection has a noticeable effect on the preexisting coronal structures above the west limb. Of particular interest is the changed appearance of the coronal ray positioned immediately south of the mass ejection. This ray is pushed aside (frames B-E) as the ejection moves outward, the bend in the ray keeping pace with the leading edge of the ejection. We note, however, that the

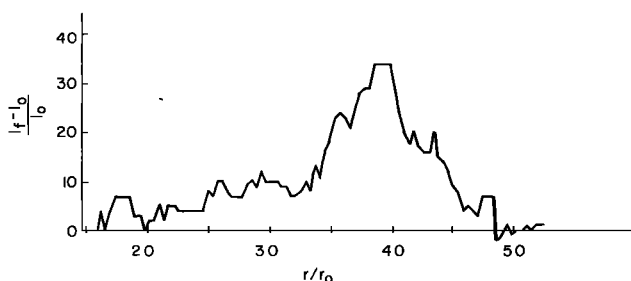


Fig. 3. Percentage change in intensity above the equator on the west limb at 1424 UT on August 10, 1973, relative to that measured at 1140 UT;  $I_t$  is the intensity measured at 1424 UT, and  $I_0$  is the intensity measured at 1140 UT.

outermost loop never comes into direct contact with this ray, implying that the changes in the ray are induced by a pressure or MHD wave running in front of the mass ejection. Such a wave ultimately must steepen into a shock, but lacking knowledge of the sonic and Alfvénic speeds in the ambient corona ahead of the ejections, we cannot yet determine whether the wave is a shock at the time of these observations. At least three radio observatories were monitoring the sun at the time of this event (Solar Geophysical Data, 1973). None of these observatories have reported radio burst activity in connection with this mass ejection. Thus either the wave running ahead of the material is not a shock, or conditions favorable for the emission and/or ground detection of type 2 radiation are not present here.

#### GENERAL CHARACTERISTICS OF MASS EJECTIONS

Most of the features of the August 10, 1973, event are common to almost all of the mass ejections or transients observed with the Skylab coronagraph. Here we summarize these common features and mention features more rarely observed.

1. The transients usually take the form of magnetic loops expanding outward from the sun. Oftentimes, the material is concentrated in clearly distinguished loops; for other events it is more diffusely spread over the entire region within the loop.

2. All looplike structures observed within the field of view of the coronagraph ( $1.5-6 R_{\odot}$ ) eventually escape from the sun; the speeds vary from event to event, ranging from about 200 to greater than  $1100 \text{ km s}^{-1}$ . We have no evidence to support the notion [Schatten, 1970; Hundhausen, 1972] that expanding looplike structures are ever stopped by magnetic forces, solar gravity, radiation of energy, or transfer of momentum to the ambient corona; that is, the structures are never observed to move sunward. However, we cannot eliminate the possibility that some material drains back to the sun along the lower extremities of the loops.

3. The transient loops retain their connection to the sun. It is difficult to find positive evidence for magnetic reconnection within the field of view of the coronagraph: detached, closed loops have not yet been identified.

4. The 'roots' of the magnetic loops generally persist as recognizable entities for several days following an outburst of material. They are seldom, if ever, distinguishable at subsequent limb passages.

5. Pressure or MHD waves run out ahead of the material ejecta; at times, these waves can be detected by their effect on nearby coronal structures.

6. Looplike transients are most commonly found in association with eruptive and active prominences and surges. Eighteen of the events have known associations with these phenomena; however, it is unlikely that all of the transient material observed by the coronagraph is chromospheric in origin—a fraction probably originates in the lower corona overlying the chromospheric eruption.

7. Only three of the Skylab transients detected during the first 118 days of the mission appear to have been flare initiated. One of these, associated with a 2B optical flare with strong X ray emission, had material velocities in excess of  $980 \text{ km s}^{-1}$ , had associated type 2 and 4 radio bursts, and gave rise to a major interplanetary disturbance at 1 AU.

8. At least 16 events occurred in conjunction with no other signs of surface or limb activity. It seems likely that these mass ejecta originate on the back side of the sun.

9. Unusual coronal activity prior to a transient above the

TABLE 1. Transients and Radio Bursts During the First 118 Days of Skylab

Transients and Radio Bursts	No. of Events*
<i>Events</i>	
Total transients observed	38(+3)
Transient events associated with ground-detected† type 2 (only) bursts	7(+2)
Transient events associated with ground-detected type 4 (only) bursts	2(+1)
Transient events associated with ground-detected type 2 and 4 burst pairs	3
Total transient events with ground-detected type 2 and/or 4 burst associations	12(+3)
<i>Front Side/Back Side Transients</i>	
Transients with radio bursts and with associated H $\alpha$ event (front side events)	9(+2)
Transients with radio bursts and without associated H $\alpha$ event (back side events)	3(+1)
<i>Radio Bursts Followed by Transients</i>	
Total ground-detected type 2 and/or 4 burst events reported during 118 days	24
Radio burst events followed within 3 hours by coronagraph observations	17
Transients observed in association with the above bursts‡	12(+3)

\*The values in parentheses refer to possible events. Identification was difficult owing to poor temporal coverage.

†'Ground detected' means reported in Solar Geophysical Data (1973).

‡The two radio burst events lacking a transient association followed flare and/or surge activity within 20° of central meridian.

region from which material is ejected is difficult to detect or is nonexistent. For example, we are aware of no instances where a streamer 'collapsed' prior to a mass ejection, as has been suggested by *Brueckner* [1972] for a mass ejection event detected by the Oso 7 coronagraph.

10. Table 1 shows that the relationship of coronagraph-observed transients and ground-detected metric type 2 and/or type 4 radio bursts is not simply one to one but is more complicated. The section of Table 1 on 'radio bursts followed by transients' shows that if the coronagraph was observing shortly after a type 2 or 4 burst and if the source was near the limb, a coronal transient was observed. Thus each ground-detected type 2 and/or type 4 burst from near the limb was accompanied by a transient, but the converse is not true; that is, not all transients are accompanied by ground-detected type 2 and/or type 4 bursts.

If the lack of a visible chromospheric event with a coronagraph-observed transient indicates that the transient originated from behind the limb and if the sources of coronagraph-observed coronal transients lie with equal frequency in front of and behind the limb, then the section of Table 1 on 'front side-back side transients' indicates that ground detection of type 2 and/or type 4 bursts accompanying a 'back side' transient is less likely than ground detection of those bursts accompanying a 'front side' transient. This result is not totally unexpected because radio emission from sources behind the limb is expected to be refracted away from the

earthward direction and possibly absorbed by intervening, denser coronal plasma [*Riddle*, 1974].

Summarizing, we can say that ground-detected type 2 and/or type 4 metric radio bursts from sources away from the central meridian were almost invariably accompanied by coronagraph-observed transients. The converse was not true. The absence of ground-detected type 2 bursts with the majority of coronagraph-observed events implies either (1) that shocks usually do not form close to the sun, where they can generate metric wavelength bursts, or (2) that conditions favorable for the emission of metric type 2 radio bursts (e.g., a wave running into a streamer) are generally not present, and/or (3) that conditions favorable for the detection of metric type 2 radio bursts (e.g., negligible refraction by the intervening corona) are generally not present.

The absence of ground-detected type 4 bursts with the majority of coronagraph-observed events implies that typically, MeV particles are not accelerated in conjunction with the events. Certainly, the geometry of most events is favorable for trapping MeV particles.

## DISCUSSION

*Classes of interplanetary disturbances.* There appear to be two distinctly different classes of nonrecurrent solar wind disturbances detected near 1 AU. Disturbances of the first class occur about 10 times per year at the earth and are properly called flare-produced interplanetary disturbances [*Hundhausen*, 1972, chapter VI]. It is this class of disturbance that has received the most attention in the scientific literature. These disturbances usually follow large flares (2 or greater) accompanied by type 2 and (less often) type 4 radio bursts. Characteristically, their signature at 1 AU includes a shock followed later by a large helium enrichment ( $\geq 15\%$  relative to hydrogen) [e.g., *Hirshberg et al.*, 1972] and anomalously low solar wind temperatures [*Gosling et al.*, 1973; *Montgomery et al.*, 1972]. Energetic solar protons ( $\geq 0.5$  MeV) often accompany such disturbances [e.g., *Kahler*, 1969]. Members of the second class of disturbance, accounting for about two thirds of all nonrecurrent interplanetary disturbances (J. T. Gosling, unpublished data, 1974) usually have none of the above associations except that they may have shocks at their leading edges. Their solar origin has remained obscure until now.

We have established that most of our observed mass ejections do not follow large flares. (This is true even if we allow for the possibility that several of our back side events follow large flares on the far side of the sun.) Further, the great majority of mass ejections do not give rise to ground-detected type 2 bursts, even when they originate in favorable positions relative to the earth; nor do they give rise to type 4 bursts. Thus it appears unlikely that the majority of our observed mass ejections lead to the first class of solar wind disturbances at 1 AU, although a few of our events undoubtedly do so. We suggest that the majority of our observed mass ejections are the coronal counterparts of the second class of nonrecurrent interplanetary disturbance, whose solar origin was previously obscure.

We can add substance to the above arguments by comparing the mass and energy flow in the August 10, 1973, ejection with that of the two classes of disturbances described above. Table 2 has been constructed for this purpose. This table shows that our estimates of the mass and energy contained within the field of view of the coronagraph at 1424 UT are comparable to the corresponding estimates for nonrecurrent solar wind streams,

TABLE 2. Mass and Energy Content and Flow Rates of the August 10, 1973, Mass Ejection Compared With Those of Nonrecurrent Streams and Flare-Produced Shock Wave Disturbances at 1 AU

	Mass Content, $10^{15}$ g	Mass Flow Rate, $10^{10}$ g s <sup>-1</sup>	Energy Content, $10^{30}$ ergs	Energy Flow Rate, $10^{25}$ ergs s <sup>-1</sup>
August 10, 1973, mass ejection at 1424 UT	4	112	2.7† (8.4)‡	77†
Nonrecurrent solar wind stream at 1 AU*	2.2	1.3	2.1 (6.3)‡	1.2
Flare-produced shock wave disturbance at 1 AU†	35	41	70 (140)‡	81

\*Derived from Figures 6 and 7 of Gosling *et al.* [1972], although some of the streams included in that study are recurrent. Flow rates assume cross-section area of  $3.85 \times 10^{25}$  cm<sup>2</sup>. Content assumes flow enhancement lasts 2 days.

†From Hundhausen [1972, p. 205]. Flow rates assume that major enhancements of mass and energy flux pass a point in 1 day.

‡Equivalent energy release at solar surface; accounts for change in gravitation potential.

§Assumes that the temperature is  $10^6$  °K and the conduction flux is negligible; kinetic, gravitation, and enthalpy terms are included.

whereas they are factors of 9 and 17 times lower than the estimates for flare-produced shock wave disturbances. Note that the mass and energy flow rates (Table 2) must decrease by a factor of about 60–90 in transit from the sun to the earth if transient ejecta such as that of August 10, 1973, are indeed sources of nonrecurrent streams. Such a reduction should cause no conceptual difficulties, since flow rates are not conserved quantities. We expect decreases in the flow rates to arise naturally from the broadening of the disturbance with increasing heliocentric distance.

**Distribution of energy flux.** Finally, it is of interest to examine the way that energy is distributed among its various flux components (kinetic, enthalpy, gravitation, and conduction) in the normal coronal expansion in contrast with the way that it is distributed among these components during the August 10, 1973, ejection. Models of the normal expansion indicate that the heat conduction flux and the work done against gravity are the dominant terms in the expansion in the inner corona, being approximately equal but opposite in sign [e.g., Hundhausen, 1972, p. 71]. The enthalpy flux is approximately a factor of 2 lower, and the kinetic flux is negligibly small. On the other hand, our best estimates of these various energy terms at 1424 UT on August 10, 1973, are: kinetic,  $3.2 \times 10^{30}$  ergs; gravitation,  $-1.9 \times 10^{30}$  erg; enthalpy,  $1.4 \times 10^{30}$  ergs; conduction, unknown. That is, the kinetic term is 50% larger than the gravitation term, whereas the enthalpy term is 35% smaller than the gravitation term. The conduction term is difficult to estimate; however, it seems certain that it is considerably different from what it is in the normal expansion. The difference arises because the normal coronal expansion proceeds along field lines that are open to interplanetary space, whereas the field lines in the August 10, 1973, ejection (as well as in other events) are rooted in the sun at both ends. Thus we expect conduction to be considerably reduced for mass ejection events.

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