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Coronal Mass Ejections

Tutorial Lecture

by
A. J. Hundhausen
High Altitude Observatory
NCAR

CEDAR PRESENTATION ON CORONAL MASS EJECTIONS

I. Introduction

A. Coronal mass ejections are spectacular (even beautiful) disruptions of the solar corona (**Figure 1**) – but what on earth are they doing at a CEDAR meeting?

1. Ultimate responsibility rests on organizers
2. But my answer to this question would involve
 - a. Culture
 - b. Physics (and chemistry) – the same laws apply on the sun and on the earth
 - c. The solar-terrestrial connection (**Figure 2**)

B. Approach in this presentation

1. Large body of observational/empirical knowledge
2. Description of mass ejections based on that knowledge
 - a. Role of theoretical models in
 - i. Sharpening the description
 - ii. Making it a physical description based on known physical processes
 - b. Remaining crucial gaps that compromise the description
3. Get to key issues or questions regarding
 - a. The origin(s) of mass ejections
 - b. The interplanetary and terrestrial effects of coronal mass ejections
4. These two foci are related to recent fame (or notoriety) of mass ejections in contexts of
 - a. “The Solar Flare Myth”
 - b. “Space Weather”

II. Observational/empirical foundations

A. Mass ejections have been observed by the thousands since discovery about 25 years ago (**Figures 3, 4, 5**)

1. Occur in a highly structured background corona
 - a. Eclipse photo shows that structure (**Figure 6**)
 - b. Interpretation as magnetically-dominated equilibrium between plasma and field with both open and closed magnetic regions (**Figure 7**)
2. Many beautiful mass ejections that give special insights, are starting point for interpretation
 - a. Will use SMM event of August 18, 1980, to illustrate
 - i. Formation of mass ejection in a closed magnetic field region (**Figure 8**)
 - ii. Motion of materials in the ejection
 - α. Trajectories are not ballistic (**Figure 9**)
 - β. Implies a driving force with long range or duration
 - iii. Additional example of latter point shows acceleration that persists for over ~12 hours (**Figure 10**)

3. Measurements of physical properties or characteristics from enough ejections to give statistical description, test validity of any ideas (**Figure 11**)

B. Emphasize two of these properties

1. Speed of outward motion (**Figure 12**)
 - a. Range from 10 km sec^{-1} to 2000 km sec^{-1}
 - b. Comparison with sound and Alfvén speeds (~ 150 and $\sim 750 \text{ km sec}^{-1}$ respectively)
2. Mass of ejected material
 - a. Radiation is photospheric light scattered by electrons in the high temperature, ionized gas
 - i. Because corona is optically thin, integration along line of sight is inherent to data
 - ii. Thus integration over area in images gives mass content
 - b. Isolation of “moving” mass in difference image (**Figure 13**)
 - c. Integration gives that mass with a minor dependence on geometry
 - d. Histogram of this estimated mass content (**Figure 14**)
 - i. Average of a few $\times 10^{15} \text{ gm}$
 - ii. Again, large range of values

III. Empirical description or model of physical structure based on these observations

- A. Basic ambiguity regarding densities – they depend strongly on geometric assumption
- B. Thus alternate interpretations of the true physical structure that gives rise to the bright frontal rim seen in many mass ejections (**Figure 15**)
 1. As a “thin,” dense loop, or
 2. As a bubble of lower (but still enhanced) density
- C. Resolution through statistical evidence (and a more direct line below) favoring the latter
- D. Resulting “ice-cream cone” model for our now standard event (**Figure 16**)
 1. Outer “bubble” is ~ 5 times as dense as the background corona
 2. Inner cavity is $\sim 1/2$ as dense as background
 3. Prominence can be very dense (and may account for a substantial part of total mass)
- E. No information on temperature
- F. Indirect inference of magnetic geometry from
 1. Expectation of closed field lines in pre-event coronal helmet streamer (**Figure 17**)
 2. Frozen-in nature of fields (**Figure 18**)
 3. Thus these closed field lines must be stretched out in mass ejection
 4. Late stages should have drawn out fields, but with change in sense of field (or a current sheet) near the center

IV. Our tentative understanding of the origin of coronal mass ejections

- A. Some implications of our description above
 1. Occurrence in closed magnetic regions
 2. Involve a very large spatial scale
 3. The driving force must be effective over

- a. Spatial scales of several solar radii, or
 - b. Time scales of tens of minutes to hours
- B. Implications of associations with other forms of solar activity deeper in the solar atmosphere
 - 1. Traditional argument starts with association of geomagnetic activity and solar flares as observed in H α (**Figure 19**)
 - a. Illustration of such an “optical” flare (**Figures 20–24**)
 - b. “Explosive nature” is suggested by ejection of H α emitting material (**Figures 25, 26**)
 - c. Same argument applied to interplanetary shocks in the 1960s
 - d. And then to coronal mass ejections in the 1970s and 1980s
 - 2. Specific concept, and quantitative models, of mass ejections driven by the thermal energy (and high pressure) released in flares
 - 3. Changes in the picture implied by Skylab and later observations
 - a. Poor correlation of observed mass ejections with optical (or H α) flares (far poorer than with prominence eruptions)
 - b. However, a good correlation with flaring seen in soft X-rays
 - i. Simple meaning of soft X-ray emission as thermal emission from the million degree corona
 - ii. Observability of “X-ray corona” on disc (**Figure 27**)
 - iii. Occurrence of enhanced emission from spreading loops or arcades of loops (**Figures 28–31**)
 - iv. Known as “long-duration events” from integrated light curve
 - v. Example of association with an observed mass ejection (**Figure 32**)
 - c. Differing conclusions
 - i. The X-ray flare reflects the thermal energy that drives the mass ejection
 - ii. The X-ray flare is a post-ejection energy deposition as field lines relax from their “stretched out” configuration (**Figure 33**)
- C. My own version of our present understanding
 - 1. There is considerable evidence against the thermal-driver concept and models
 - a. Timing of mass ejection and X-ray flare (**Figure 34**)
 - b. The X-ray emission does not come from the coronal mass ejection itself (the ejected material is not exceptionally hot) (**Figure 35**)
 - c. X-ray intensities (thus thermal energies) are poorly correlated with mass ejection speeds, energies, etc.
 - 2. Most of this same evidence is qualitatively consistent with the post-ejection flare concept
 - 3. Can the flare (or some smaller flare) drive the mass ejection by a different physical mechanism?
 - 4. Or must we look elsewhere for the mechanism(s) that drives mass ejections?

- a. Are they a response to the slow evolution of coronal boundary conditions, leading to instability or a breakdown of equilibrium?
 - i. Shear of fields across the neutral line
 - ii. Emergence of new magnetic flux
 - b. Or an inherent characteristic of the coronal structure near a prominence?
 - i. Buoyancy of cavity breaking down restraining effect of magnetic tension
 - ii. Magnetic buoyancy of fields that are “poorly rooted” to lower atmosphere
- D. This is precisely where theoretical models could
 - 1. Produce focus on physical structure and processes
 - 2. Demonstrate what can or cannot work
 - 3. Be tested by real comparisons with observations
- E. Difficulty of constructing such models
 - 1. Geometric and physical difficulties
 - 2. Uncertainties regarding the physical state, and the boundary conditions, involved in mass ejection formation
- F. The latter point is crucial!
 - 1. It is obvious that the coronal magnetic field is central to mass ejection formation
 - 2. But our knowledge of that field, even in the pre-ejection corona, is sketchy
 - 3. For purposes of physical understanding, to say nothing of prediction, real quantitative knowledge of the field is essential

V. Our better understanding of the interplanetary consequences of coronal mass ejections

- A. Models of solar wind dynamics based both on observations and theory
 - 1. Steepening of solar wind streams to form shocks
 - 2. Propagation of shock waves
- B. Simple physical argument illustrates important conclusion – damping of speed differences into background or ambient wind
 - 1. Cone with $\sim 25^\circ$ half width of typical mass ejection
 - a. Subtends $\sim 5\%$ of solid angle around sun
 - b. Extension to orbit of earth is filled with a four or five day supply of solar wind at rate of 5×10^{15} gm day $^{-1}$
 - 2. Mass ejection that drives to orbit of earth in 2 days (average speed of ~ 1000 km sec $^{-1}$) sweeps up 10^{16} gm of solar wind
 - 3. Compare to mass distribution of mass ejections – this swept-up mass is greater than that in most coronal mass ejections
- C. Actual calculations quantify this effect
 - 1. Damping of 2000 km sec $^{-1}$ with different durations (**Figure 36**)
 - 2. Ordering in terms of masses
 - 3. Observed example of a rare 10^{16} gm, 2000 km sec $^{-1}$ ejection that could reach earth without major damping or slowing (**Figure 37**)
- D. Is this a tractable problem?

1. Yes in that we probably know the essential physics
2. Yes in that a realistic geometry isn't impossible
3. But we do not know the boundary conditions for ejections directed toward the earth
 - a. Most mass ejection observations are at the limb
 - b. We do know several signatures of mass ejection occurrence on visible disc
 - c. But we do not know speeds or mass of the later
4. Halo mass ejections (**Figure 38** as example)
 - a. Unknown propagation speed of top of ejection (**Figure 39**)
 - b. Poorly known masses as well

VI. So where are we?

- A. Considerable understanding of a phenomenon known for only 25 years (**Figure 40**)
- B. Origins remain controversial, but they are pretty clearly not what was expected
- C. The phenomenon fits neatly into our understanding of the solar wind
- D. But how well can we quantify this knowledge?
 1. Hierarchy of models from
 - a. Phenomenologically descriptive, to
 - b. Physically descriptive (identify the physical processes that explain the phenomenon), to
 - c. Physically predictive
 2. In our studies of mass ejections as part of the solar-terrestrial system, we are
 - a. In the physically descriptive phase in following the interplanetary effects of mass ejections
 - b. Well short of that phase in our weakest link, describing the origin of mass ejections
 3. And some of us remain suspicious of "intermediate models," such as correlations of flares properties with mass ejection properties as shortcuts to prediction (**Figure 41**)

Reference review papers:

- Hundhausen, A. J., Coronal Mass Ejections, pp. 259-296 in Cosmic Winds and the Heliosphere, ed. by J. R. Jokipii, C. P. Sonett, and M. S. Giampapa, Univ. of Arizona Press, Tucson, 1977.
- Hundhausen, A. J., Coronal Mass Ejections, pp. 143-200 in The Many Faces of the Sun, ed. by K. T. Strong, J. L. R. Saba, B. M. Haisch, and J. T. Schmelz, Springer, New York, 1999.

These reviews give the detailed references.

DATE
14 APR
1980

YEAR: DOY
80: 105

TIME
05:44:18

FILTER
GREEN

POLAROID
CLEAR

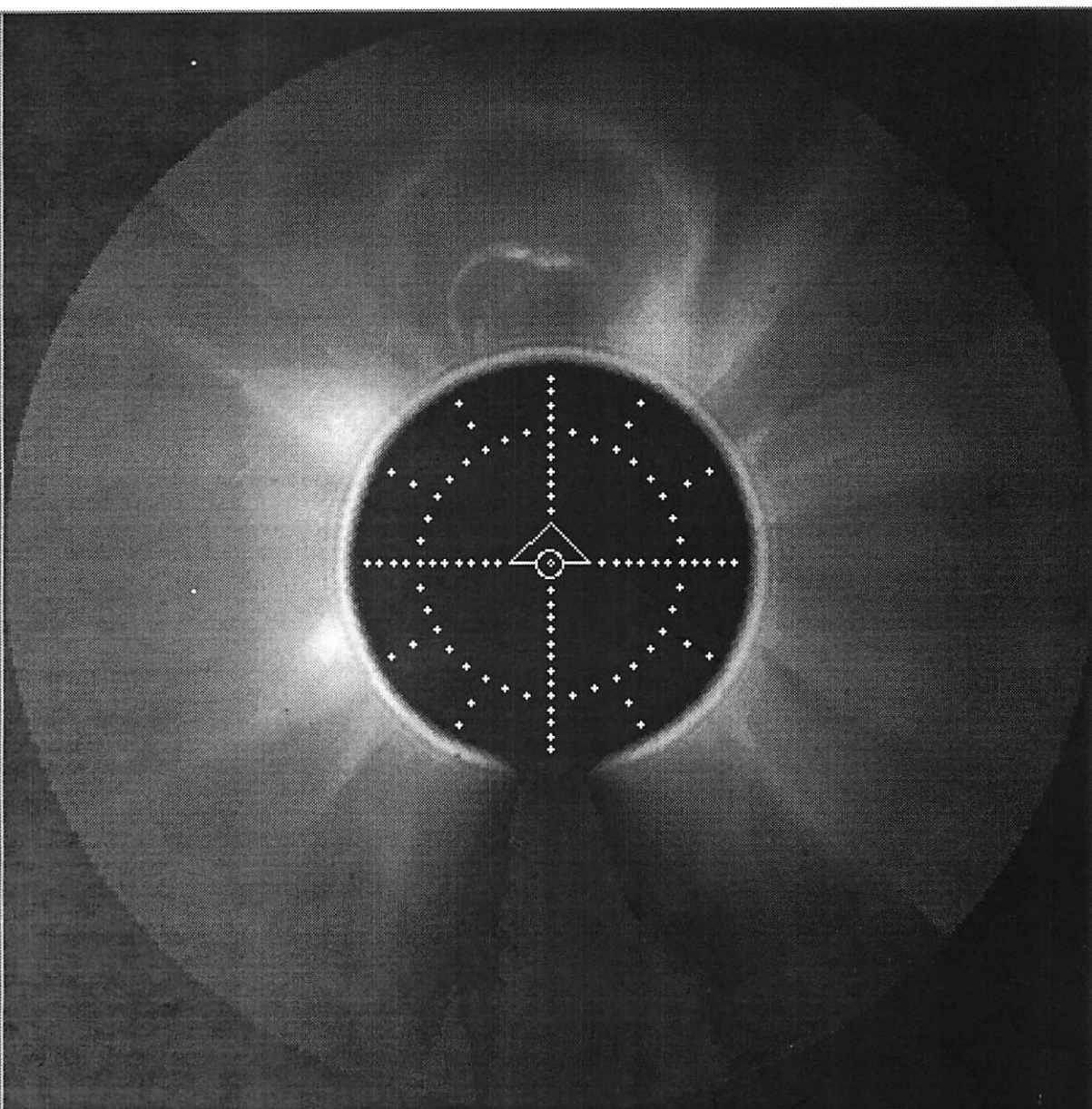
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ROLL
-43

FRAME
2883



$S+(F+K)*V$

HAO/SMM CORONAGRAPH/POLARIMETER

0 64 128 192 255

Figure 1. A coronal mass ejection (at top) observed with the Solar Maximum Mission (SMM) coronagraph on April 14, 1980.

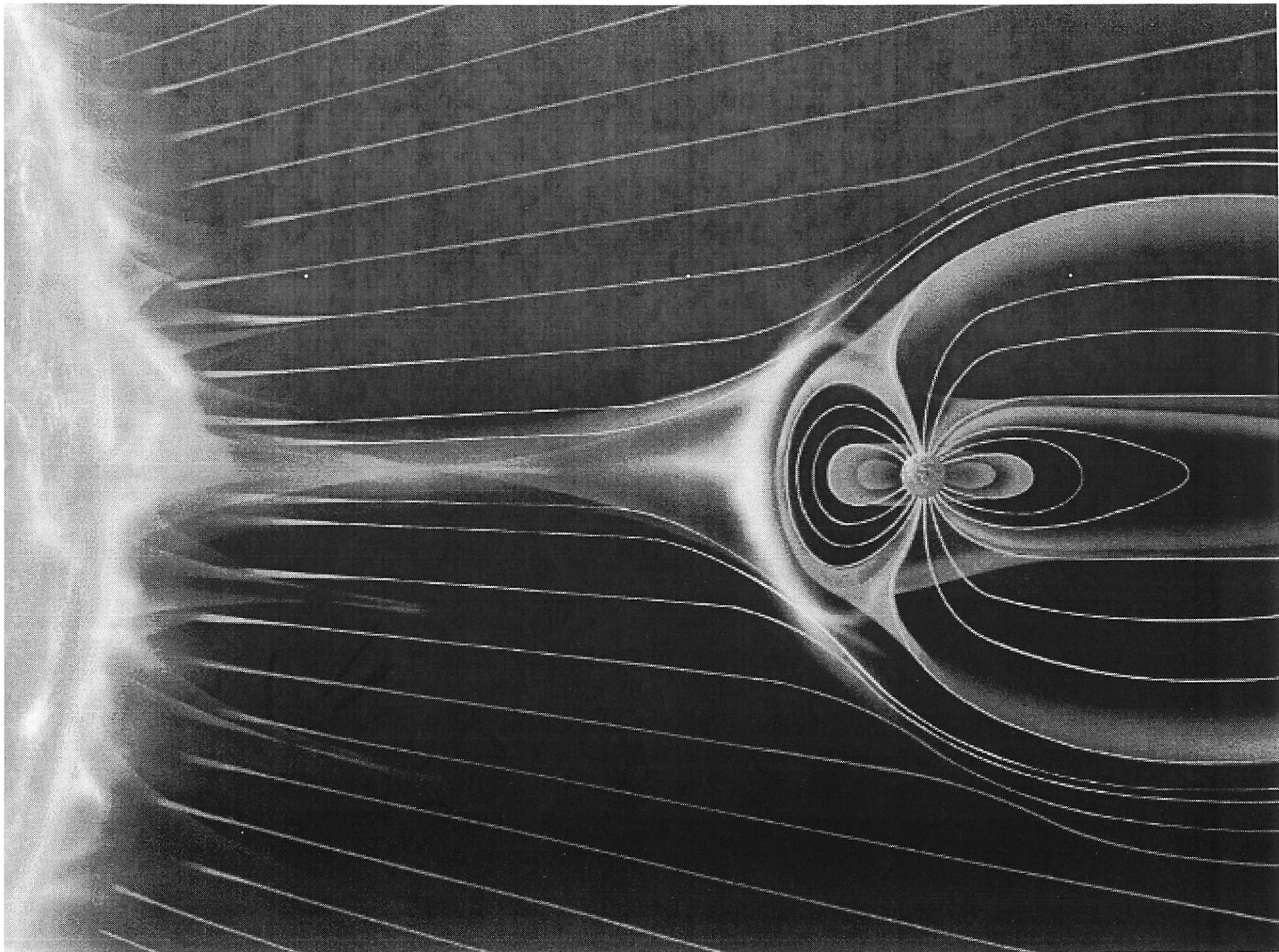


Figure 2. The solar-terrestrial connection.

Figure 3. Skylab example of a mass ejection.

DATE
10 JUN
1973

YEAR:DOY
73:161

TIME
09:59:34

ORIGIN
HAO/SKYLAB

TELESCOPE
WLCE/S052

INSTRUMENT
35MM FILM

OBJECT
SOLAR CORONA

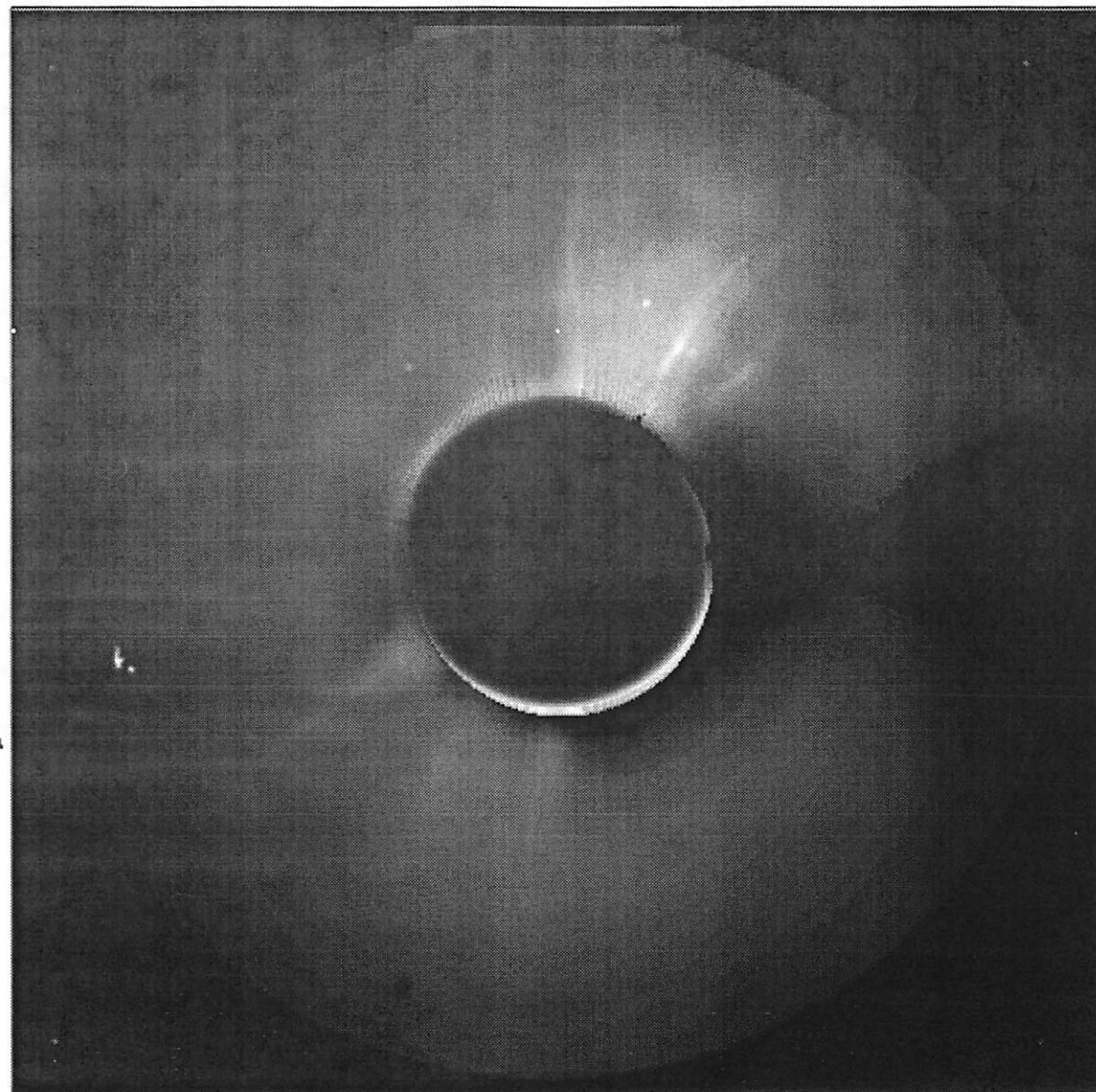
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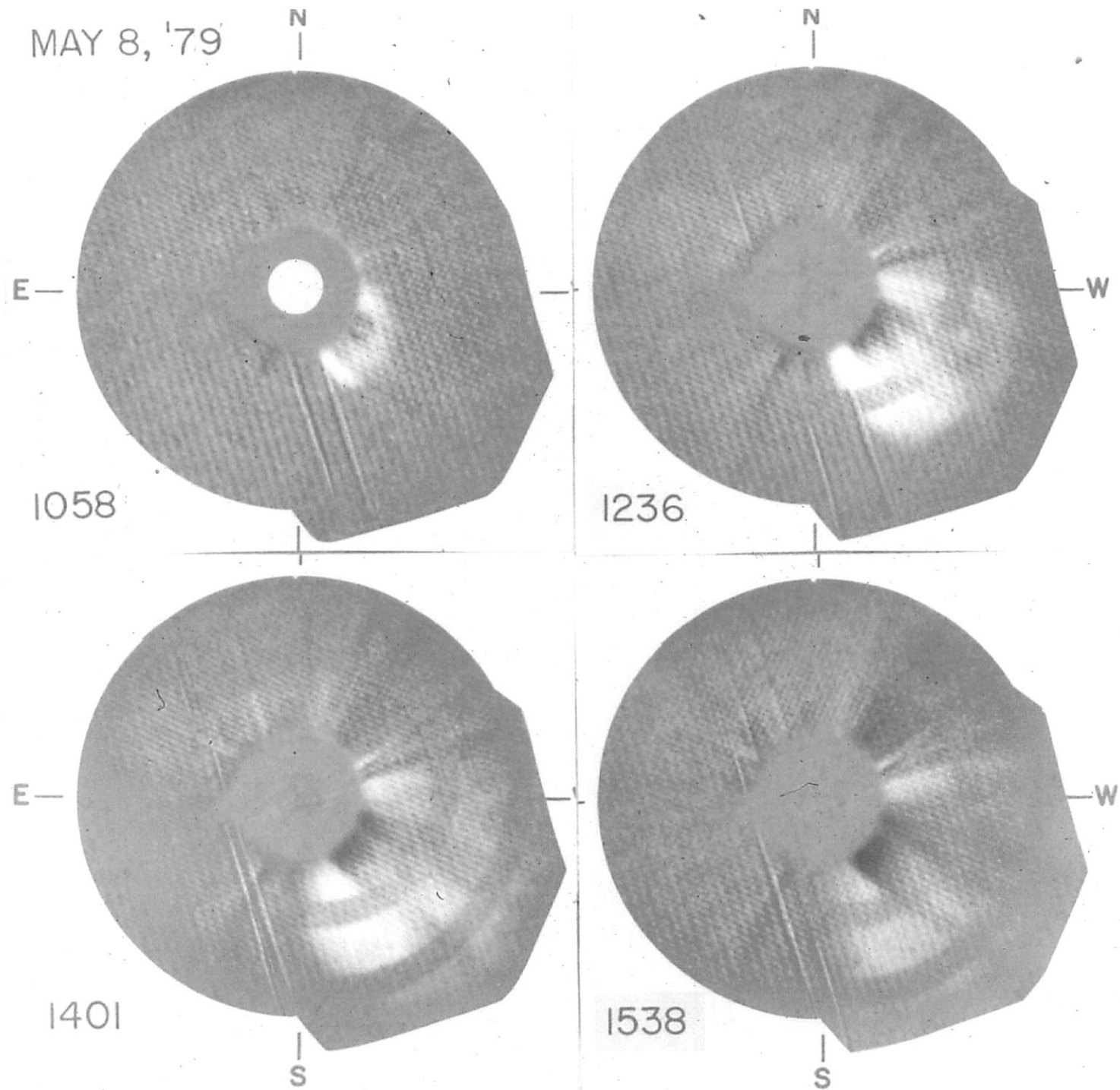
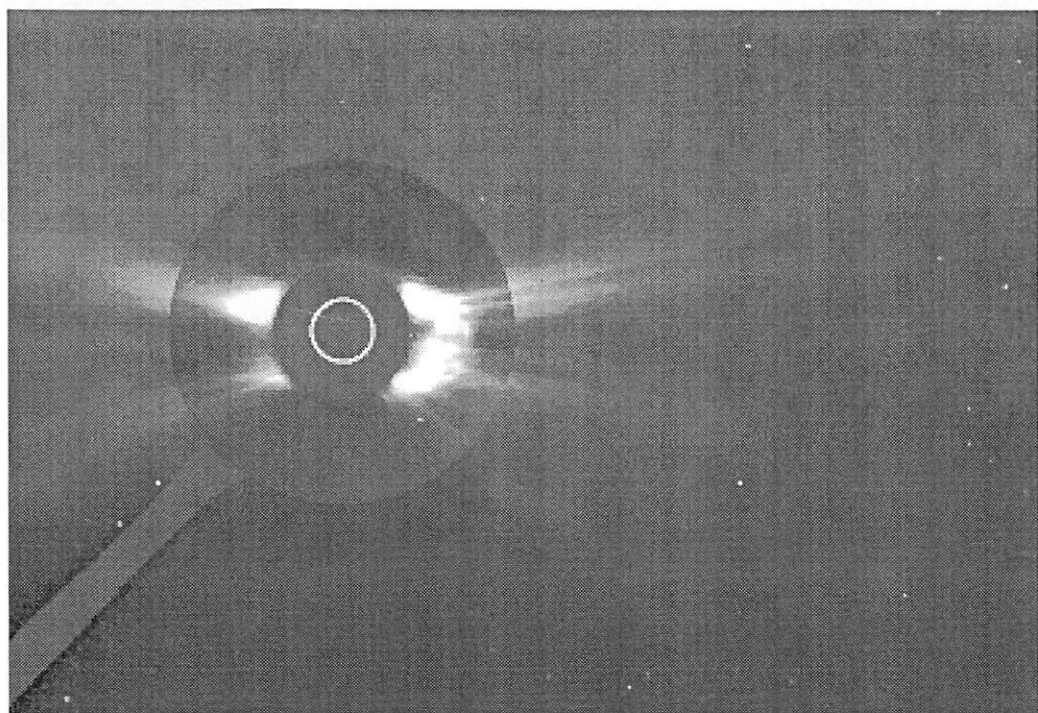
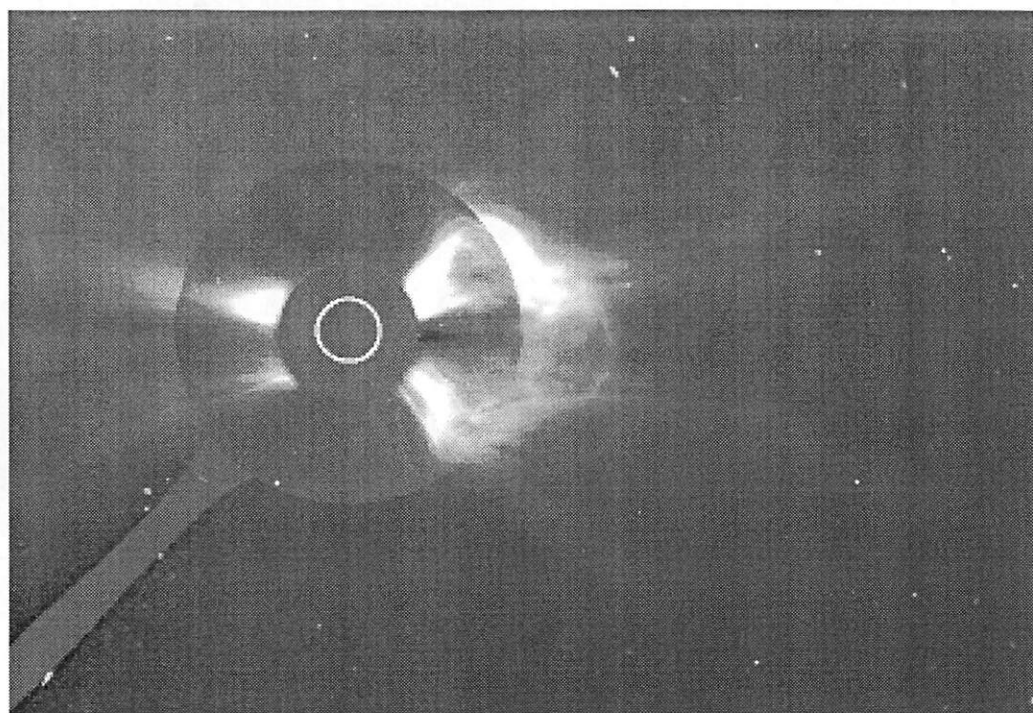


Figure 4. Solwind example of a mass ejection.



1997/11/06 12:10(C2) 11:50(C3)



12:36(C2) 12:41(C3)

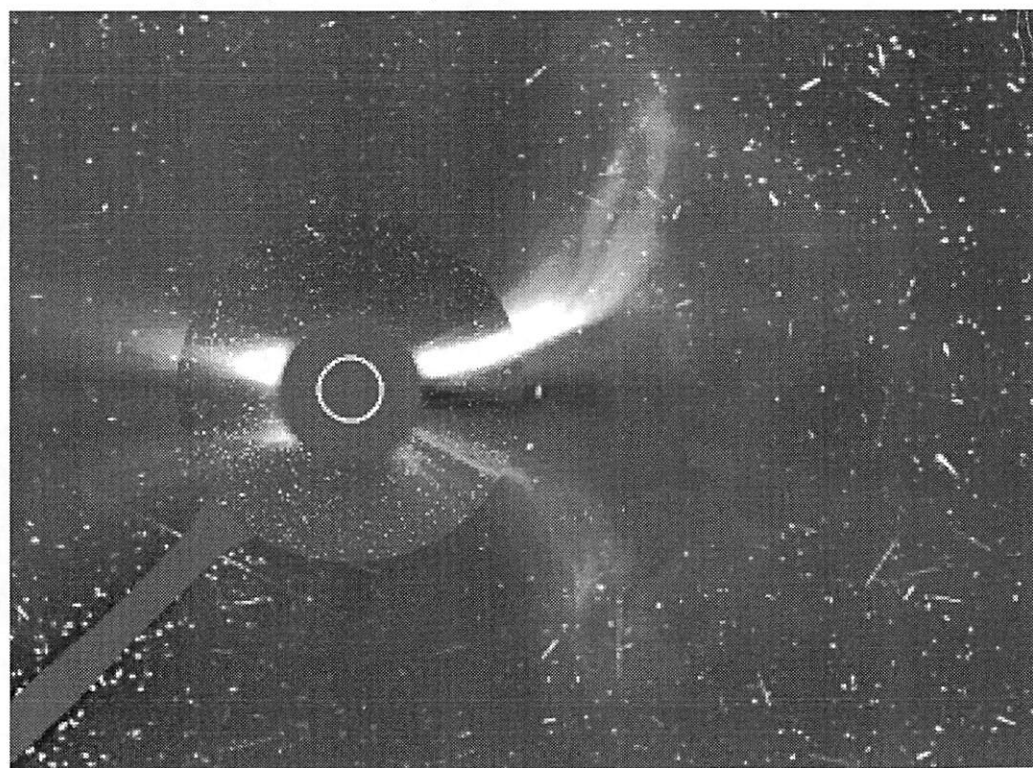
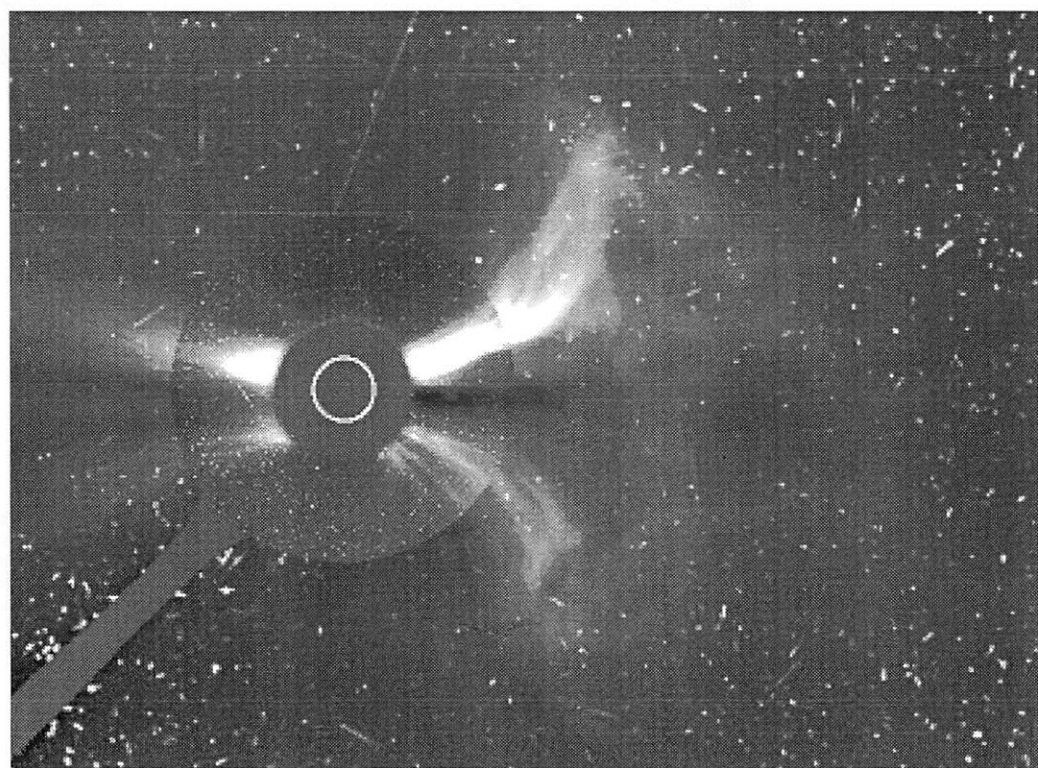


Figure 5. SOHO example of a mass ejection.

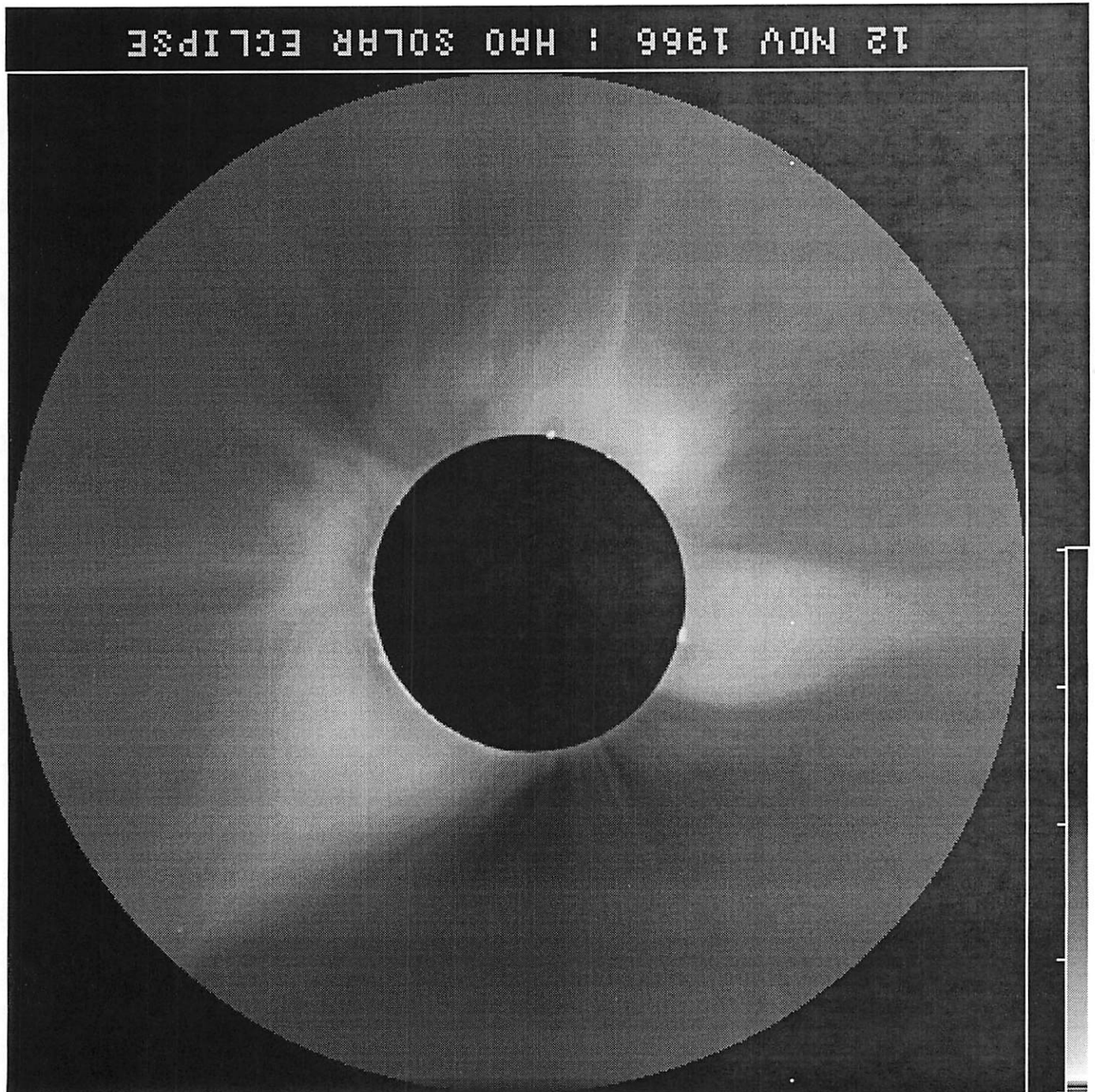


Figure 6. Eclipse photo of the corona on 12 Nov. 1966 (rotated 180° so solar N is at the top).

1966 SOLAR ECLIPSE

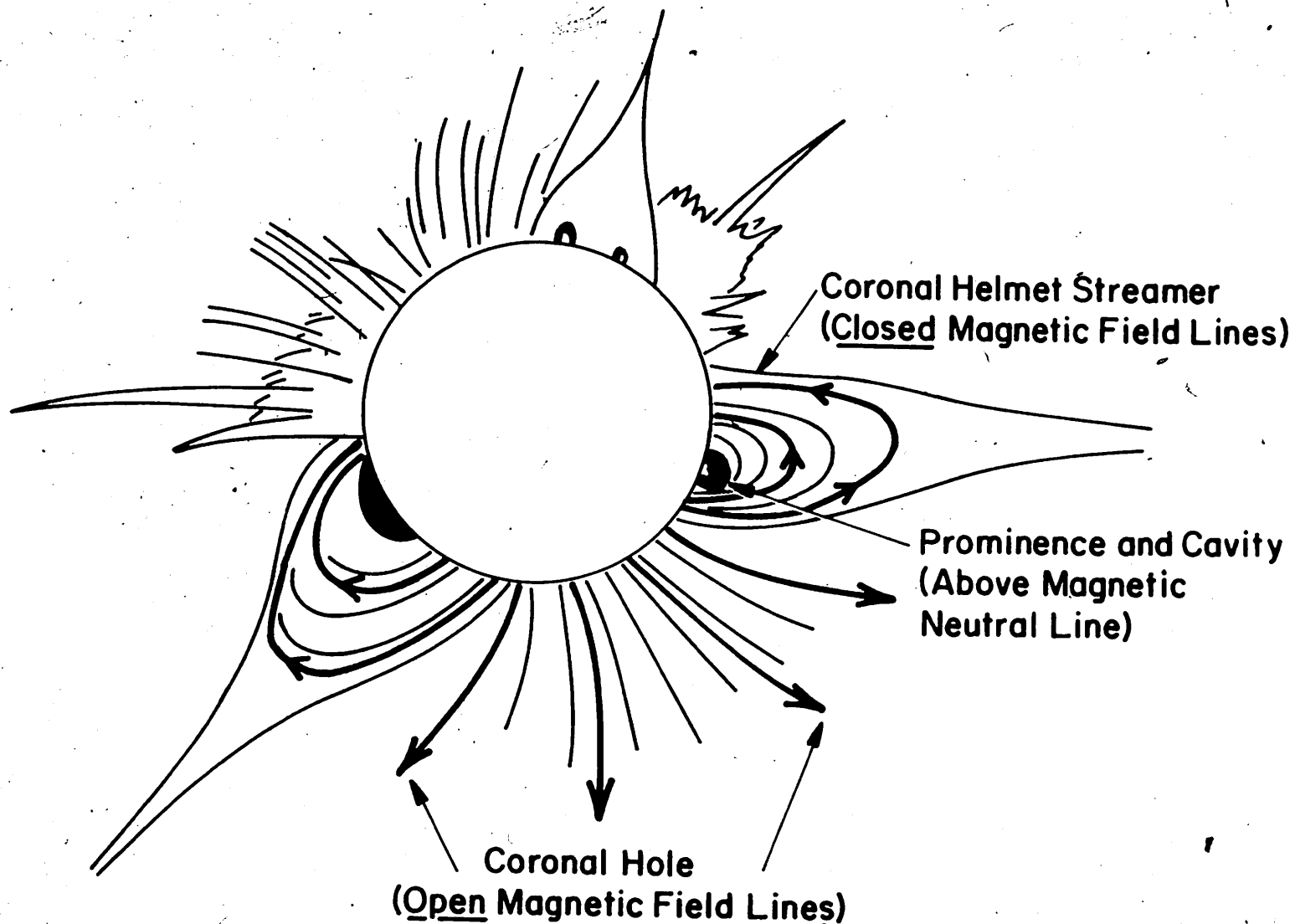
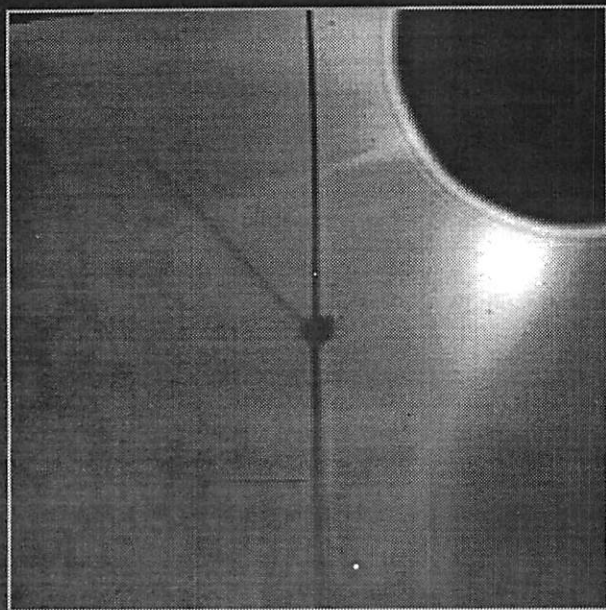
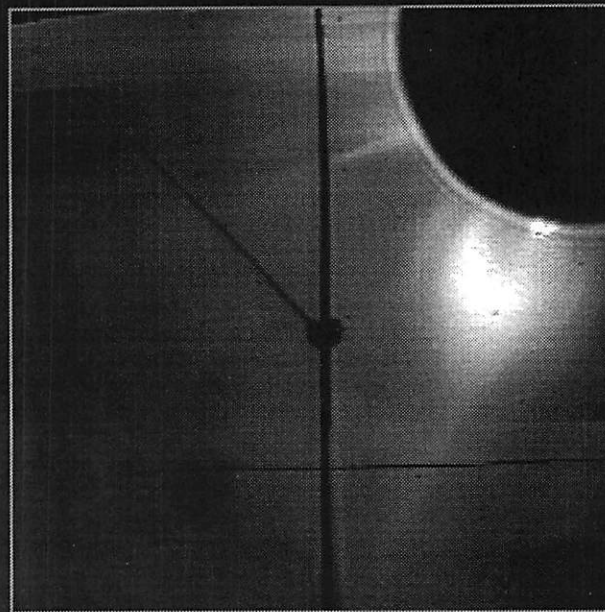


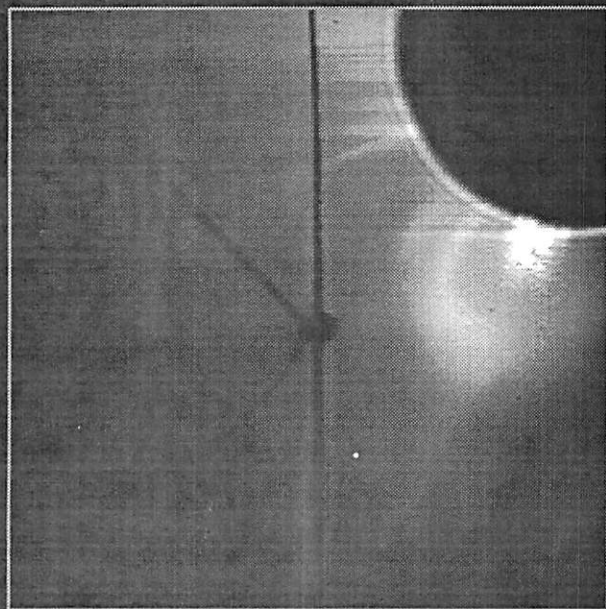
Figure 7. Magnetic sketch of the corona from the Southern Hemisphere in the same orientation as the eclipse photo in Figure 6.



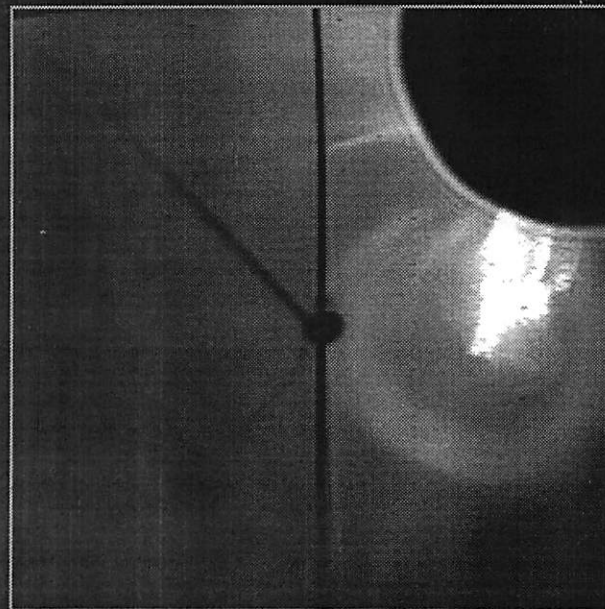
18 AUG 1980 08:59 UT



18 AUG 1980 11:43 UT



18 AUG 1980 11:54 UT



18 AUG 1980 12:15 UT

Figure 8. Four SMM images of a mass ejection on August 18, 1980.

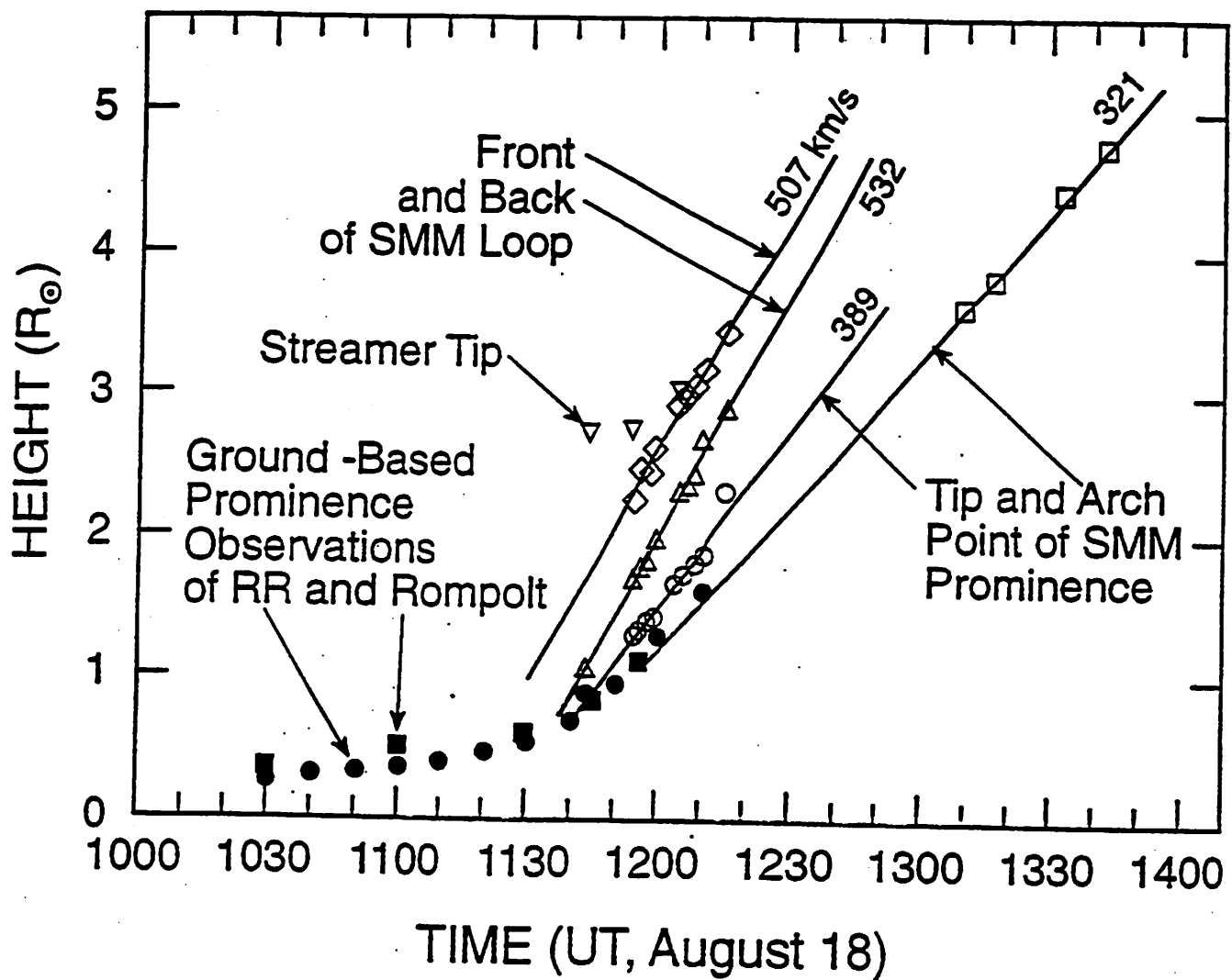
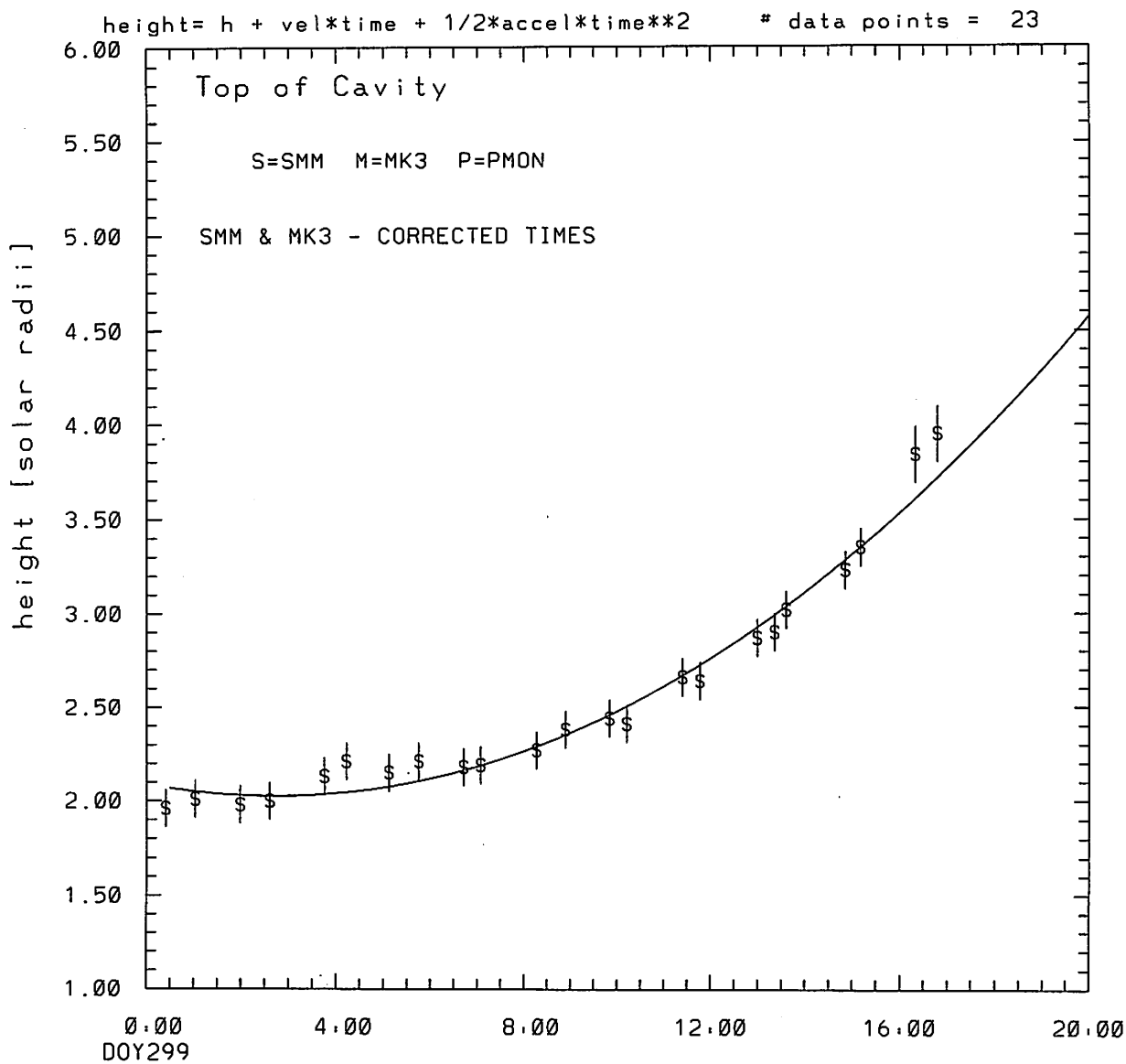


Figure 9. Heliocentric positions measured (on a time sequence of images) for several features in the August 18, 1980, mass ejection (adapted from Illing and Hundhausen, 1986). The SMM prominence locations have been supplemented by the ground-based observations of Rusin and Rybansky (1982) and Rompolt (1984).

SMM C/P 1986 DOY299 94 +/- 0 degrees



tstart=DOY299 2.43 from derivative=0

Event begins at 2.03 Solar Radii

radial acceleration = 0.0009 ± 0.0001 [km/sec**2]

Figure 10. Trajectory of a different ejection showing slow acceleration over approximately 12 hours.

TABLE ONE: Some Average Characteristics of Coronal Mass Ejections

	Skylab (1973-74)	Solwind (1979-80 & 1984-85)	SMM (1980, 1984-89)
Angular Size	42°	43°	47°
Speed	470 km sec⁻¹	460 km sec⁻¹	350 km sec⁻¹
Mass	—	4.0 × 10¹⁵ gm	2.5 × 10¹⁵ gm
Kinetic Energy	—	3.4 × 10³⁰ ergs	3.1 × 10³⁰ ergs[†]
Potential Energy	—	—	5.4 × 10³⁰ ergs[†]
Mechanical Energy	—	—	8.5 × 10³⁰ ergs[†]

[†]SMM mass and energy analyses completed only through 1988.

Figure 11. Table of average values of six mass ejection properties.

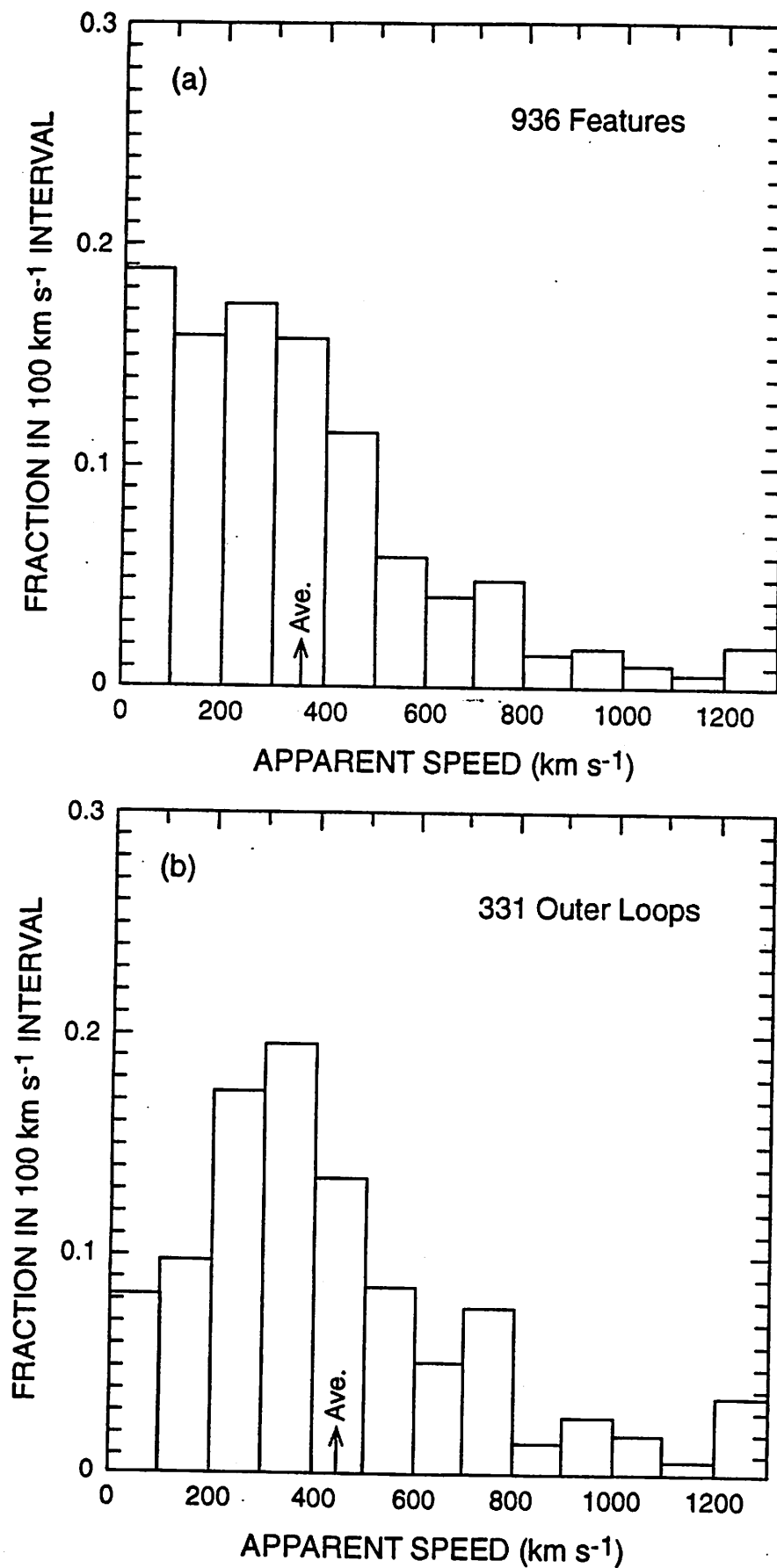


Figure 12. The distributions of apparent speeds for all mass ejection features and for bright frontal loops observed by the SMM coronagraph (from Hundhausen et al., 1993). The last interval contains all values greater than 1200 km sec⁻¹. The average speeds (with no corrections for projection effects) are 350 km sec⁻¹ for all features and 445 km sec⁻¹ for the outer loops.



Figure 13. Difference image for the August 18, 1980 ejection.

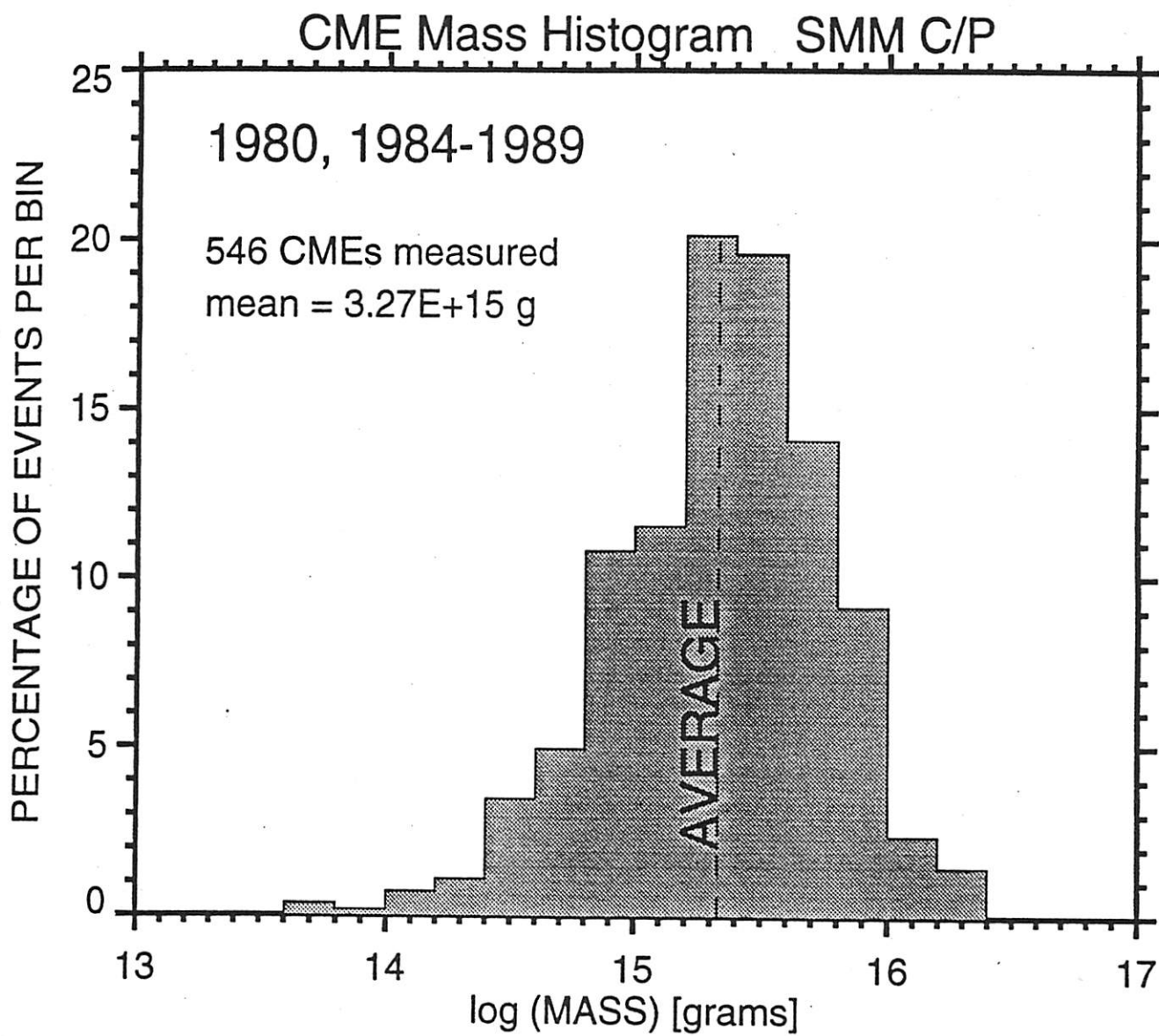
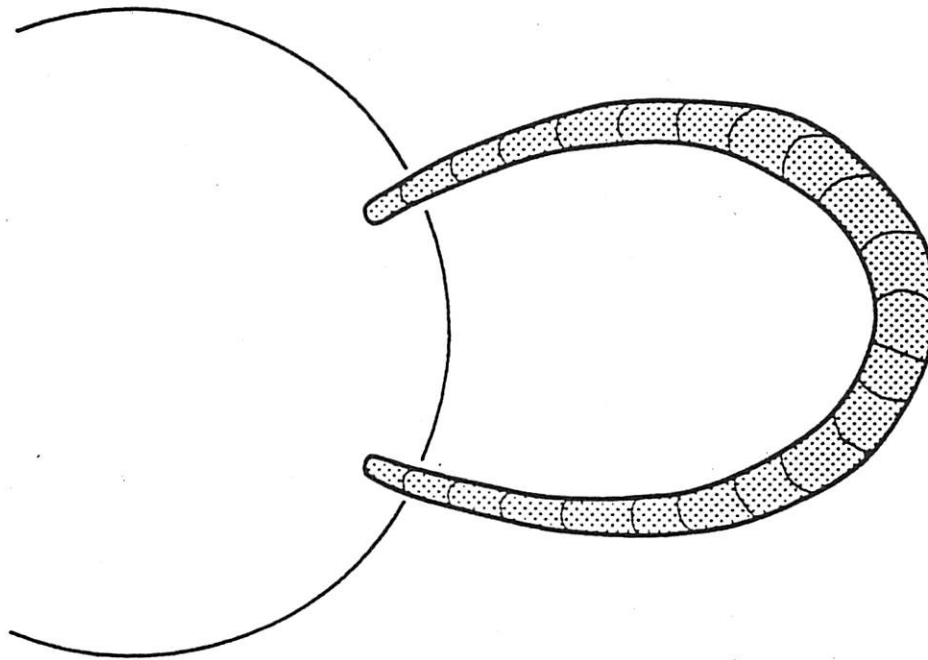


Figure 14. Histogram of masses estimated from SMM observations.

(a) Loop or Rope of Dense Plasma



(b) Shell or Bubble of Dense Plasma

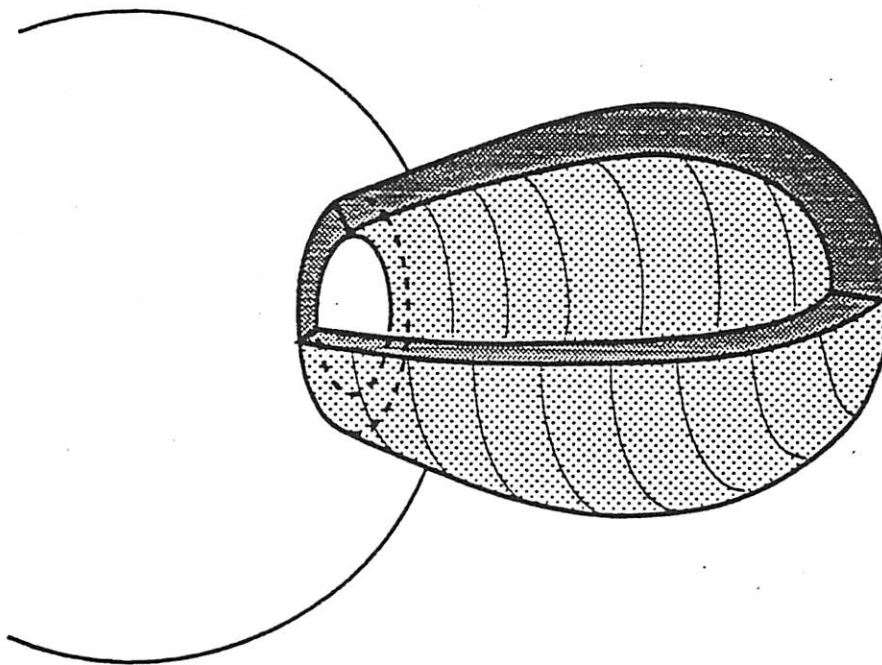


Figure 15. A sketch of two possible geometries for regions of dense plasma that would have a loop-like appearance in scattered light. At the top is a dense loop or rope of plasma that would obviously appear to be a loop in a coronagraph image. At the bottom is a shell or bubble of dense plasma; a section has been cut away to illustrate the three-dimensional nature of the dense region. The line of sight through the dense region is longest near the inner edge of the dense shell; hence it would appear as a loop because of the "limb-brightening" effect.

Aug 18, 1215 UT

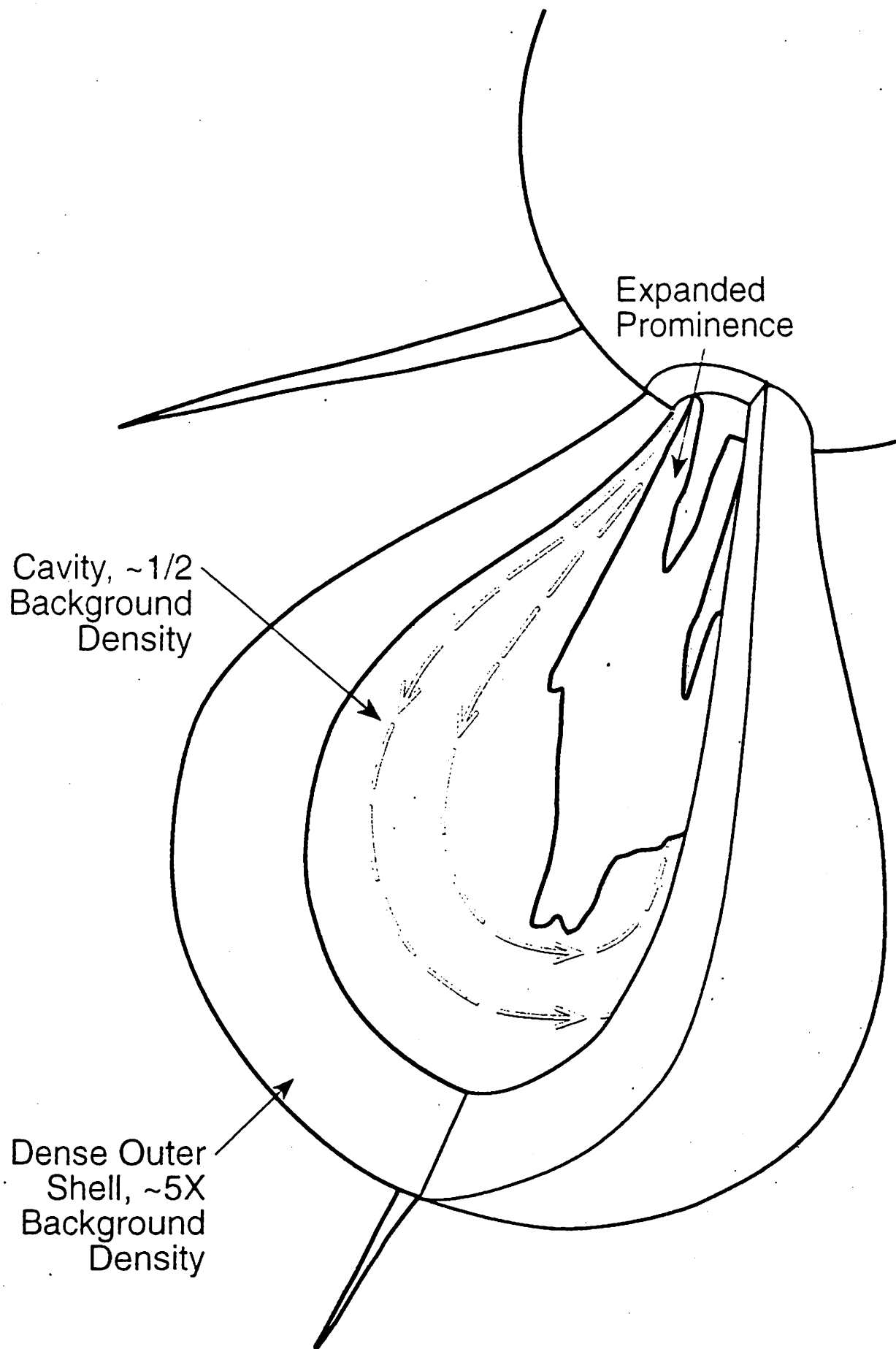
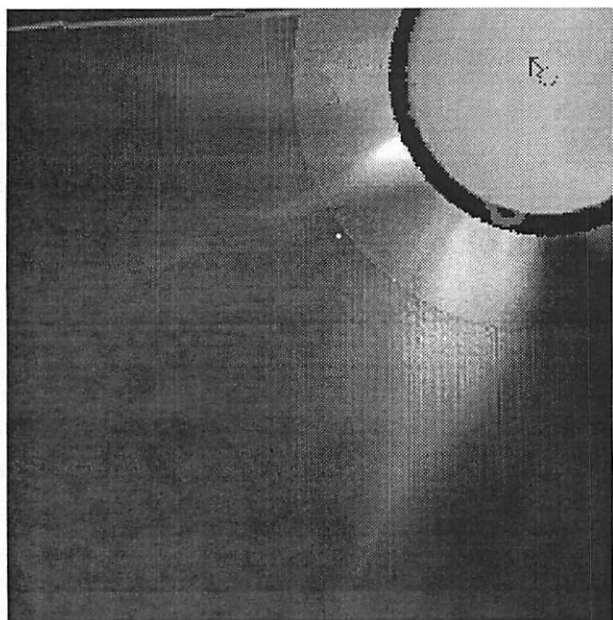
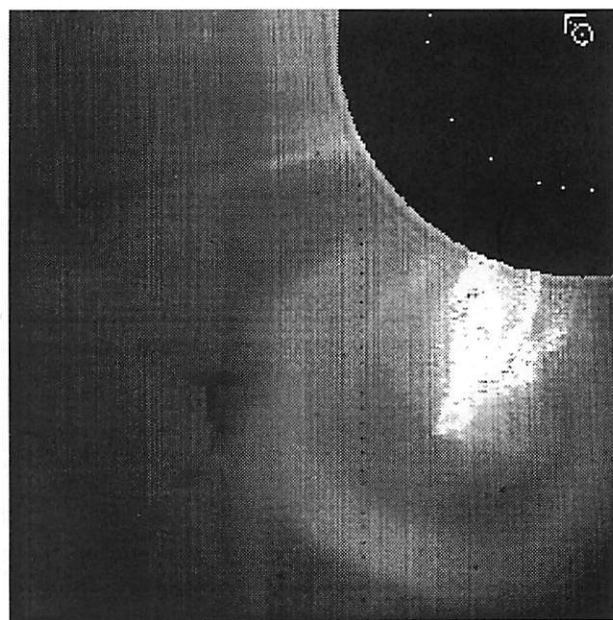


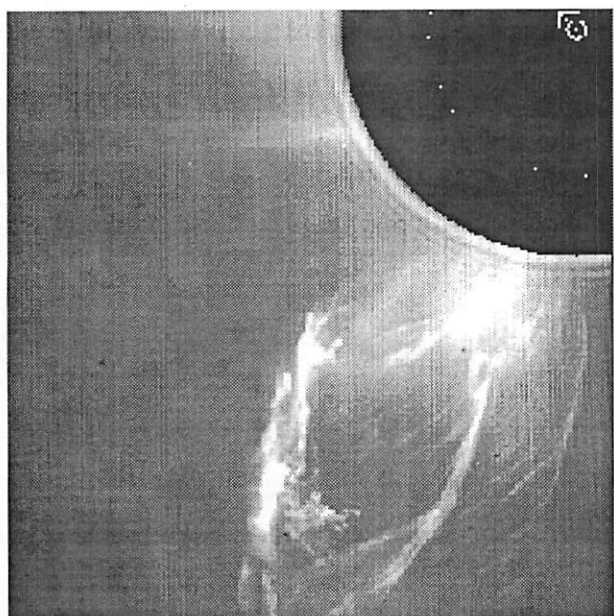
Figure 16. Ice-cream cone model of the density structure in the August 18, 1980 ejection.



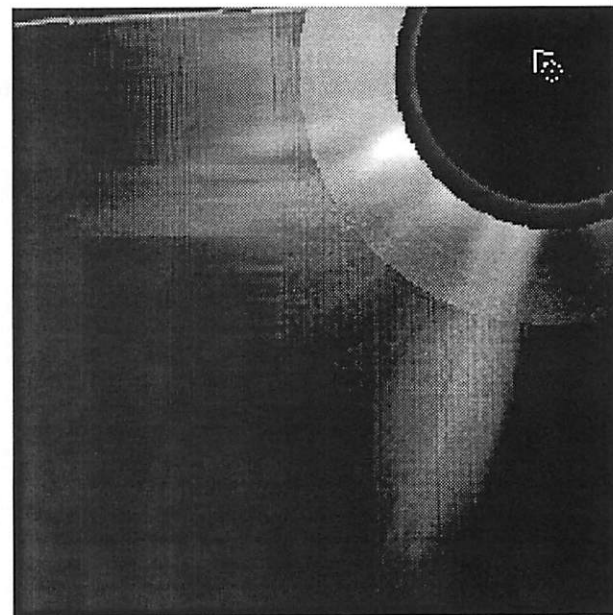
August 17 22:58



August 18 12:15



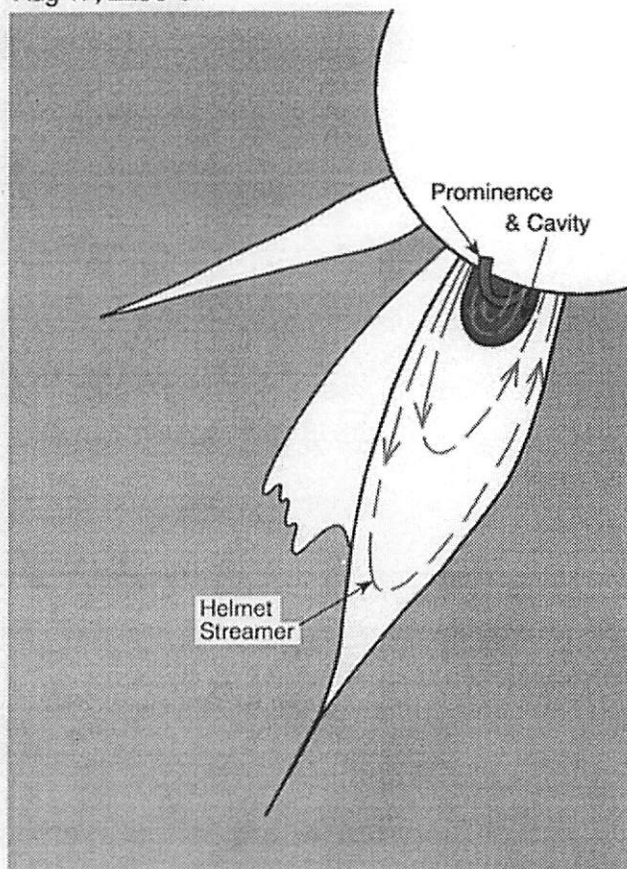
August 18 13:10



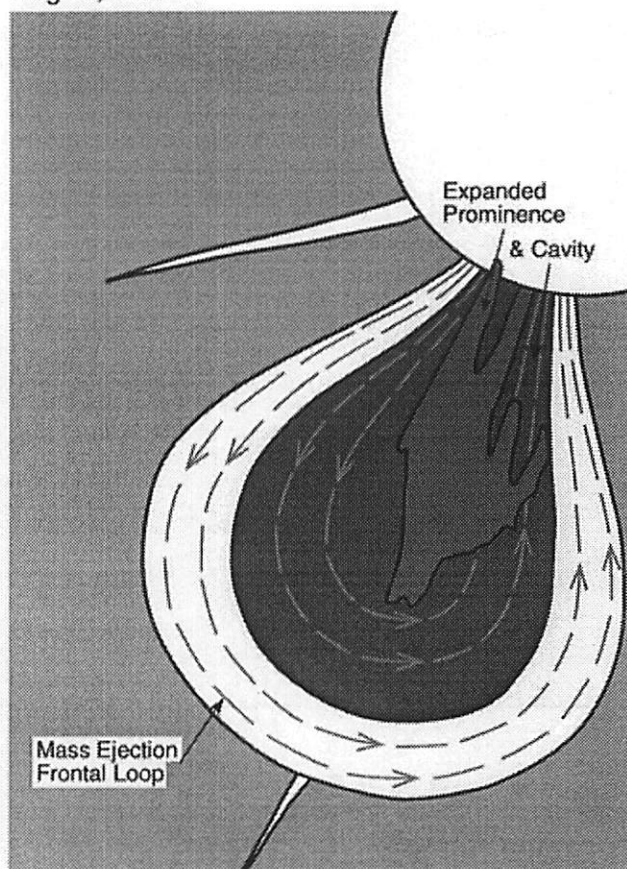
August 18 19:34

Figure 17. Four images of the August 18, 1980 ejection.

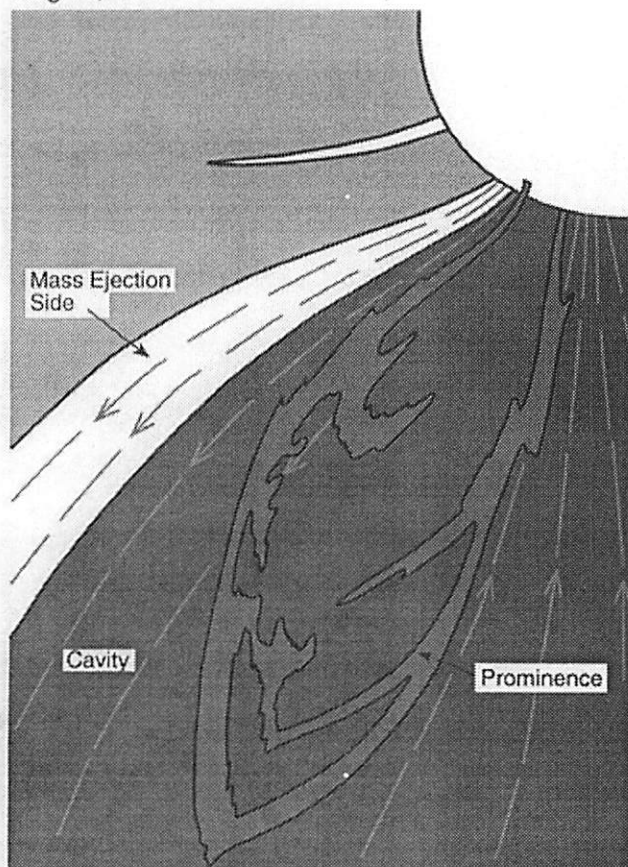
Aug 17, 2258 UT



Aug 18, 1215 UT



Aug 18, 1310 UT



Aug 18, 1940 UT

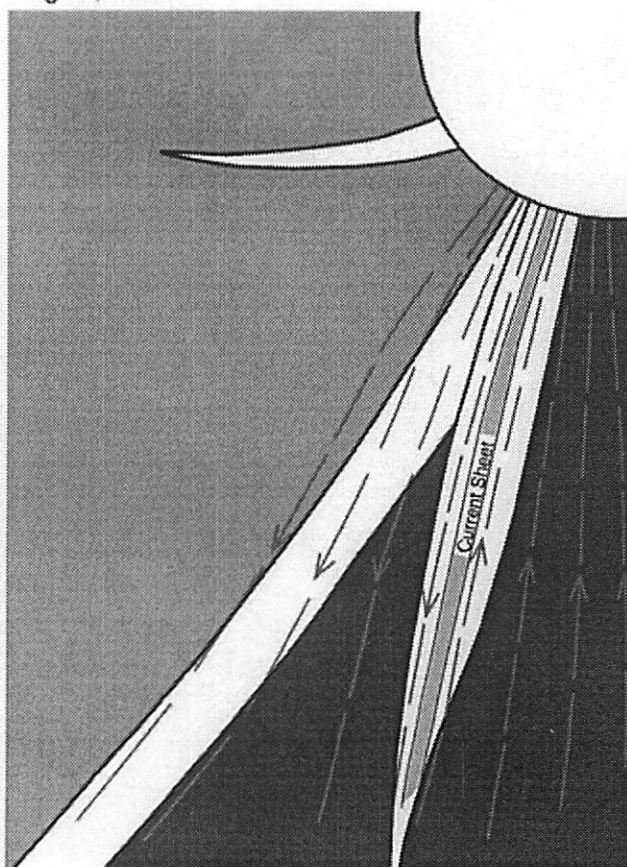


Figure 18. Sketch of the magnetic structure of the ejection.

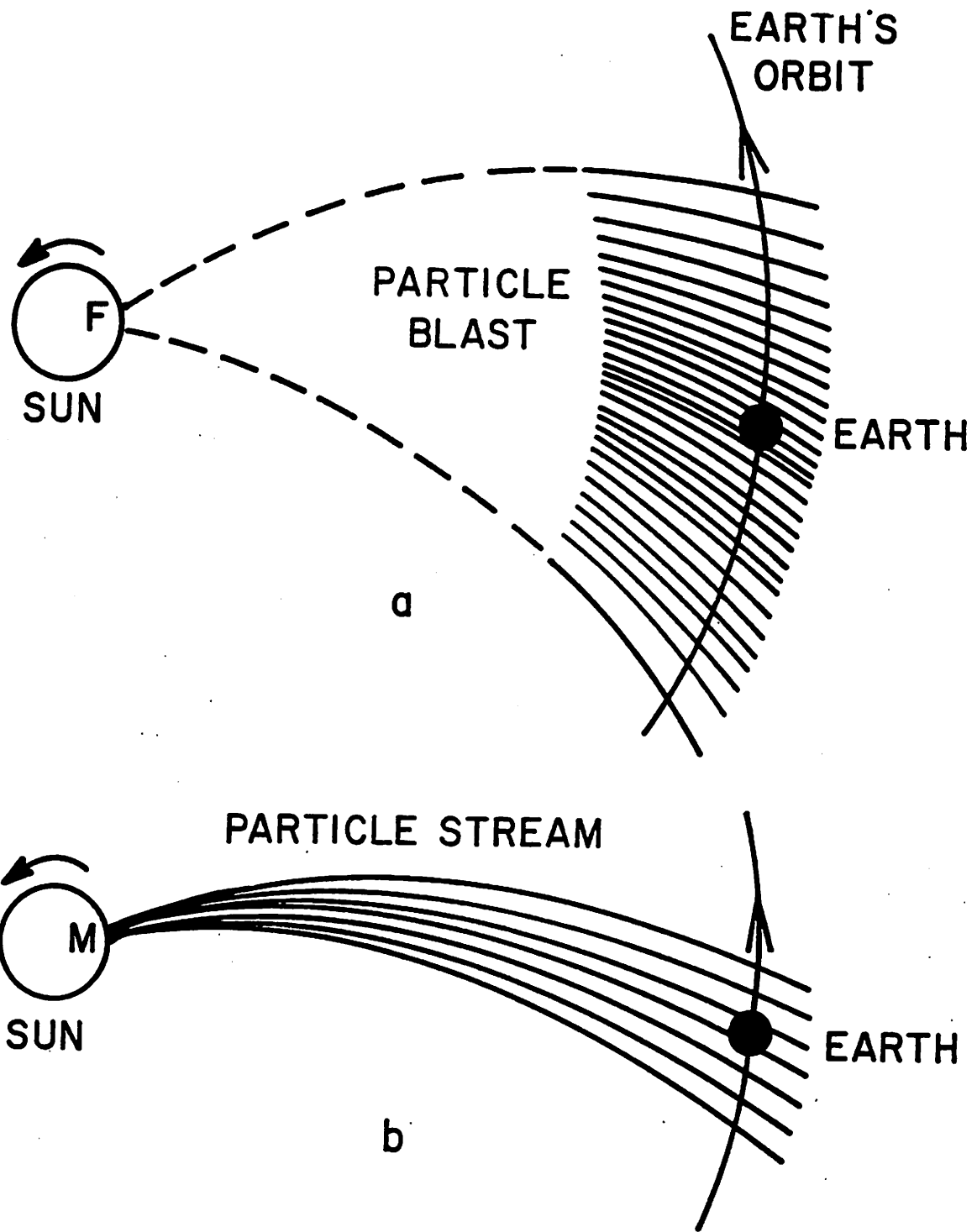
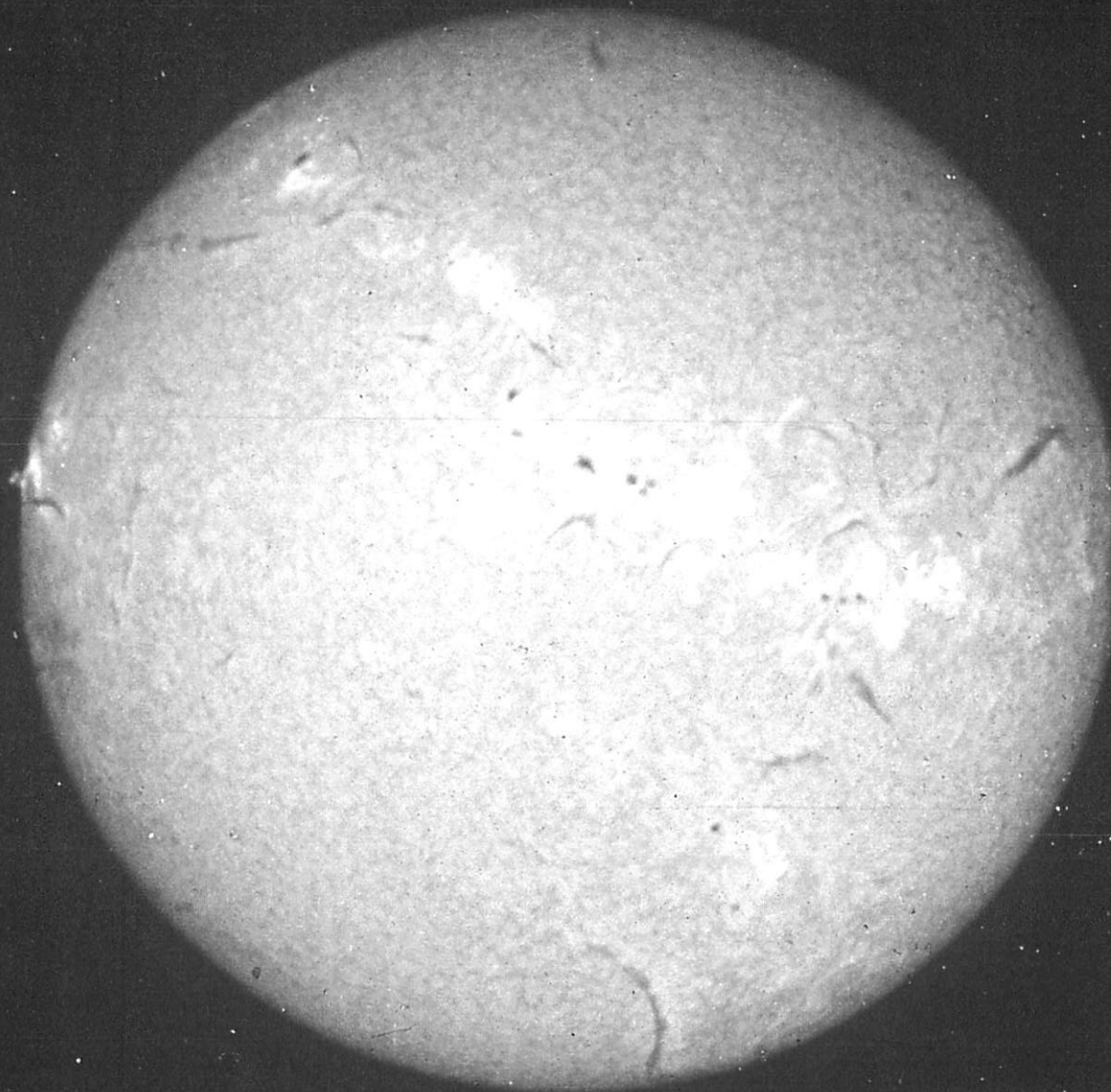


Figure 19. Flare-associated blast wave (top) inferred in antiquity.

1256 193757 254 89



Figures 20 (-24) H-alpha flare in central disk on September, 1989 between 1937 and 1953 UT. (Flare is not visible on copies so this shows only 1937 UT.)

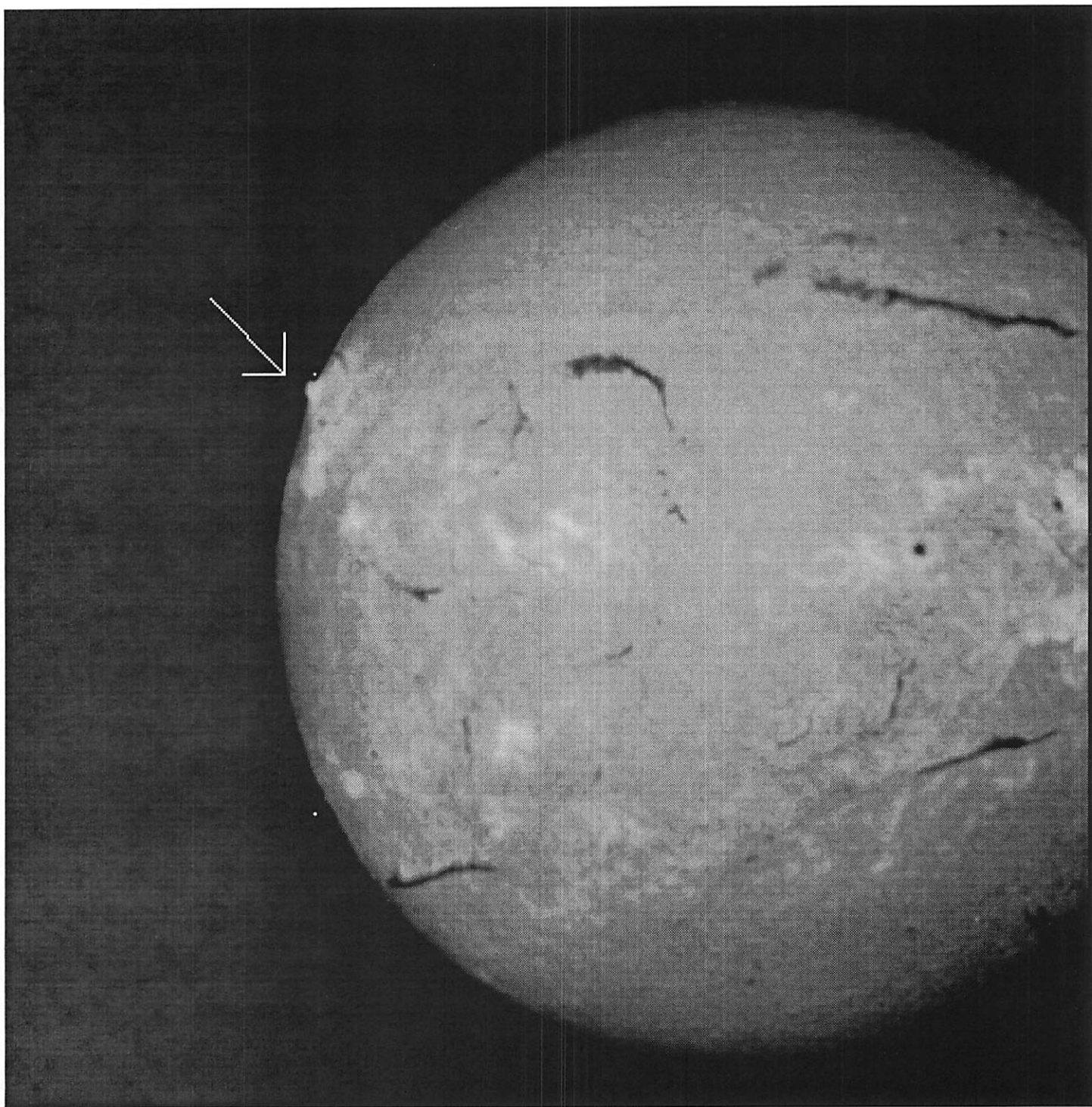


Figure 25. H-alpha flare on the limb.

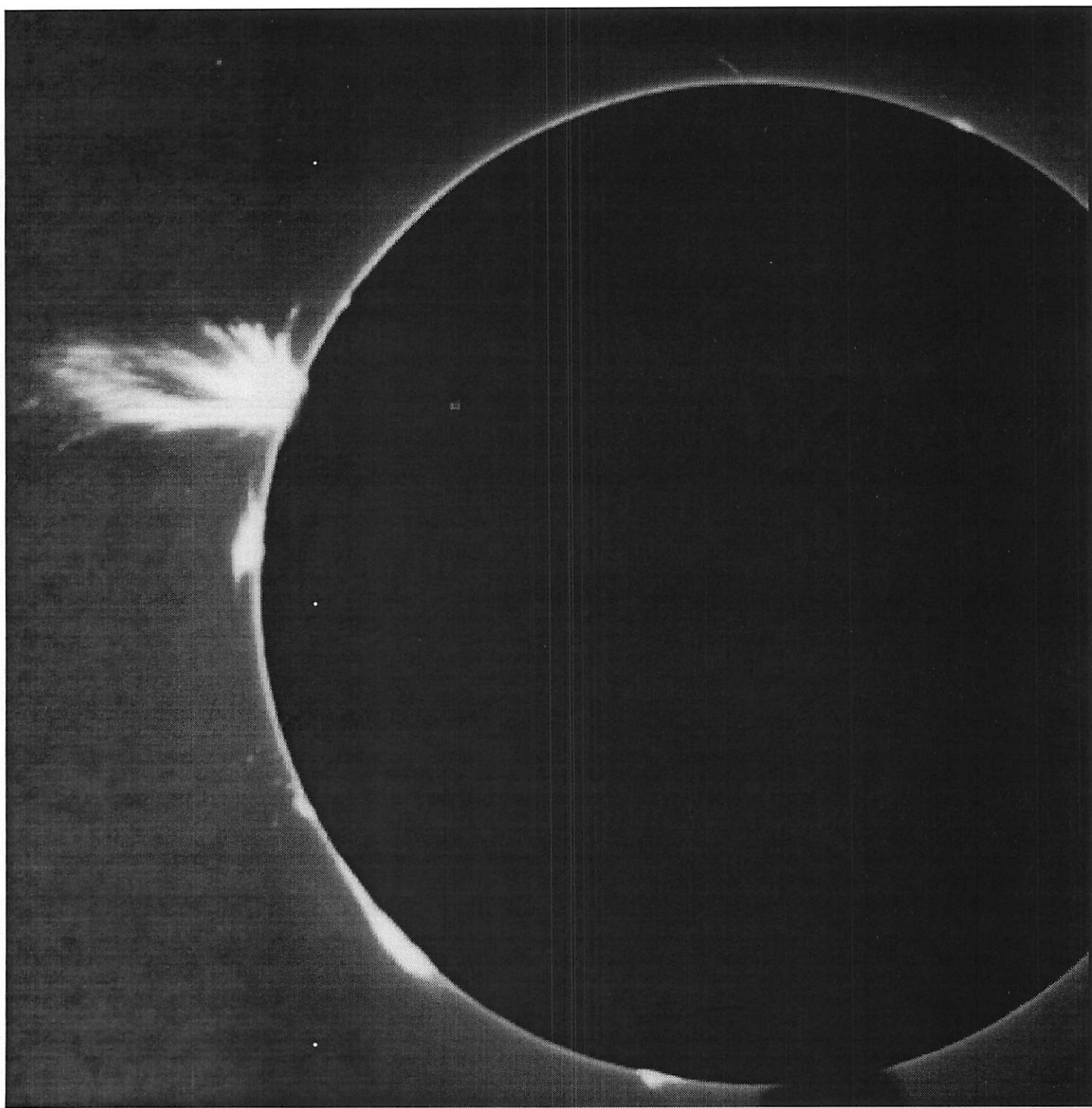


Figure 26. Ejection of H-alpha emitting material from flare of Figure 25 (seen in image with longer exposure).

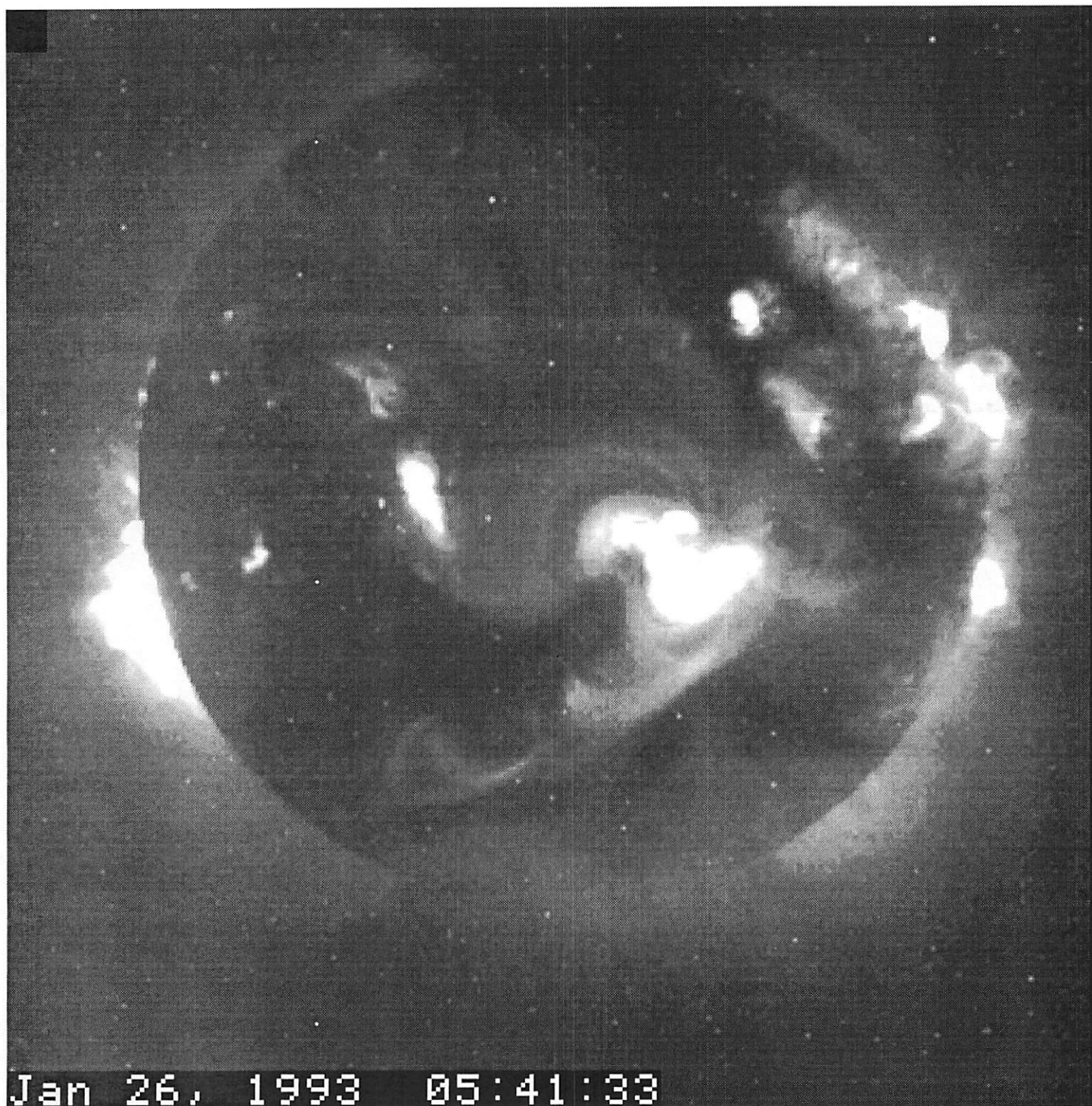


Figure 27. Yohkoh image of the sun in soft X-rays at 0541 UT on January 26, 1993.

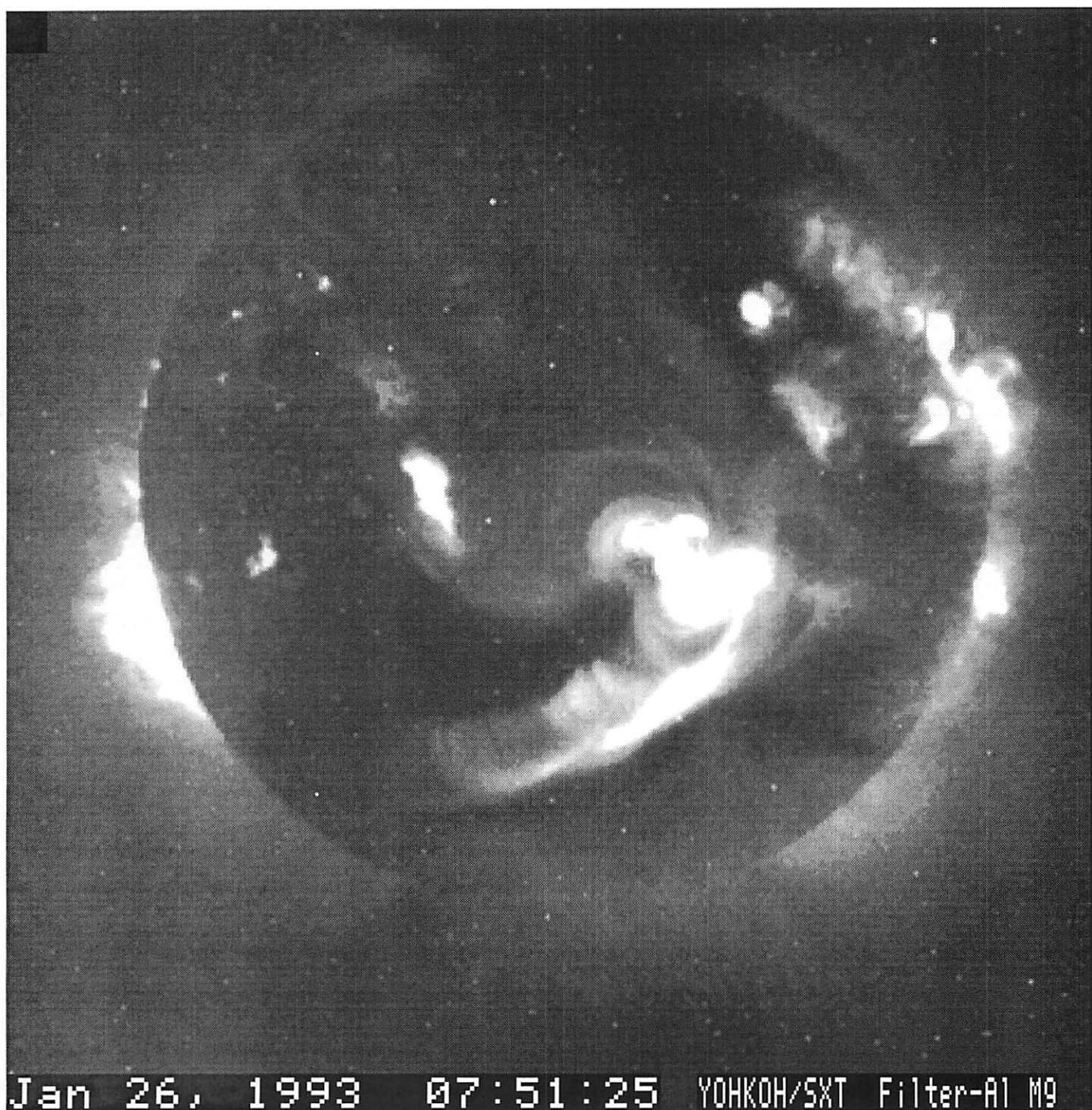


Figure 28. X-ray brightening (or flare) from Yohkoh image at 0751 UT on January 26, 1993.

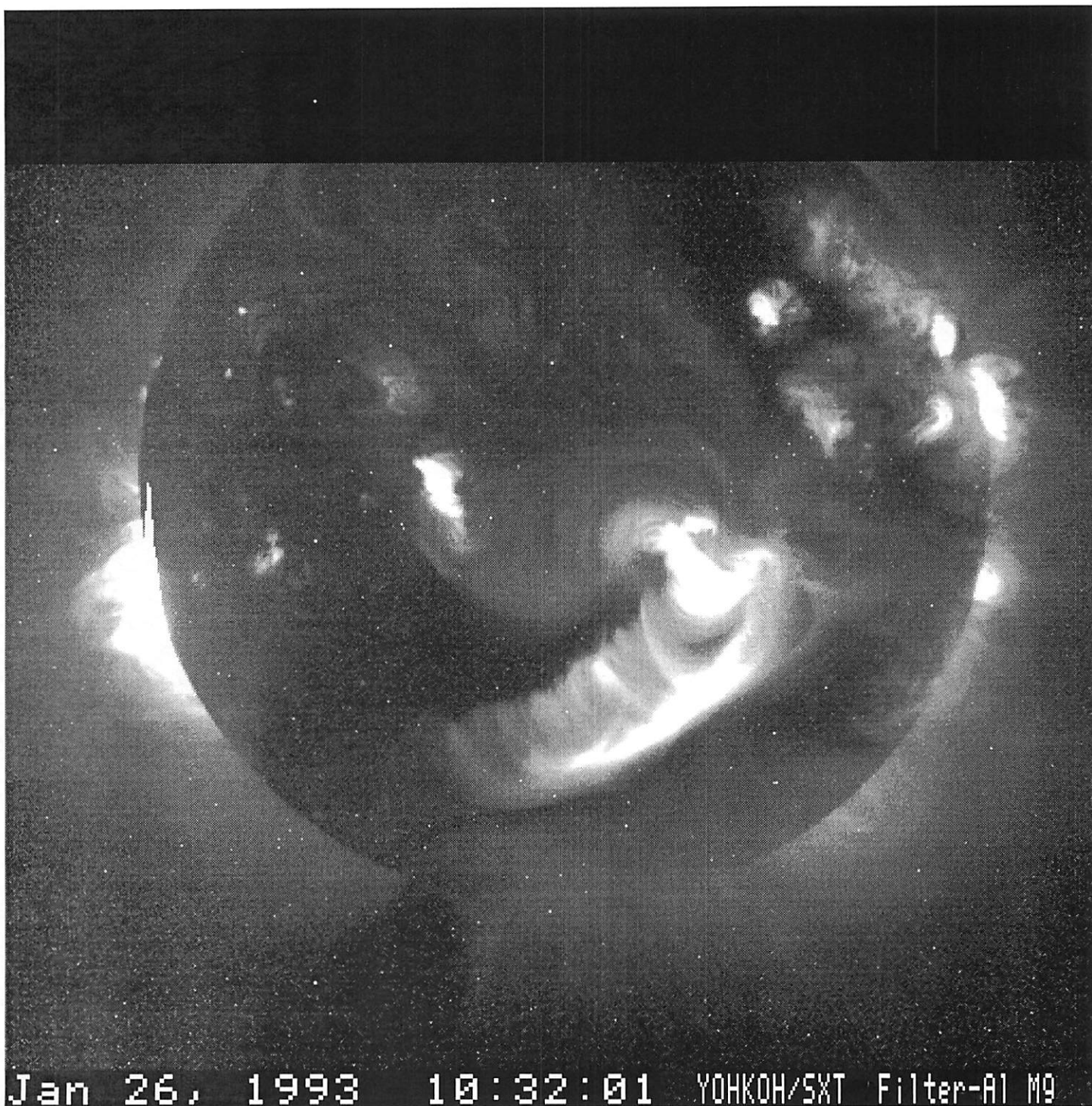


Figure 29. X-ray flare from Yohkoh image at 1032 UT on January 26, 1993.

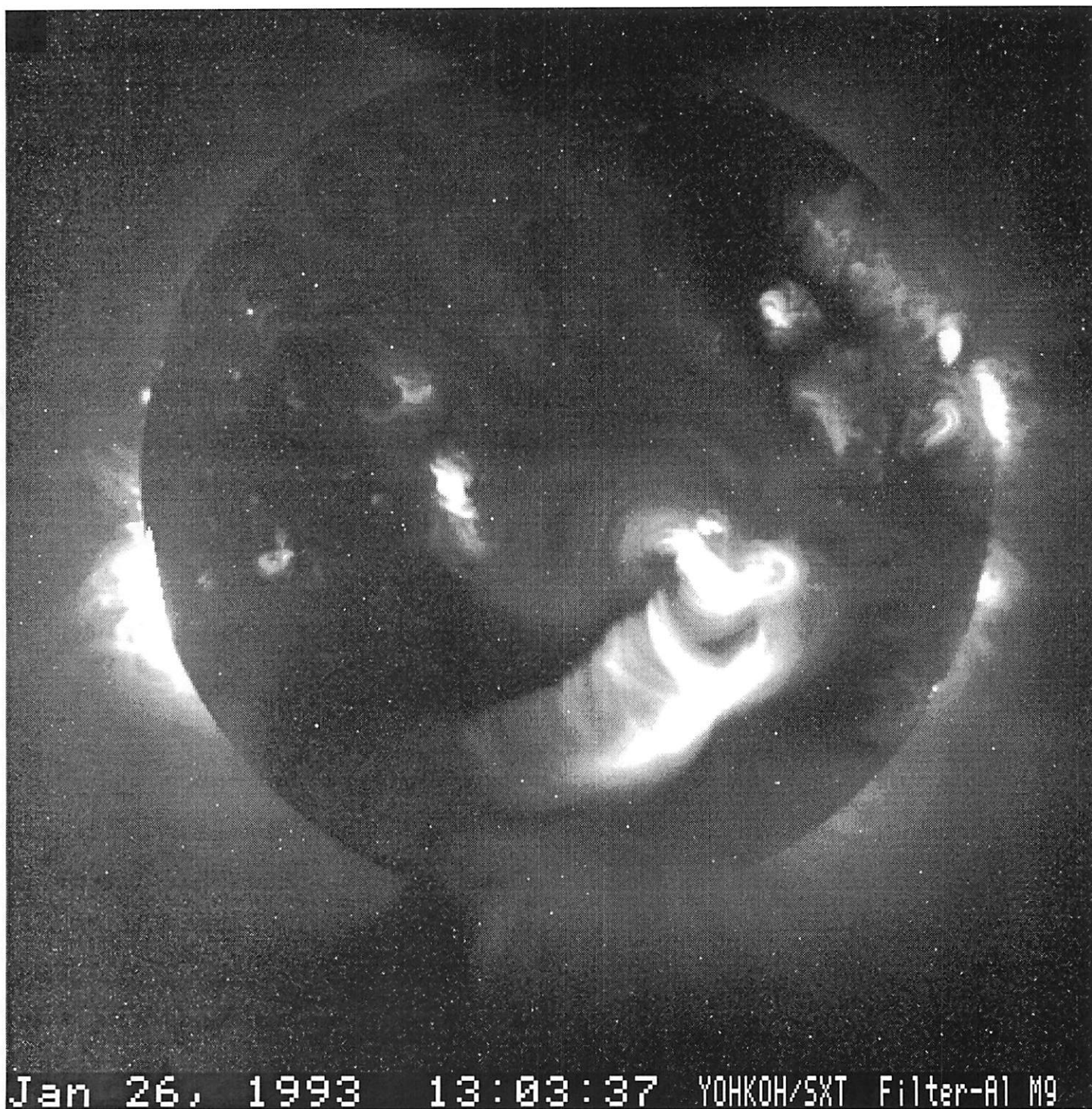


Figure 30. X-ray flare from Yohkoh image at 1303 UT on January 26, 1993.

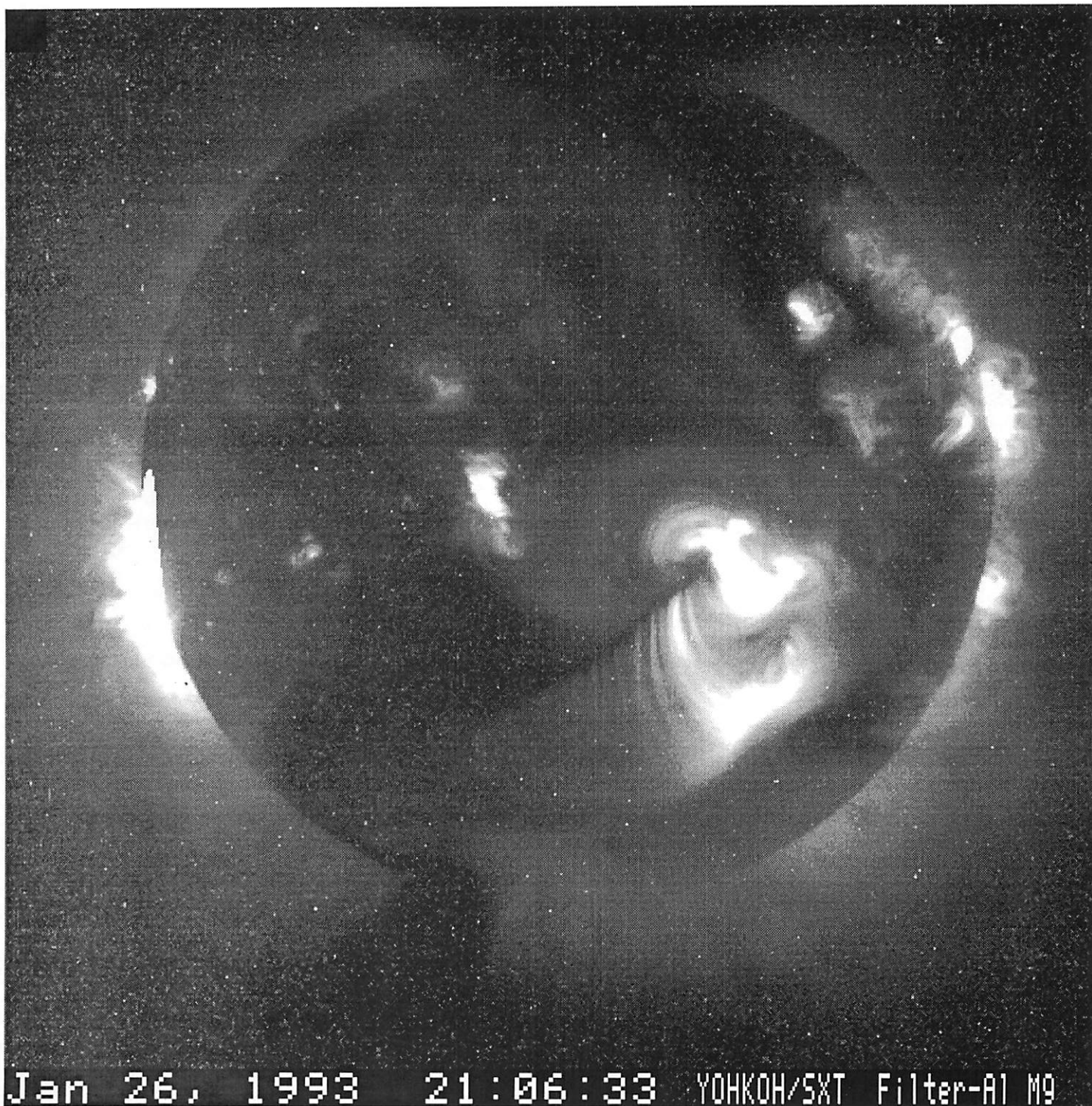


Figure 31. Fading of X-ray flare from Yohkoh image at 2106 UT on January 26, 1993.

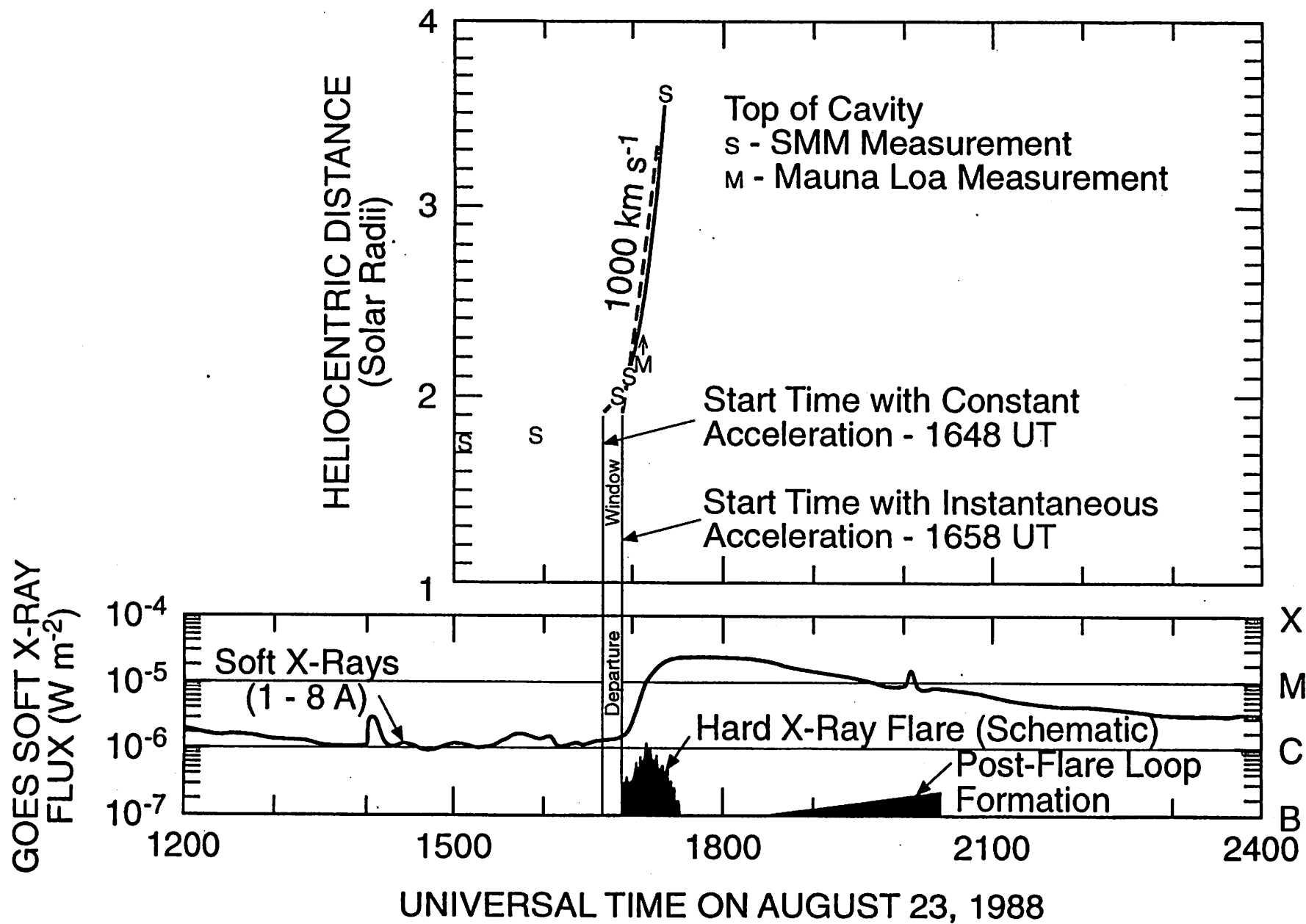


Figure 32. Association of X-ray flare (brightening in flux shown in bottom frame) with observed mass ejection.

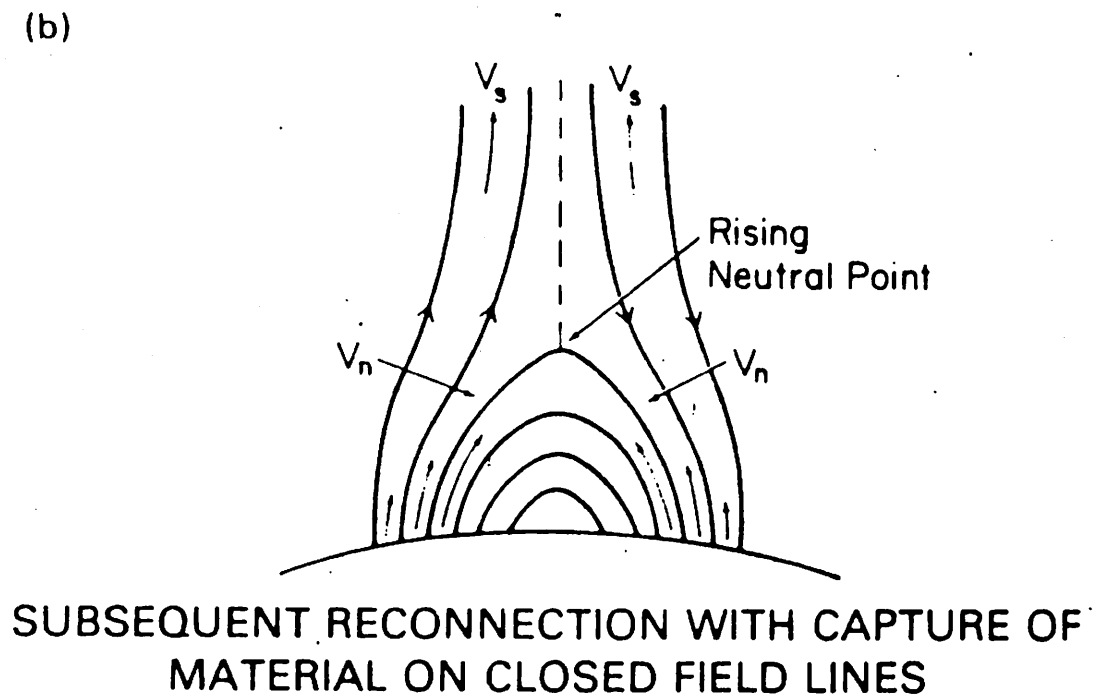
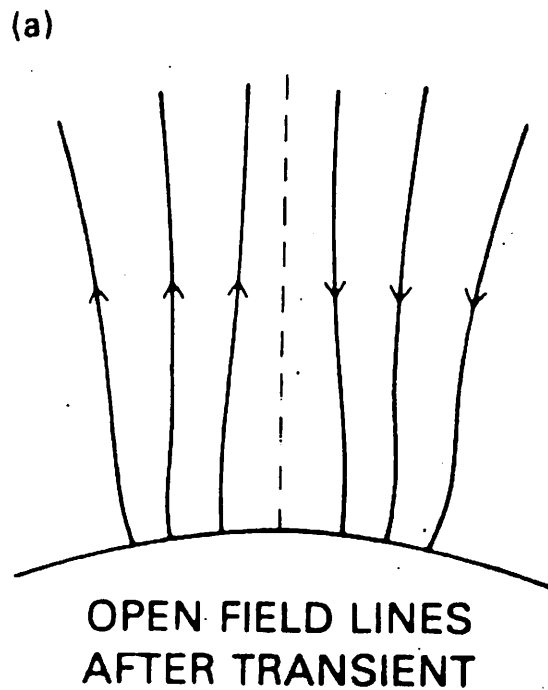


Figure 33. Kopp-Pneumom model for post-ejection flare produced by magnetic reconnection.

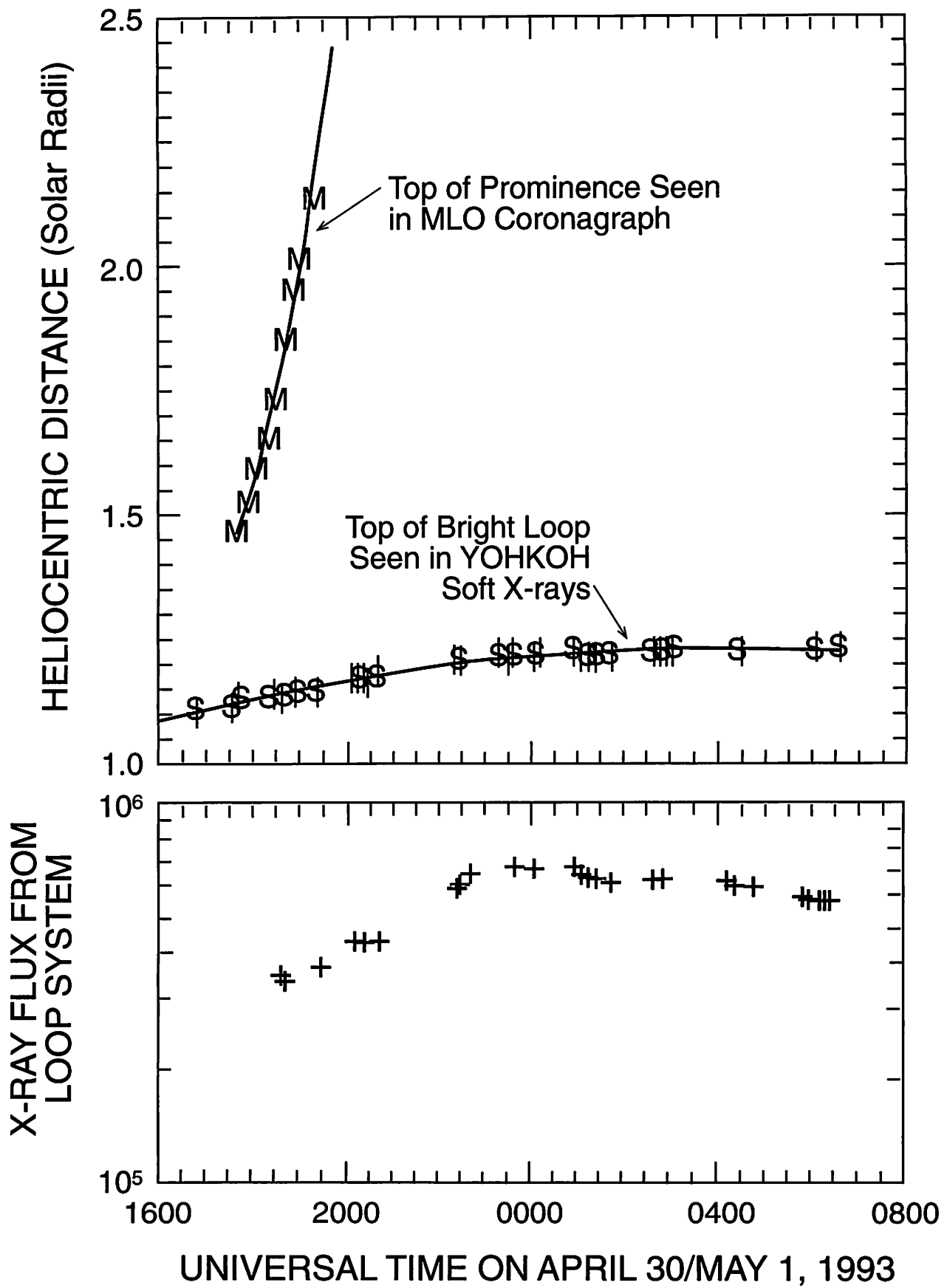
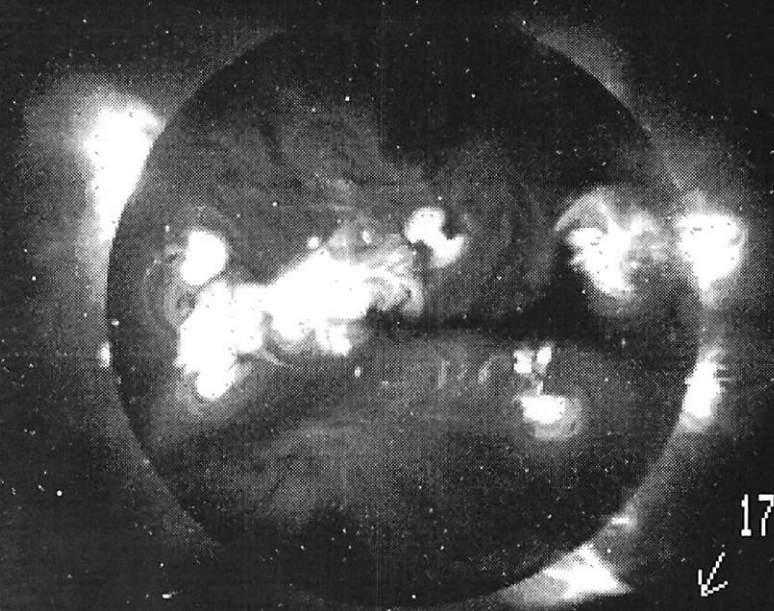


Figure 34. Timing from Yohkoh event.

YOHKOH SXT-22:28:38



17:36:10



+++++



19:13:49

Yellow crosses indicate Prominence trajectory in MK3 Coronameter

APRIL 30, 1993

Figure 35. Yohkoh image showing formation of X-ray flare as small nest of loops in region vacated by mass ejection.

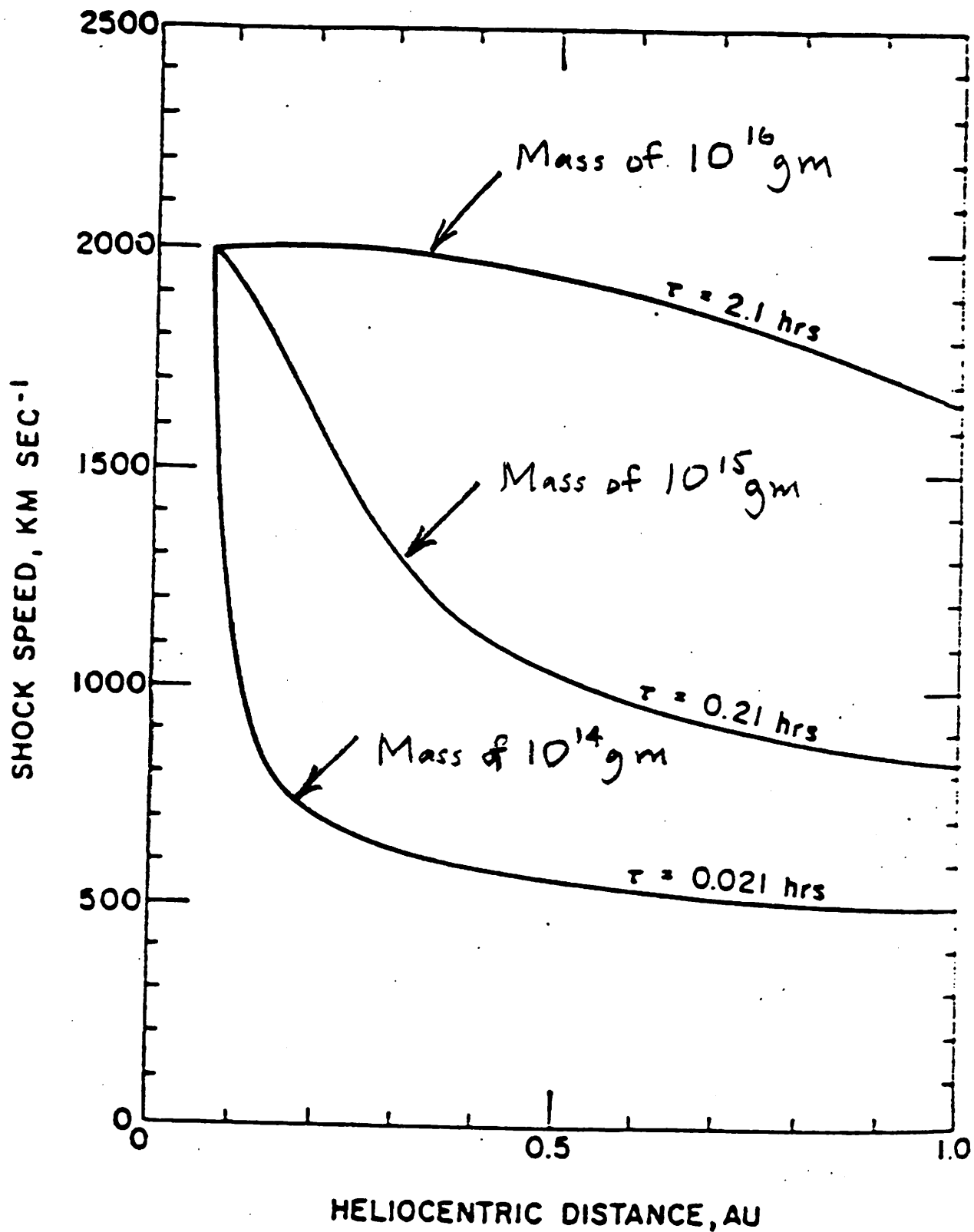


Figure 36. Propagation through the solar wind of shocks with an initial speed of 2000 km sec⁻¹, but with different masses (produced by different initiating times τ at approximately 0.1 AU).

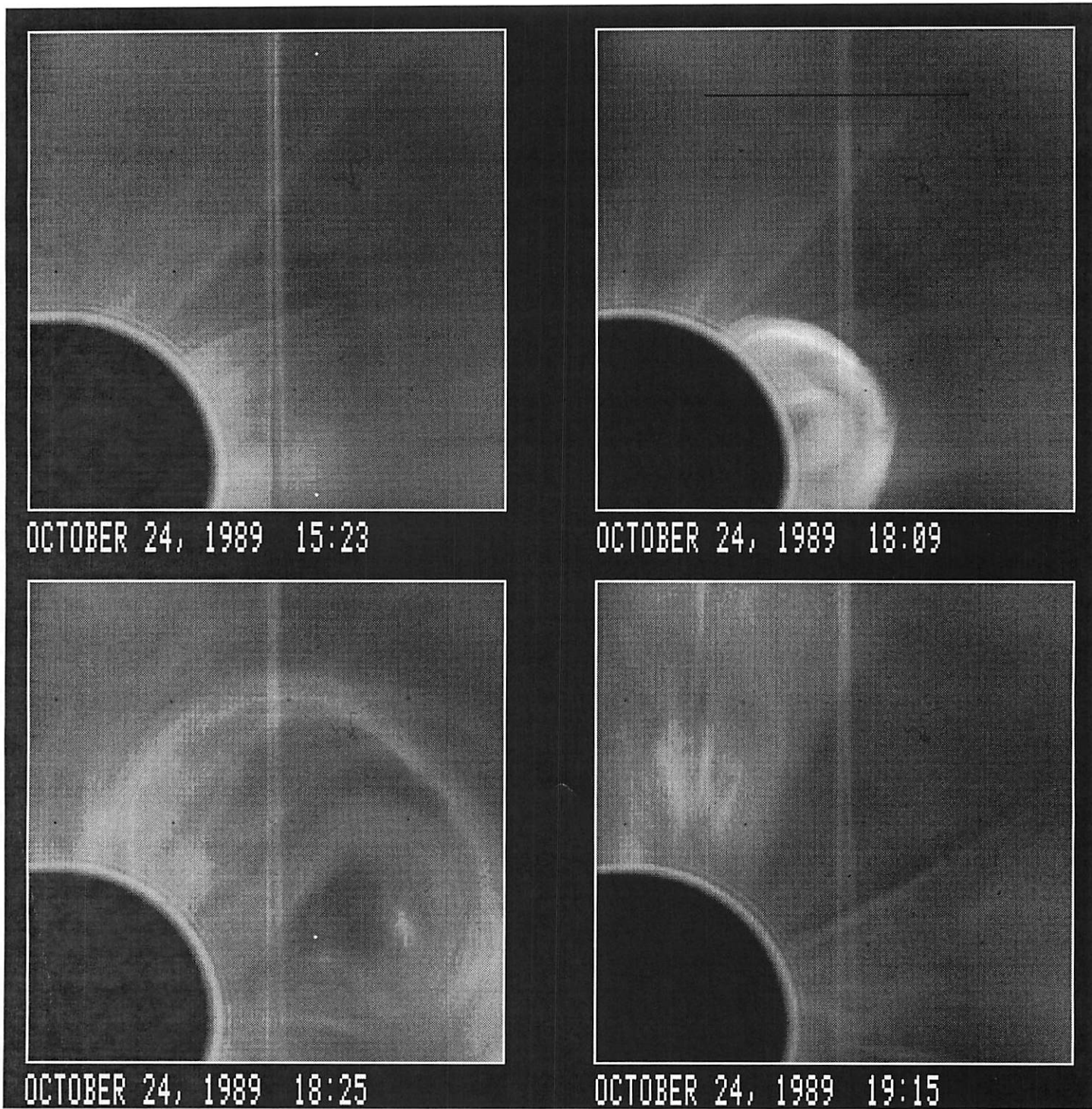


Figure 37. A very massive (10^{16} gram), fast-moving (2000 km sec⁻¹) example of a mass ejection.

27 NOV. '79 "HALO" CORONAL TRANSIENT

(PRE-EVENT IMAGE SUBTRACTED,
CONTOURS ENHANCED)

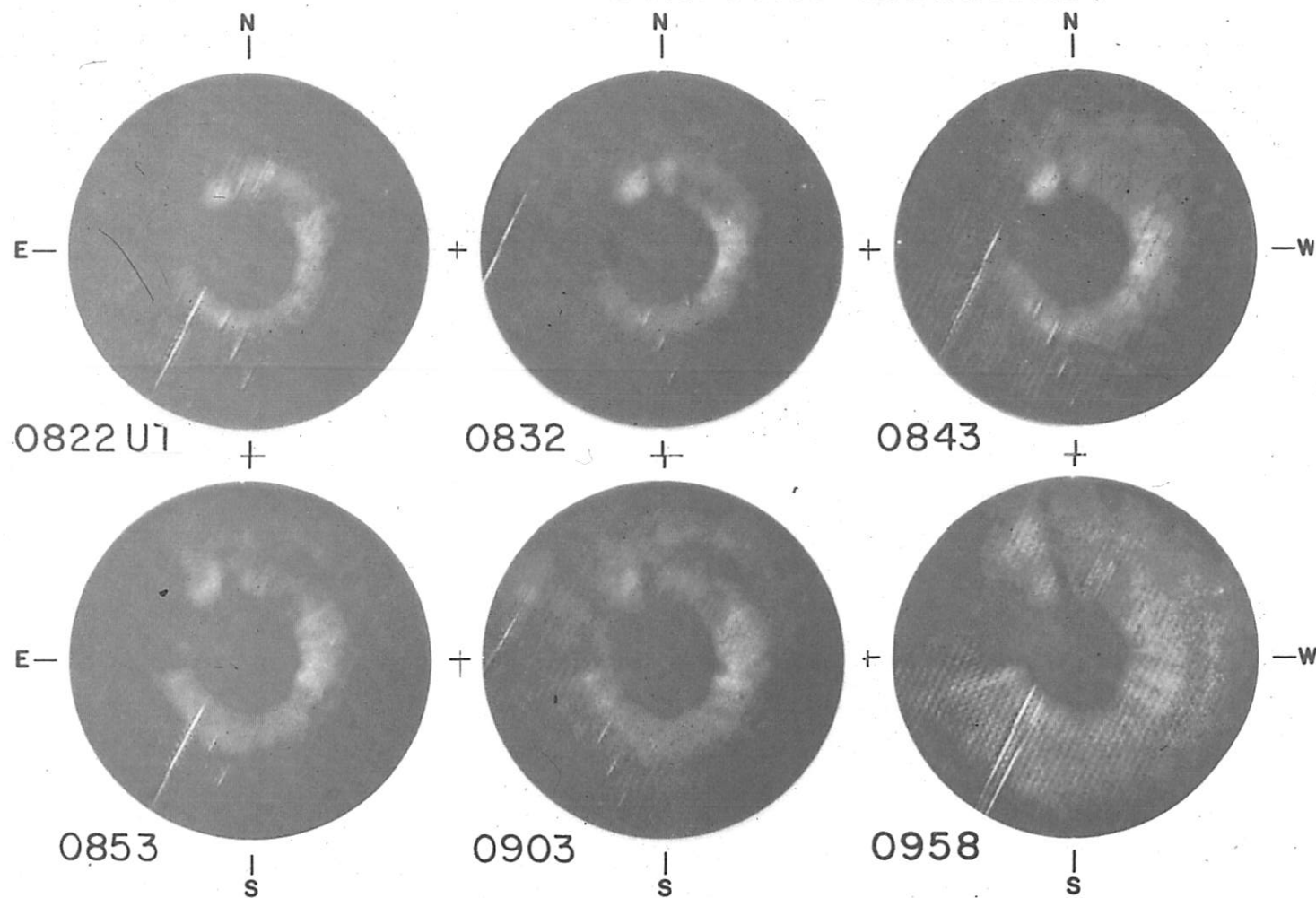


Figure 38. Solwind "Halo" ejection.

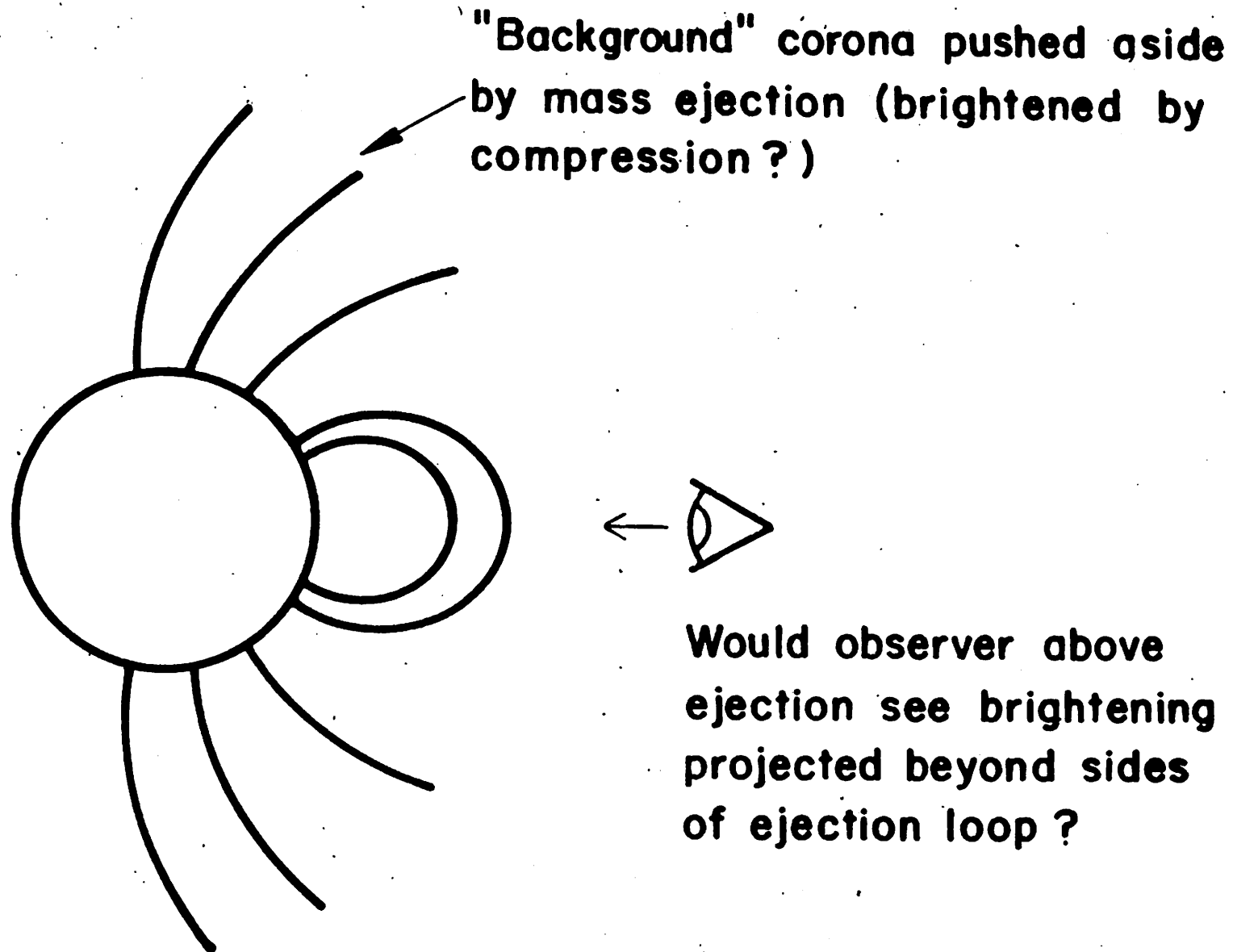


Figure 39. Geometry for halo.

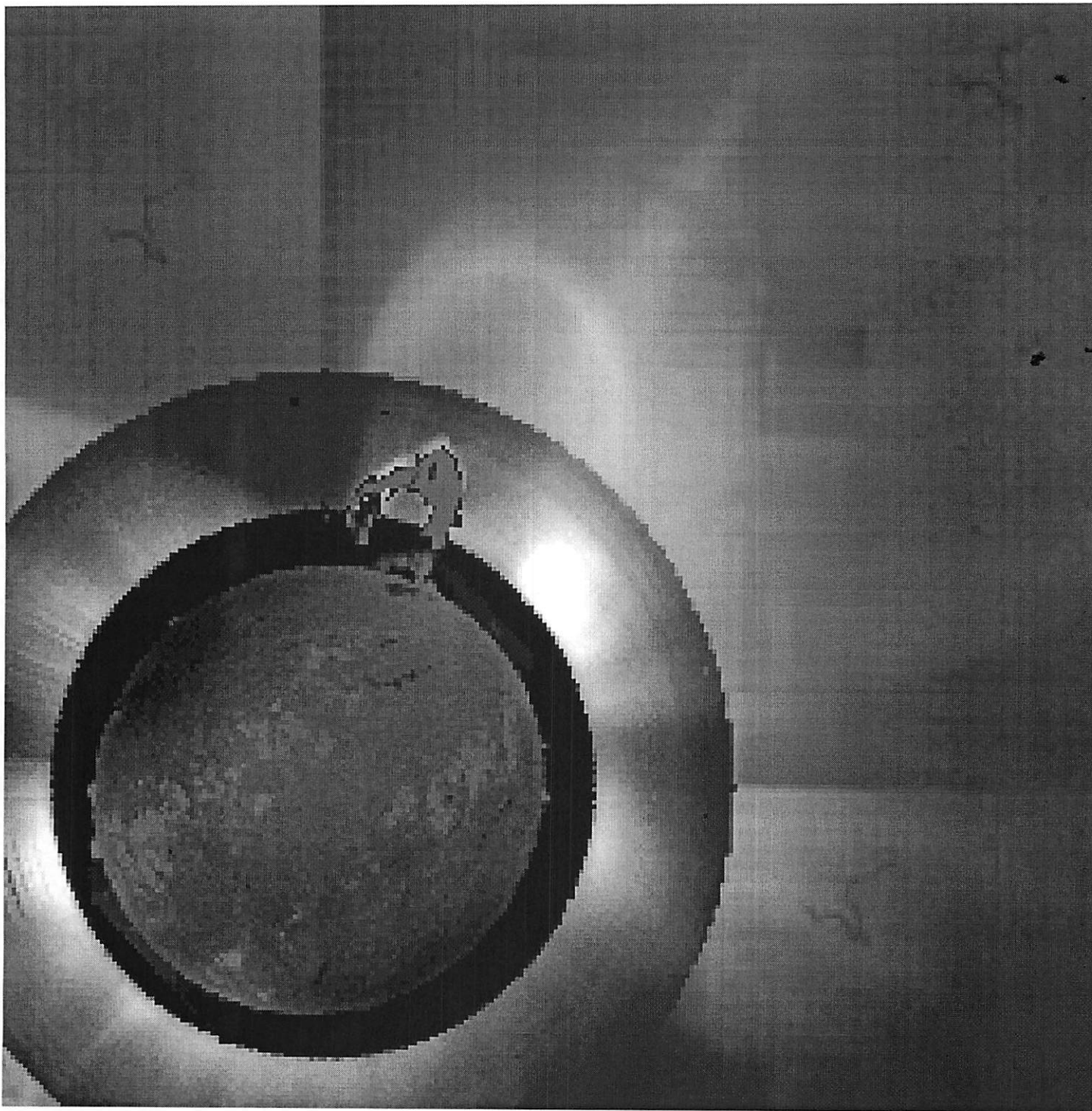


Figure 40. Mass ejection example showing eruption of a prominence beneath the "loop" of coronal plasma.

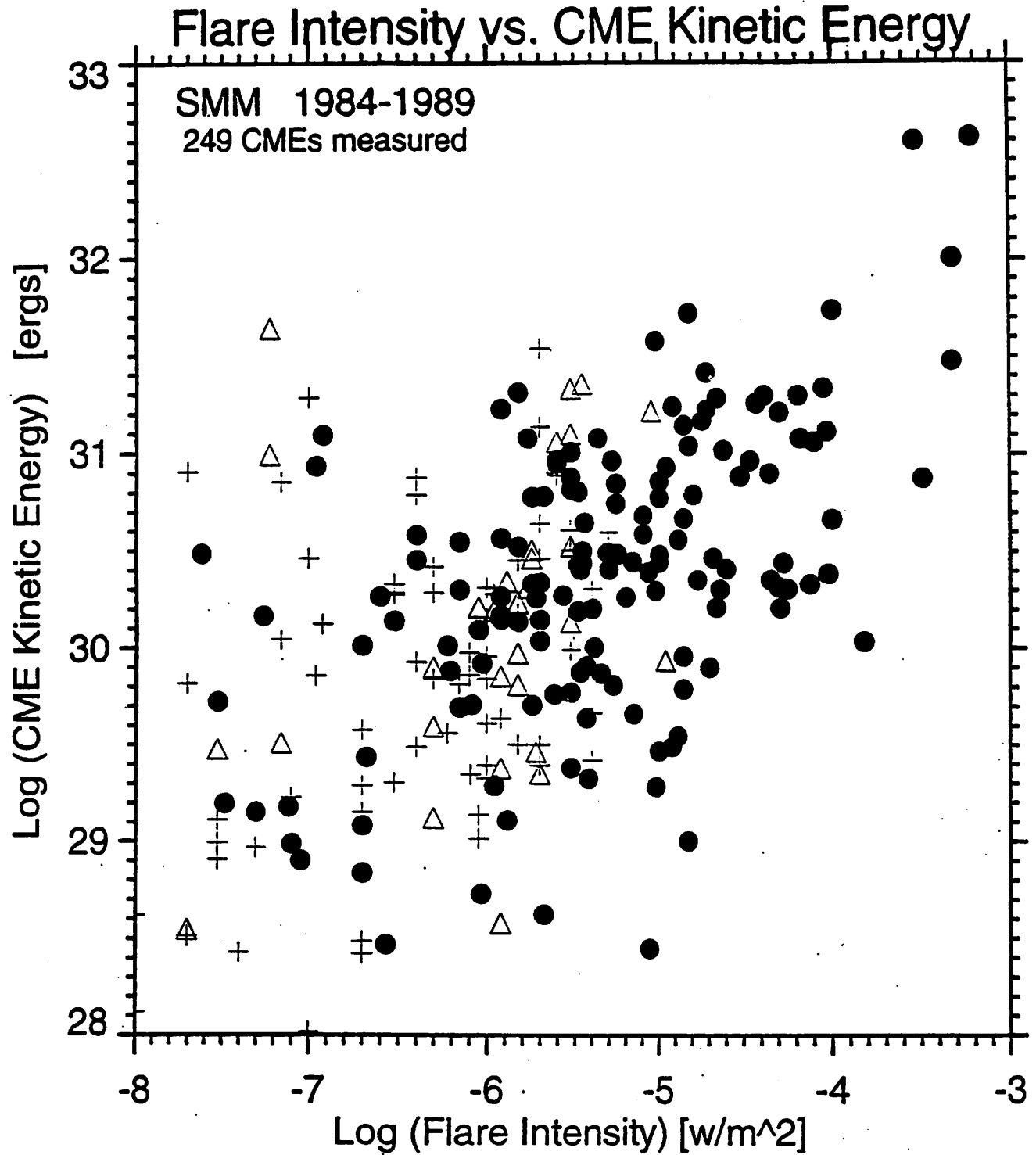


Figure 41. Flare intensities and CME energies.