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Solar coronal transients

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We generalize new data on solar coronal transients (CTs) and associated phenomena. In this review we describe general information about CTs and methods of observing them and detail the following problems: differences in CT data obtained by the P78-1 and SMM earth satellites; the relationship between a CT, a precursor, and a flare; the eruption of filaments (prominences) and the initial phase of CT formation; radio emission from CTs; CTs and the concluding phase of a flare; model representations of CTs; CTs and slow shocks; variations of CT parameters with the phase of the activity cycle; CTs and the evolution of the corona; the three-dimensional structure of CTs; interplanetary manifestations of CTs; CTs from flares and disappearing filaments—a unified spectrum of solar eruptive phenomena.

Coronal transients (CTs) or coronal mass ejections (CMEs) are large-scale ejections into the corona of discrete formations of magnetized plasma. These ejections occur with a characteristic time of tens of minutes to several hours, have sizes of several $R_\odot$ and velocities of from tens to 2000 km/sec, and contain a large amount of matter (10^{15}-10^{16} g). They are associated with flares (F transients) and flare-like phenomena like eruptive prominences or disappearing filaments (EP transients).

It has recently become increasingly obvious that CTs are one of the fundamental manifestations of solar activity and an extremely important link in the system of solar–terrestrial relationships (see, e.g., Refs. 1-3). They contain most of the energy liberated in flares. It is impossible to imagine the scenario for a large flare as a whole, in accordance with modern experimental data, without the inclusion of a CT as one of its main elements. The ascent of a CT in the corona is accompanied by a pronounced reorganization of the magnetic field and many associated effects. Coronal transients are an important component of the overall evolution of the corona and its individual structures. As they propagate from the sun, CTs change into interplanetary disturbances (magnetic clouds and shocks) and may ultimately result in geomagnetic storms. Moreover, CTs play an important role in solar proton events, providing for the escape and perhaps for the acceleration (reacceleration) of energetic particles that are observed in interplanetary space and determine the radiation environment in near-earth space, as well as the conditions for shortwave radio communication in the polar regions.

It is not surprising that many dozens of papers have been devoted to the investigation of CTs in the world literature. In such a situation, it becomes timely to generalize data on CTs and to analyze the conditions of their origin and propagation, particularly on the basis of studies of the dynamics of active regions and magnetic fields on the sun, as well as the electromagnetic radiation associated with CTs.

One of the reviews devoted to CTs and associated phenomena was compiled in 1985.[4] In it we described the methods of observing CTs, their shape and main parameters (velocity, mass, and angular size), the properties of F and EP transients, features of their radio emission and its relationships to other phenomena, CT models, the results of an analysis during the Solar Maximum Year, interplanetary manifestations of CTs, etc. The present paper is essentially a continuation of that review in the form of brief answers to the question of what new has been learned about CTs in recent years. This is preceded by a section containing general information about CTs. We devote principal attention to the analysis of experimental data. We can discuss only the most important aspects in a short review, of course. We must particularly emphasize that the data given below must not be treated as some conclusive results with a universal nature. We are most often discussing relationships discovered in the course of research, far from complete and based in some cases on an analysis of relatively few events. Additional information about recent results on CTs can be found, e.g., in Refs. 5-10 and 108 and the literature cited therein.

1. GENERAL INFORMATION ON CTS

We briefly recall the main characteristics of CTs and methods of their observation (see Ref. 4 and the bibliography given there). Observations in white light, using coronagraphs on near-earth spacecraft, are the main source of information on CTs. They are detected as formations, moving away from the sun, of enhanced brightness owing to Thomson scattering of photospheric light by free electrons contained in eruptive plasma structures with an excess density. Such observations have now been carried out with four instruments on the OSO-7, P78-1, and SMM earth satellites and the *Skylab* station.

Data obtained with orbiting coronagraphs enable us to trace CT motion at heliocentric distances from $r \sim 1.5$-$2.6\ R_\odot$ to $r \sim 6$-$10\ R_\odot$. In coronal regions closer to the sun, CTs are observed using ground-based optical instruments, particularly the Mark III K coronagraph of Mauna Loa Observatory (Hawaii) with a field of view at $r \sim 1.2$-$2.0\ R_\odot$, and the monochromatic coronagraph of Sacramento Peak Observatory, providing images in a number of lines at $r \sim 1.15$-$1.55\ R_\odot$. A typical picture of a CT, enabling one to judge the considerable scale and the structure of these grandiose phenomena, is shown in Fig. 1.

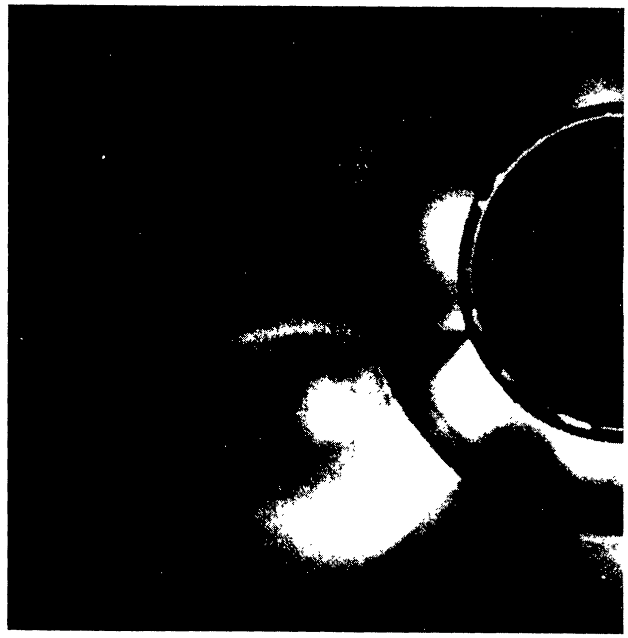

FIG. 1. Combined image of a three-component, loop-shaped CT on 5 August 1980 ($\sim 19^h59^m$ UT) based on the coronagraph polarimeter on the SMM ($r > 1.7\ R_\odot$) and the K coronagraph ($1.2\ R_\odot < r < 1.7\ R_\odot$) and the H$\alpha$ coronagraph ($1\ R_\odot < r < 1.2\ R_\odot$) at Mauna Loa Observatory.[8]

It turns out to be very fruitful to use optical observations combined with broadband radio spectrographs and the largest radio heliographs in the meter range. The latter make it possible to obtain radio images of CTs at a number of frequencies with a spatial resolution of several arcmin, providing a considerable advance in the study of the entire complex of phenomena associated with CTs, including the mechanisms generating the various types of radio bursts that accompany them.

At larger distances from the sun ($r > 10\ R_\odot$), CTs appear as propagating interplanetary disturbances and are observed by means of their low-frequency radio emission (e.g., as slowly drifting type II bursts at $f < 2$ MHz), using radio transillumination by signals from artificial and natural sources, using the zodiacal light photometers on the *Helios* spacecraft, by direct measurements of the parameters of the interplanetary plasma on spacecraft and earth satellites, and based on the effects produced by those disturbances in the earth's magnetosphere.

Many CTs observed in white light have the form of an expanding loop or bubble occupying a range of position angles of several dozen degrees in the plane of the sky. In many cases a system or arcade of loops is detected rather than one. The heated matter of an eruptive prominence is often seen inside a loop-shaped CT. Single, double, or multiple wedges (spikes) are a very common form of CT. There are CTs of the fan type, a curved front, diffuse amorphous clouds, a luminous quadrant, a radial tongue, a "blown-off" coronal ray, and of the "halo" type. The latter variety is observed as an expanding emission region around the entire eclipsing screen of the coronagraph and is interpreted as a three-dimensional CT traveling along the line of sight, toward the earth, in particular. Albeit, some contribution to the increase and variation of white light brightness in such events may come from the deflection and compression of existing coronal structures by a propagating CT.[11]

Depending on the nature of the events with which CTs are associated, they are divided into two classes: a) flare F transients, i.e., CTs associated, as a rule, with prolonged, unpulsed flares having a complicated space–time structure; b) EP transients, which are observed after the eruption of prominences or the disappearance of dark Hα filaments located outside of active regions. It should be noted that CTs of both classes have the same nature (see below). The eruption of a prominence in a flare is also a most important factor for CT formation.[12] Flare F transients carry more mass into the outer corona, have a higher velocity, and are more energetic, on the whole, than nonflare EP transients. According to existing estimates, the energy of F transients can reach 10^{31}-10^{32} erg, which is most of the energy of a large flare, with magnetic energy being the dominant form of CT energy.

The eruption of a CT is accompanied by varied electromagnetic radiation. Long-duration events (LDEs) predominate in soft x rays. At centimeter wavelengths, the accompanying events range from relatively weak emission of the "gradual rise and decay" type to large, prolonged microwave bursts. Drifting enhancements of a noise storm or weak type IV bursts are often detected in the meter range in association with EP transients. The radio emission of F transients can include type II bursts associated with shocks, which often propagate inside a CT rather than at its front, as radio heliograph measurements have shown, as well as stationary and moving type IV bursts, whose sources are located at the bases of loop-shaped CTs or in moving bright (dense) elements of CTs, respectively. The generation of type IV radio bursts is due to plasma or gyrosynchrotron emission from accelerated electrons (see Ref. 4 for more details).

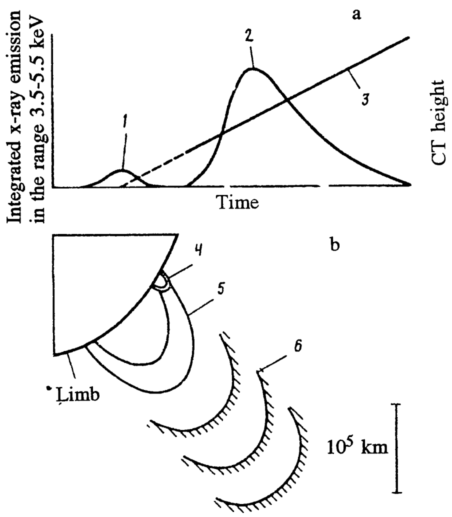

FIG. 2. Idealized picture of the temporal (a) and spatial (b) relationship between a precursor in the soft x-ray, a CT, and a flare:[14] 1) precursor; 2) flare; 3) height–time trajectory of the CT; 4) site of the flare; 5) arch of the precursor; 6) CT.

2. CTS, PRECURSORS, AND FLARES

An investigation of the following question is of great importance for clarifying the nature of both flares and CTs: is a CT the result of flare energy release or can a CT erupt independently of a flare and even stimulate one? Increasing evidence has recently been found that events exist in which CT eruption precedes the pulsed phase of a flare and is the cause rather than a consequence of the flare, on the whole.

A comparison of data on a number of events from the x-ray photometer (range 3.5-30 keV; spatial resolution down to 8″) and the coronagraph polarimeter on the SMM satellite showed that a CT originates at the time of a weak precursor in the soft x-ray, which precedes the pulsed phase of the flare by 10-30 min (Refs. 9 and 13). Such a conclusion was first drawn on the basis of the extrapolation of one-dimensional CT trajectories in the height–time plane to the photosphere level[14] (Fig. 2). Here the pulsed phase was determined from the time of an abrupt rise in x-ray or microwave radiation, and the CT velocity was assumed to be constant. Allowance for CT acceleration at small heights does not rule out but, on the contrary, strengthens the conclusion that the transient is formed before the flare.

A further analysis showed that the x-ray precursor and the newborn CT display not only a temporal but also a spatial relationship.[15,16] Judging from x-ray heliograms, precursors are observed in double sources, separated by $\simeq 10^5$ km, and they produce an arched system of equal or larger extent. As a result of the destabilization, ascent, and expansion of the large arc of the x-ray precursor, a CT is detected first by a ground-based coronagraph and than by an orbital coronagraph in white light. In other words, the CT develops from the large loop of the precursor. Here the arc of the x-ray precursor and the CT loop have similar spatial locations in position angle, a similar configuration, and the same angular sizes (Fig. 2). It is significant that the flare that follows the x-ray precursor occurs mainly near one base of the precursor's arc and has the shape of a small loop ($\sim 10^4$ km) in the x-ray. At this time the mass ejection reaches $\sim 0.5\ R_\odot$ above the photosphere.

Flare precursors with similar time profiles are observed not only in the soft x-ray[17,18] but also in the centimeter-wave range.[19,20] Moreover, cases were recorded by the *Helios* spacecraft in which a precursor in the form of a weak rise in the flux of electrons with energies $E > 1$-2 MeV and protons with energies of several dozen MeV was observed 1-3 h before an abrupt rise in the fluxes of energetic particles from a flare with gamma-ray lines.[21] This means that particle acceleration occurs for a long period before the pulsed phase of a flare, during the development of the precursor. In this connection, we can assume that the emission from the precursor is nonthermal, on the whole, and the precursor in the soft x-ray is the result of plasma heating by accelerated particles.

How typical this picture of the relationship between the precursor, CT, and flare is remains an open question, and many of its details are still unclear. There are data indicating that such a scenario occurs in many flares. In particular, Harrison[15] has established, from an analysis of 48 events, that considerable asymmetry of the loop-shaped transient relative to the flare is observed in ~81% of cases (also see Ref. 13). This means that often a flare actually occurs near one base of the CT loop; in ~65% of cases, the flare occurs at the loop base nearer to the equator. Incidentally, the validity of such a procedure for estimating the mutual positions of the precursor loop and the source of flare energy liberation is disputed in Ref. 22.

The starting phase of a CT has been investigated in detail in Ref. 23 using observations of the lower corona at heights up $0.2\ R_\odot$ above the photosphere using the K coronagraph at Mauna Loa Observatory. In 1985-1987, a special program of coordinated x-ray and optical observations of the birth phase of CTs and their relationship to flares was carried out using the SMM satellite.[24] On the whole, the results support the conclusion that CTs may originate before the pulsed phase, close to the time of the x-ray precursor, and the subsequent flare brightening is located near one base of the loop-shaped CT structure.

In evaluating these data, as well as those given in subsequent sections pertaining to the "CT–flare" problem, one must bear in mind, however, that the flares observed up to now in the indicated experiments have been relatively simple in structure and of low intensity. In large flares with a well-developed space–time structure, a more complicated relationship obviously occurs between CT eruption and flare energy liberation. Moreover, as an analysis shows (see below, as well as Ref. 4), there are numerous so-called pulsed flares that often display no relationship at all to CTs. On the other hand, an extensive class of events is known in which CTs are observed following the disappearance of Hα filaments and are not accompanied by explosive energy liberation.

3. INITIAL PHASE OF CT FORMATION

In those cases in which CT origin is associated with the eruption of a prominence, the formation of the CT may begin with the ascent into the lower corona of a tenuous cavity surrounding the prominence (filament), and the eruption of the filament itself and the ensuing pulsed phase of the flare are the result rather than the trigger for this process.[6,7]

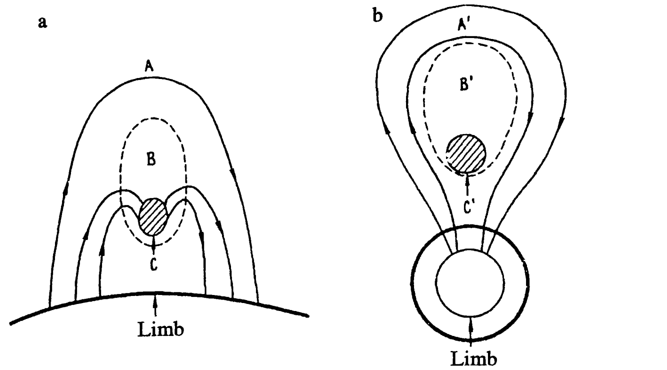

FIG. 3. Diagram illustrating the relationship between the structures of an eruptive prominence (a) and a CT (b) (Ref. 7): A) magnetic field lines above the prominence; B) cavity of the prominence; C) filament; A′) loop of the CT; B′) cavity of the CT; C′) bright core of the CT.

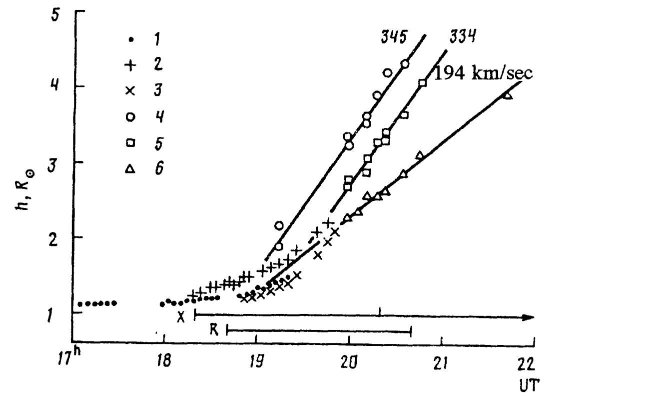

FIG. 4. Height−time trajectories of three components of an eruptive prominence [1) frontal layer; 2) dark cavity; 3) core] and a CT [4) loop; 5) upper edge of the cavity; 6) bright inner core] based on observations on 5 August 1980 with a ground-based K coronameter and the SMM coronagraph.[25] The time intervals of soft x-ray (X) and microwave (R) bursts are shown at the bottom.

This fundamental conclusion is also based on observations of the initial stage of CT development in the lower corona with a ground-based K coronameter and Hα coronagraph in combination with the satellite white-light coronagraph on SMM. Both F and EP transients are primarily detected as a moving cavity, i.e., a region of reduced density, surrounding a filament. Its ascent into the corona is accompanied by entrainment of magnetized plasma and the ascent of the prominence, on the one hand, and by sweeping up of overlying plasma and the resulting formation of a bright frontal layer of increased density, on the other.

There is a quite definite correspondence between elements of the typical three-component CT structure in the lower corona and at large heights (Figs. 1, 3, and 4): the tenuous cavity is observed as the inner dark part of the CT; the eruptive prominence submerged in it changes into the bright dense core of the CT, while the frontal layer of plasma, displaced by the movement of the cavity, is transformed into the main loop of the transient.[25] The dark cavity not only begins to rise earlier than the prominence, but at a higher velocity. The onset of eruptive motion of the filament (prominence), in turn, is considerably ahead of the pulsed phase of the flare. According to Ref. 26, the eruption occurs in the form of gradual smooth acceleration, which (and this is especially important) is not accompanied by any abrupt, discontinuous velocity changes during the pulsed phase. The eruption of a prominence may be preceded by its oscillations, associated with plasma heating, for example, and manifested in preflare variations in x-ray and microwave emission.[27]

4. MODEL CONCEPTS

The combination of the data given in the two preceding sections raises the question of the universality of the very popular belief that the ejection of a CT is the response to explosive energy liberation during the pulsed phase of a flare.[28,29] Strong experimental bases are being found for the concepts that CT eruption results from an overall disruption of the equilibrium of the evolving magnetosphere above an active region, its individual structures, or a more extensive region of the corona, and the flare, particularly the pulsed energy liberation, occurs after the ascent of the CT and is even initiated by it.[10,30-32]

Possible reasons for the disruption of equilibrium may be the upwelling of magnetic flux or of individual magnetic islands, motion of the bases of coronal loops, the formation of magnetic shear configurations, and other pronounced changes in the magnetic field at the photosphere, as well as the buildup of electric current in a filament to the critical value, heating of coronal arches, the evolution of higher coronal structures, MHD disturbances from activity in neighboring regions, etc.[10,33-37] Some of these processes are usually treated as possible factors associated with the origin of flares (see Refs. 1, 38, and 39).

One version of such a scenario, which applies to both F and EP transients, has been considered in Ref. 40. Here the

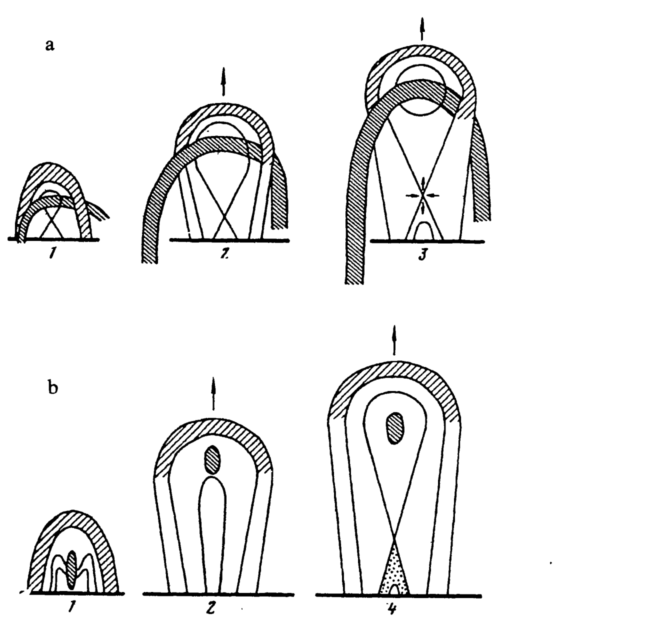

FIG. 5. Model explaining the eruption of a filament and a CT as the result of disruption of the equilibrium of magnetic structures with the subsequent formation of a reconnection region for a filament outside of an active region (a) and within an active region (b). 1) Equilibrium state; 2) CT eruption; 3) onset of reconnection; 4) reconnection and postflare loops.[40]

disruption of equilibrium, eruption of the three-component cavity–dome-shaped prominence–CT system associated with the magnetic field, and its ascent in the corona lead to the drawing out of field lines and thereby create the conditions for magnetic reconnection in the region below the prominence, i.e., they initiate flare energy liberation (Fig. 5).

According to Ref. 41, CT eruption can also be a consequence of the evolution of coronal rays, particularly the nonsteady nature of magnetic reconnection in a vertical current sheet at the axis of a coronal ray. At a certain stage, the electron velocity in the current sheet of a sufficiently high ("old") coronal ray exceeds the critical value. As a result, instability develops, leading to rapid magnetic reconnection and separation of the upper part of the coronal ray, which is identified with certain varieties of CTs. Such events are actually observed in the form of so-called disconnection events.[42] It is significant that in the model in Ref. 41, the large-scale magnetic field configuration in the corona is represented as a system of interacting coronal rays. Owing to such interaction, the eruption of a high coronal ray can initiate flare energy liberation in the current sheet of a neighboring, lower ("younger") coronal ray and simultaneously involve considerable regions of the corona in the eruption.

The solution to the problem of the origin of CTs and their relationship to flares and eruptive prominences, of course, requires both new experimental data and a more detailed analysis of theoretical models. A more detailed survey of model concepts of CT origin has been given in Ref. 109.

5. RADIO EMISSION FROM CTS

New support for the picture of CT development described above and data on features of the associated radio emission have been obtained from observations of a number of specific events using radio heliographs in the meter range. Since observations with the radio heliograph at Culgoora (Australia) ceased, the radio heliographs at Clark Lake (USA) and Nançay (France) have been widely used for these purposes.[43-45]

The results of such an analysis for one of the CTs recorded by the SMM satellite following its repair in 1984 are given in Fig. 6 (Ref. 46). The CT's height–time trajectory again indicates that its origin coincided in time with a precursor in the soft x-ray, which in this case preceded the pulsed phase by ~30 min. It is significant that weak type III bursts were detected in the meter range in association with the precursor, indicating the appearance of accelerated electrons at that stage. The source of the moving type IV burst is associated with the bright core of the CT, has the same velocity ($V \sim$ 360-400 km/sec), and is interpreted in this case as gyrosynchrotron emission from energetic (hundreds of keV) electrons trapped in the CT plasmoid with a magnetic field $H \sim$ 2-3 G at heights of 1-2 $R_\odot$. [In a number of other events, the plasma mechanism for generating a moving type IV burst is preferable (see Ref. 4, as well as Ref. 47).] The source of the type II burst propagated away from the CT at a far higher velocity ($V \sim$ 1000 km/sec). An analysis shows that the shock corresponding to the type II burst could not be associated directly with CT motion, but is the result of energy liberation in the pulsed phase of the flare.

Some other properties of coronal type II bursts, their herringbone structure, in particular, also indicate that most of

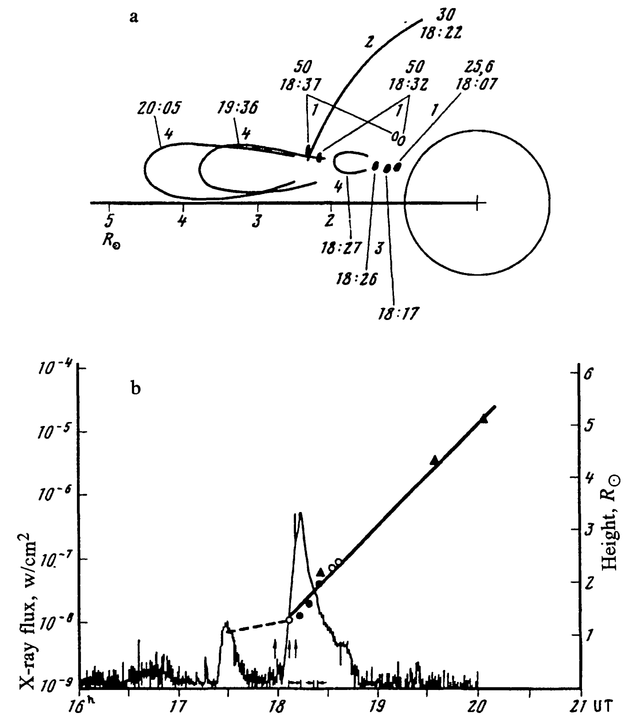

FIG. 6. Data on bursts and a CT from a flare on 27 June 1984 (Ref. 46): a) location in the plane of the sky of the sources of radio continuum (1) and type II bursts (2) at 25.6, 30, and 50 MHz relative to the eruptive prominence (3) and CT (4); b) burst with a precursor in the soft x-ray and height–time diagram indicating the position of the prominence (filled circles), the CT (triangles), and sources of type IV radio bursts (open circles).

them are initiated by explosive shocks originating during the pulsed phase.[48]

Measurements of Faraday rotation of a radio signal in the body of a CT by the transillumination method, in combination with data on the electron density in the line of sight, determined from white-light CT images, have made it possible to estimate the strength of the longitudinal magnetic field component $H_\parallel$ averaged over the line of sight.[49] The resulting fields $H_\parallel \sim$ 0.01-0.1 G (calculated for $r \sim 2.5\ R_\odot$) are far lower than the total field strength in a CT ($H \sim$ 2-4 G) that follows from the observed characteristics of type IV radio bursts. The reason for this discrepancy may be contorting or random alignment of the magnetic field vector in the body of the CT at scales considerably smaller than its thickness.

The fairly extensive observations of CTs and the associated radio bursts make it possible to analyze the relationship between different parameters of those events, rather than just their presence in one event or another. As a result of such an analysis in Ref. 50, it was found, in particular, that more intense type II bursts with a more complicated dynamical spectrum, and with decreased initial and final frequencies, are recorded predominantly in flares with CTs. The intensity (and the probability of appearance) of the type IV continuum and type II bursts increases with increasing CT velocity and angular size. These relationships are merely trends, however, and a deeper analysis is needed to determine them more accurately.

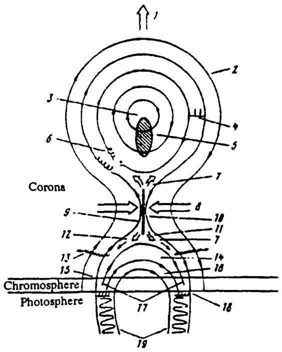

FIG. 7. Development of a large flare following the eruption of a CT and relaxation of the magnetic field in the corona with the formation of a vertical current sheet and a postflare system of loops:[53] 1) ascending CT; 2) magnetic field lines; 3) eruptive prominence; 4) shock (source of type II bursts); 5) prominence matter; 6) source of noise continuum (type IV bursts); 7) outflowing plasma; 8) inflowing plasma; 9) current sheet; 10) region of electron and proton acceleration; 11) postflare loops being formed; 12) fast electrons; 13) source of microwave emission; 14) postflare loops in the soft x-ray; 15) postflare loops in the hard x-ray; 16) postflare loops in Hα; 17) evaporation; 18) white-light flare; 19) flare ribbons.

A close relationship between the character of microwave bursts (a combination of the maximum flux density S and the effective duration d at the $0.5S$ level) and CT parameters (angular size, velocity, mass, and shape) has been found by Chertok et al.[51] Their main conclusion is that a wide spectrum of events exists with different relationships between CT eruption and flare or flare-like energy liberation, and those relationships are clearly reflected in the characteristics of the microwave (as well as soft x-ray) bursts. Large, high-velocity CTs of complicated shape are observed, as a rule, in combination with the most intense and prolonged bursts. Those CTs having average parameters and a relatively simple shape are identified with moderate unpulsed bursts of soft x-ray and microwave emission, as well as with relatively weak but prolonged radio bursts of the "gradual rise and fall" (GRF) type with no pulsed phase. Most pulsed bursts generally are not accompanied by CTs, but the most intense of them may be associated with small CTs of simple shape. These relationships can serve as a basis for electromagnetic diagnostics of CTs.

According to Ref. 22, a significant correlation (~ 0.62) is also observed between the duration of soft x-ray bursts and the angular size of CTs.

6. CTS AND THE CONCLUDING PHASE OF FLARES

Following the eruption of a large CT in the corona, various dynamical phenomena encompassing all layers of the magnetosphere above the active region continue for many hours.

The propagation of a CT significantly reorganizes the magnetic field structure in the corona. As a result, a helmet-shaped configuration is transformed into a configuration with a predominance of open field lines. So-called transient coronal holes, which are observed, e.g., in the He 10830 Å line,[52] have a lifetime up to 10-20 h, and are sources of high-velocity solar wind, are formed near a region of CT eruption.

Subsequent events are determined by the gradual relaxation of the magnetic field toward its original state. It is accomplished by magnetic reconnection with the formation of a vertical current sheet in the corona and the subsequent formation of a post-flare system of loops (Fig. 7; see the Kopp–Pneuman–Anzer model[53,54] and a modification of it[55]). That process is accompanied by prolonged energy liberation and particle acceleration. Reconnection occurs initially in lower layers of the corona, and the reconnection region then ascends gradually at a velocity 0.5-50 km/sec. More and more new higher loops are formed in the process. The loops are initially filled with hot plasma and radiate in the soft x-ray, and as they cool, they become visible in Hα.

This process is accompanied by long-duration bursts in the soft x-ray (LDEs), gradual hard x-ray[56] and millimeter-wave[57-60] bursts, generated high in the corona [up to $h \sim (1\text{-}2)\cdot 10^5$ km], and by multicomponent microwave bursts with a soft radio spectrum (spectral maximum at $f_m \sim$ 3-5 GHz).[61,62] At meter and decimeter wavelengths one observes an elevated continuum for many hours with a large number of surges and intensity variations at different scales: a type IV burst changing into a noise storm.

An analysis[63] shows that the prolonged particle acceleration during the formation of the post-flare system of loops may also be the source of a proton flux in interplanetary space with increased (excess) intensity at $E > 10$ MeV and a long time delay (≥ 10 h) in the flux maximum relative to the respective flare. Particle acceleration in so-called high coronal flares may be associated with CT eruption and magnetic reconnection in the vertical current sheet of a coronal ray.[64]

As a whole, the process of CT eruption and subsequent relaxation of the magnetosphere above an active region toward the initial state may lead to the formation of discrete disconnected ejections of plasma with their own closed magnetic field – so-called plasmoids. How typical such a structure is for CTs remains unclear. A number of data, pertaining both to the outer corona and to interplanetary space, indicate the existence of CTs with a disconnected magnetic field structure in at least 10% of cases.[65]

Additional evidence that magnetic reconnection occurs in the corona in the post-eruptive phase has been obtained in Ref. 110. An analysis of white-light images of the region of CT eruption shows that the bright quasiradial structures observed

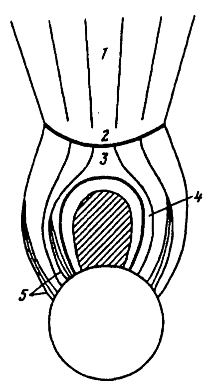

FIG. 8. Configuration of a slow shock with a concave front ahead of a CT (Ref. 66): 1) background corona; 2) slow shock front; 3) flux behind the front; 4) CT loops; 5) diverging coronal rays.

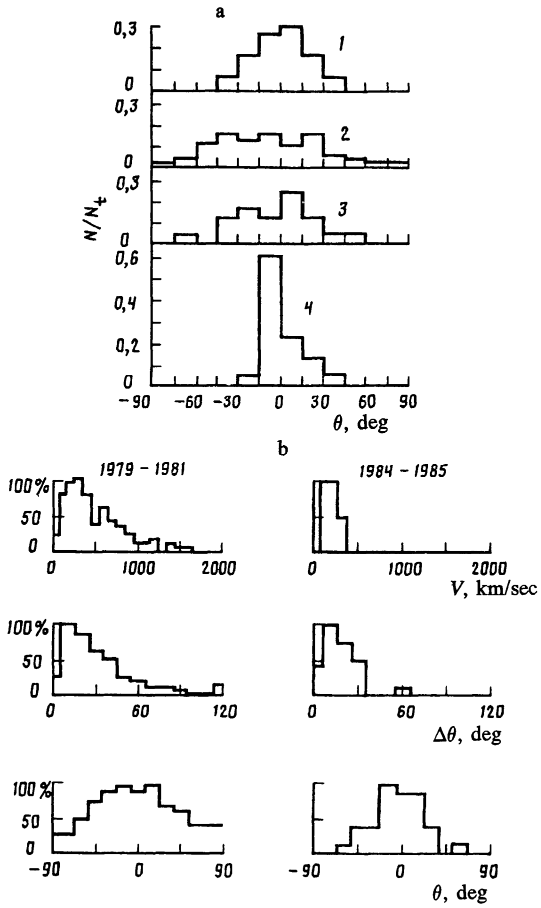

FIG. 9. Dependence of CT parameters on the phase of the cycle: a) distribution with respect to position angle θ of the relative numbers of CTs detected by *Skylab* in 1973-1974 (1, N_t = 77) and SMM in 1988 (2, N_t = 77), 1984 (3, N_t = 35), and 1985 (4, N_t = 40) (Ref. 5); b) distributions of CTs detected by P78-1 in 1979-1981 and 1984-1985 with respect to velocity V (N_M = 59 and 2), angular size $\Delta\theta$ (N_M = 241 and 12), and position angle θ (N_M = 125 and 12) (Ref. 73).

for many hours after a CT ejection most likely consist of the tops of newly formed coronal rays containing vertical current sheets, separating opposite magnetic fields, rather than the unipolar bases (footpoints) of a departing loop-shaped CT.

7. CTS AND SLOW SHOCKS

The nature of the interaction of an ascending CT with the surrounding coronal plasma depends on the ratio of the CT velocity (V_{CT}), on the one hand, and the speed of sound (V_s) and the Alfvén velocity (V_A), on the other. In the middle corona at a heliocentric distance $r \sim 3\,R_\odot$, $V_s \sim$ 150-200 km/sec and $V_A \sim$ 500-800 km/sec, while the velocities of most CTs are $V_{CT} \sim$ 100-1500 km/sec. In addition to the aforementioned explosive shock, which develops in the pulsed phase of a flare and generates type II coronal bursts, a piston shock can be formed during CT propagation. For $V_{CT} > V_A$, a fast shock is formed with a front convex in the direction of CT motion. The condition $V_s < V_{CT} < V_A$ is satisfied for many CTs, however. In such cases, a so-called slow shock develops ahead of the CT, which differs from a fast shock by a concave front and a smaller angle between field lines and the normal to the shock front (Fig. 8).[66,67] The top of the CT should be greatly smoothed out as a result, which has been observed in a number of cases.

The velocities of some CTs exceed the Alfvén velocity but remain below the critical velocity. An analysis[68] shows that intermediate shocks may be formed in this case, and the nature of the shock can vary from one part of the front to another.

The concept of slow shocks is being applied more extensively to CTs. In Ref. 69, for example, an event was described in which the source of a type IV burst was definitely associated with a slow ($V_{CT} \sim$ 200 km/sec) CT. It was suggested that the radio emission was generated by energetic electrons accelerated in the interaction with lower-hybrid waves in a slow shock front.

Since the Alfvén velocity decreases with distance from the sun, as the disturbance associated with a CT propagates in the interplanetary medium, a slow shock may change into a fast one.[70]

8. COMPARISON OF WHITE-LIGHT OBSERVATIONS OF CTS ON TWO EARTH SATELLITES

A pronounced difference has been found between certain CT characteristics and parameters recorded in white light by the SMM and P78-1 earth satellites.[6,71,72] It is related mainly to the difference between the respective coronagraphs, as well as the measurement procedures. In some cases, for example, CTs are analyzed using difference images with subtraction of the coronal background, and in others they are analyzed directly in photographs obtained with coronagraphs during an eruption. The coronagraph polarimeter on SMM, which functioned until near the end of 1989, had a high sensitivity and covered the range of heliocentric distances 1.5-6 $R_\odot$. The K coronagraph on P78-1, which ceased to exist in September 1985, was less sensitive, had a lower spatial resolution, and monitored a somewhat more distant region of the corona (2.5-10 $R_\odot$).

A comparison of CT data recorded simultaneously with the two satellites in 1980 shows, in particular, that the CT velocity based on P78-1 data is twice as high, on the average, as that based on SMM data.[6] This difference may partially reflect the actual CT acceleration at small heights in the corona. There are also differences in estimates of the frequency of appearance and the predominant shape of CTs, their velocity, angular size, etc.[7] (see below). That fact must be taken into account in statistical studies of CTs and their comparison with other phenomena.

9. CLASSIFICATION OF CTS

Coronal transients were originally classified by the shape of white-light images, and a number of morphological types were distinguished: loops; single, double, and multiple spikes (wedges); a fan, halo, radial tongue, diffuse emission, etc.[4] Such classification is now widely used. Along with this, CTs obviously must be classified by power. A version of such classification has been suggested in Ref. 73. Unfortunately, it applies only to CTs recorded by the P78-1 satellite, since there are considerable differences between that data set and SMM observations.

A classification based on the character of an image is essentially qualitative. Two extreme classes of CT are distinguished: Y transients, i.e., the largest and brightest CTs, and N transients, i.e., the faintest CTs of small angular size. An analysis of about 1000 CTs recorded by P78-1 in 6.5 years of observations showed that many CTs of the curved-front and halo types and CTs of complicated structure belong in the Y category, and most N transients consists of spikes and diffuse fans.

A quantitative brightness classification has been introduced[73] to supplement this, i.e., based on the amount of matter in the line of sight per unit position angle for difference images. This parameter equals $2.1\cdot 10^{14}$, $1.05\cdot 10^{14}$, and $3.5\cdot 10^{13}$ g/deg for bright (B), average (A), and faint (F) CTs.

A unified CT classification system, analogous to that adopted for optical flares, must be developed in the future.

10. DEPENDENCE ON THE PHASE OF THE CYCLE

The main CT parameters, including the range of position angles, velocity, angular size, and frequency of appearance, vary considerably in the course of the activity cycle.[7,73]

At the epoch of a minimum (1974-1975 and 1985-1986), CTs are concentrated in the equatorial zone, at latitudes $\theta <$ 30°-45°, and at a maximum (1979-1981), the range of position angles in which CTs are observed expands considerably and extends to the polar regions. The angular size and velocity of CTs at a maximum of the cycle are also far larger than at a minimum (Fig. 9).

The analysis of *Skylab*, SMM, and P78-1 data, combined with data obtained by the *Helios* spacecraft using the zodiacal light photometer in 1976-1979, when no coronagraph observations were made, has provided considerably more accurate knowledge of variations in the frequency of appearance of CTs in the course of a cycle[74,75] (also see Ref. 76). Contrary to our earlier understanding,[4] it turns out that the number of CTs varies in accordance with the variation of Wolf numbers (Fig. 10): with $W \sim$ 140-160 in 1979-1981, the frequency of CT appearance was $n \sim$ 0.8-1.8 day^{-1}, and with $W \sim$ 15-40 in 1975-1976, the number of CTs decreased to $n \sim$ 0.1-0.5 day^{-1}. The number of large CTs decreases especially strongly as a minimum is approached.

If we assume that the sudden commencement of a magnetic storm (SSC) with amplitude $\geq$20 nT is an indicator of equatorial CTs, we can obtain indirect information on variations in the number of such CTs over a far longer period. According to Ref. 77, in 1870-1970 the frequency of such events clearly follows the 11-year cycle with an average relative amplitude $\sim$10. The correlation coefficient between the number of SSCs (i.e., equatorial CTs) and Wolf numbers as a whole is $\sim$0.85.

11. CTS AND EVOLUTION OF THE CORONA

Coronal transients are an important element of the overall evolution of the corona, its magnetic field, and large-scale coronal structures. This can be judged, for example, from the close relationship found in Ref. 78 between the frequency n of appearance of CTs and the time scale τ of variations of the overall electron density distribution in the corona, determined from synoptic maps of the white-light brightness of the K corona at the heliocentric distance $r \sim 1.3\ R_\odot$, constructed from data from the coronagraph at Mauna Loa Observatory. It was established that a linear anticorrelation exists between n and τ with coefficients ~ -0.95 and -0.73 for CTs recorded by the SMM and P78-1 satellites, respectively. The average frequency of appearance of CTs is highest in the period of most rapid evolution of the corona ($n \sim$ 0.9 day^{-1} for $\tau \sim$ 30 days in 1980) and decreases considerably when that evolution is slower ($n \sim$ 0.1-0.2 day^{-1} for $\tau \sim$ 80-100 days in 1984-1986). It is significant that the time scale τ of coronal evolution in the course of the activity cycle as a whole varies in antiphase with the Wolf numbers, but displays no detailed correlation with them, and the very presence of CTs can change τ by no more than 5%, according to Ref. 78. Moreover, the power involved in the overall reorganization of the corona far exceeds the energy contained in the observed CTs. These data provide additional reasons to believe that the eruption of a CT is a consequence of the evolution of large-scale coronal structures.

The eruption of a CT can encompass magnetic structures extending far beyond the given active region or the vicinity of a coronal ray.[79] An analysis[80] of high-quality data pertaining to the start of the new cycle (1986-1987) showed, for example, that CTs were observed in association with high-latitude sunspot groups most often in those cases in which at nearby solar longitudes there was another equatorial sunspot group from the old cycle at a distance of dozens of degrees in latitude or an even remoter high-latitude sunspot group from the new cycle in the opposite hemisphere. Here the location, shape, and considerable angular size of the CTs clearly indicate that the eruption of large-scale (including transequatorial) loop-shaped magnetic structures, connecting sunspot groups located far apart, occurred in those events. We must also note that CT ejection is those cases hardly involved nearby coronal rays, which existed and developed independently of the CTs.

On the other hand, numerous cases are known of pronounced changes in the brightness, structure, and orientation of coronal rays and even their complete blowing away in the course of CT development (Refs. 4-7, 11, and 73). Some varieties of CTs, as noted above, probably originate as a direct result of the evolution of coronal rays and their associated magnetic configurations[41] (see Sec. 4). This category includes, for example, the so-called disconnection events, observed in the form of the upper part of a coronal ray being disconnected and ejected into the corona.[42] They originate from magnetic reconnection in a region of open field lines in the vertical current sheet of a coronal ray and consist of disconnected formations with a typical U shape propagating away from the sun. Such events may initiate instability in neighboring coronal rays and (or) flare energy liberation in adjacent regions, as a result of which a CT is formed with an angular size far exceeding the size of the active region. Disconnected magnetic structures originating during CT eruption, including those associated with coronal rays, play an important role in the balance of magnetic flux carried into interplanetary space.

12. THREE-DIMENSIONAL STRUCTURE OF CTS

To supplement the data on the three-dimensional structure of CTs given in Ref. 4 (transients of the halo type, direct measurements of interplanetary disturbances, and the results of radio transillumination), we advance another series of arguments.

No preferred orientation has been found for the eruptive prominences that produce loop-shaped CTs recorded by SMM.[81]

The considerable extent of CTs in both longitude and latitude (dozens of degrees) has been determined in observations with the zodiacal light photometers on the *Helios* spacecraft[82] of rises in electron density in interplanetary space associated with CTs. The large survey angle of the photometers makes it possible, in particular, to obtain a view of a disturbance at heliocentric distances up to 0.5 AU.

The dependence of Faraday rotation on the impact parameter as the radio signal from *Helios* passed through a CT is explained satisfactorily by modeling the transient as an expanding "bubble."[83]

The ascent of loop-shaped CTs in the plane of the sky at $r \sim 2.5\text{-}10\ R_{\odot}$ can be described as the radial motion of a spherical structure with simultaneous uniform expansion.[84] The observed distributions of white-light brightness in different CTs at certain heliocentric distances correspond to a flat loop in some cases and to a hollow or filled shell in others.

According to Ref. 85, CTs observed in projection onto the plane of the sky are described well by the model of an oblate spheroid, i.e., they really are three-dimensional formations. In such a model, the shape of a given CT in white light depends on the specific observing conditions, including the coordinates of the flare, the orientation of the axis of the bipolar sunspot group, the position angle, etc., as well as the "extinction" effect, i.e., the fading of the CT's emission due to the increase in its linear size with distance from the sun. The three-dimensional configuration of a flare CT near the sun turns out to be similar to the shape of the bow part of an interplanetary shock at $r \sim 1$ AU, but the oblateness of a CT is less pronounced and is ~ 1.25.

In this connection, we note that a relationship between the shape of a CT and the accompanying microwave and soft x-ray emission has been found in Ref. 51. This is a strong argument that the different CT shapes observed with white-light coronagraphs reflect actual physical differences in the events, and are not merely a consequence of geometrical or other similar factors.

With allowance for data on the internal three-component structure of CTs (see Sec. 3), we believe that the upper part of a CT consists of a dome-shaped formation or shell, in the tenuous cavity of which is submerged a volume of dense plasma consisting of matter from the prominence.

13. INTERPLANETARY MANIFESTATIONS OF CTS

A number of helpful results have been obtained in observations of disturbances from CTs in interplanetary space by various methods, although it must be considered that, as noted in Ref. 86, the identification of interplanetary disturbances with CTs is a rather difficult task because of incompleteness of solar and interplanetary data, a high activity level, insufficiently clear model concepts, etc.

In direct measurements of the parameters of the interplanetary plasma on the ISEE earth satellite, in particular, it has been established that one of the most stable indicators of CTs is the transition from a unidirectional flux of quasithermal electrons with $E \sim 135\text{-}360$ eV in the solar wind to a bidirectional angular distribution.[87] Many such events are observed 10-15 h after the passage of a shock and coincide with the entry of the craft into a plasma structure that is characterized, in particular, by an enhanced, slowly varying magnetic field strength and gradual rotation of the field vector. In Ref. 87 such events are interpreted as interplanetary manifestations of CTs in the form of "magnetic clouds" or plasmoids with their own magnetic field, disconnected from the solar field. But bidirectional fluxes, generally speaking, can also occur in particle propagation in other structures, such as elongated loop-shaped "magnetic bottles," the bases of which remain connected to the sun, or in particle reflection from magnetic mirrors formed by open field lines, which have no direct relationship to CTs and converge in interplanetary space due to the nonuniform azimuthal velocity distribution of the solar wind. Electrons ($E \sim 0.2\text{-}2$ MeV) and protons ($E \sim 22\text{-}27$ MeV) accelerated in solar flares were used in Ref. 88 to obtain information about the topology of interplanetary manifestations of CTs. It was found by direct measurements, in particular, that there are events in which those energetic particles penetrate rapidly into structures containing bidirectional fluxes associated with a previous CT eruption from the same active region. The magnetic field in such structures therefore remains connected to the sun and cannot consist of an isolated plasmoid. On the whole, the question of the magnetic topology of the interplanetary disturbances produced by CTs remains open.

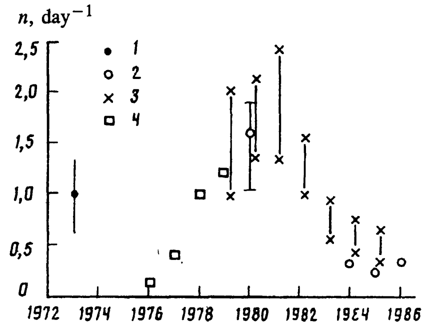

FIG. 10. Variation of the frequency of appearance of CTs with the phase of the cycle based on data from *Skylab* (1), SMM (2), P78-1 (3), and the zodiacal light photometer on *Helios*-2 (4) (Ref. 74).

The results of white-light observations in 1976-1979 of transient events in interplanetary space using the zodiacal light photometers on the *Helios* spacecraft have been generalized in Ref. 89. It turns out that $\sim 80\%$ of such events are associated with solar CTs and are characterized by the following average parameters: duration ~ 37 h, velocity ~ 500 km/sec, radial extent ~ 0.4 AU, angular width in longitude and latitude $\sim 50°$. Approximately the same parameters are obtained when disturbances propagating in the solar wind are detected by analyzing two-dimensional distributions of the scintillation index in radio transillumination of the circumsolar and interplanetary plasma.[90-92]

Direct measurements in the interplanetary medium on one or several spacecraft serve as the basis for modeling flare disturbances. From an analysis of *Vega* 1 and *Vega* 2 data, for example, evidence was obtained[93] that such disturbances have the form of an oblate, toroidal, force-free, magnetic plasma configuration, which moves under the action of forces of magnetic buoyancy, gravity, and hydrodynamic drag. On the other hand, it is stated in Ref. 94, on the basis of measurements on six spacecraft, that magnetic clouds from flares are banana-shaped with a longitudinal extent of 60°-80° and a radius of curvature ~0.5 AU.

In the interaction of fast CTs with the interplanetary plasma, the flare ejection may become enveloped by lines of the background magnetic field.[95] Regions with pronounced north–south asymmetry, including those with $B_z < 0$, may develop ahead of the disturbance front, thereby creating favorable conditions for a strong geomagnetic disturbance.

The piston shock preceding a CT in interplanetary space is a source of low-frequency ($f \leq 2$ MHz), slowly drifting type II bursts. An analysis[96] shows that such bursts are observed after the fastest ($V \geq 500$ km/sec), most massive ($\langle m \rangle \sim 1.4 \cdot 10^{16}$ g), and largest (dozens of degrees) CTs of the halo or curved-front type, belonging to class Y, are detected in white light at $r \leq 10\ R_\odot$.

Detailed data on radio transillumination indicate that the central part of the three-dimensional interplanetary ejection from a CT sometimes propagates at a lower velocity, as a result of which a recess or gap is formed in its structure.[91] This feature is assumed to be due to slowing of that part of the ejection that interacts with a heliospheric current sheet.[97] On the other hand, according to Ref. 98, the geoefficiency of interplanetary transients and the probability of the occurrence of a geomagnetic storm with a sudden commencement increase if, at the time of arrival of the disturbance, the earth is in a heliospheric current sheet or in its close vicinity.

It has been stated in a number of papers (see Ref. 90), on the basis of radio transillumination experiments using about 900 sources, that most interplanetary disturbances that produce nonrecurrent magnetic storms are associated not with flares or disappearing filaments but with large equatorial or mid-latitude coronal holes. Such a conclusion seems wrong, however.[79,99] First, numerous and varied observations pertaining to the close vicinity of the sun show convincingly that the largest discrete plasma formations are ejected into the corona and interplanetary space in the form of CTs precisely from a region of flares or disappearing filaments, rather than coronal holes. Second, the extrapolation of the trajectories of interplanetary disturbances to the solar surface used in Ref. 90 is a very difficult procedure, which depends, in particular, on the acceleration curve of the solar wind, and it can result in considerable uncertainties. One must bear in mind that coronal holes usually occupy a fairly large area on the solar disk, and in any extrapolation procedure there is a very high probability that the projection of an interplanetary disturbance will hit the vicinity of a coronal hole.

14. F AND EP TRANSIENTS ARE A SINGLE CLASS OF PHENOMENA

Numerous data given in the preceding sections of the present review and in Refs. 4, 51, and 100 indicate that F and EP transients, corresponding to flares and disappearing filaments, are events with a similar physical nature, forming a single spectrum of eruptive solar phenomena. The disappearance and ejection of a filament outside an active region without a significant increase in Hα luminosity is a flare-like process, but less energetic.

It is sufficient to recall the role played by a filament and a prominence in the initial stage of formation of flare CTs. There is considerable similarity between F and EP transients based on white-light observations.

Interplanetary manifestations of CTs also confirm that F and EP transients have the same nature. Like flare ejections, EP transients are accompanied by shocks,[100] magnetic clouds,[101] and relatively small Forbush decreases in the intensity of Galactic cosmic rays,[102] and are responsible for a large fraction of nonrecurrent geomagnetic disturbances.[103] In the interplanetary magnetic clouds from disappearing filaments, a braided field structure is often detected, similar to what is often seen in Hα observations of eruptive prominences.[104] One of the important differences between interplanetary ejections initiated by disappearing filaments and by flare ejections is that the former propagate at a somewhat lower velocity and do not decelerate significantly within 1 AU (Ref. 105).

Moreover, like flare events, large disappearing filaments are accompanied by fluxes of energetic particles in interplanetary space, protons with energies up to 40-80 MeV, in particular (Refs. 100 and 105-107). Albeit in these cases they have a relatively low intensity, an extended time profile, and a very soft particle energy spectrum. Whether these particles are accelerated in interplanetary shock fronts or originate directly in the eruption of the EP transient and the subsequent relaxation of the magnetic field in the corona (see Sec. 6) remains an open question.

It is thus evident that CTs are an extremely multifaceted phenomenon, involving the most varied processes from evolving coronal structures, eruptive prominences, disappearing filaments, and flares to interplanetary disturbances and geomagnetic storms. Investigations of CTs are developing very rapidly, but the nature of CTs and the physics of their relationship with other manifestations of solar activity are still largely unclear. It can be expected that significant progress in solving these problems will be achieved on the basis of comprehensive international research programs, now in progress and planned for the near future, using an extensive set of satellite and ground-based observations, to record radiation and obtain solar images in different spectral ranges with high spatial resolution and to measure particle fluxes and propagating interplanetary disturbances. An important and urgent problem, among others, is that of CT diagnostics, particularly from the electromagnetic radiation accompanying them, for its subsequent use in a system of solar–terrestrial prediction.

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