THE ROLE OF SOLAR-WIND VELOCITY-WAVES IN COMET OUTBURST ACTIVITY

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Abstract. Comet outburst activity and the structure of solar wind streams were compared on the basis of Pioneer 10, 11, Vela 3 and IMP 7, 8 measurements at the heliocentric distance $r \approx 1-6$ AU. It is shown that the solar wind velocity waves which are evolving into corotating shock waves beyond the Earth orbit may be responsible for comet outburst activity. The correlation between variations of comet outburst activity with heliocentric distance and the behavior of the solar wind velocity waves is established. The closeness of the characteristic times for the velocity waves and comet outburst activity (7–8 days at $r = 1$ AU) as well as the simultaneous growth of both the characteristic times with r are noted. The observed distribution of the comet outburst activity parameters during the 11-year cycle is also in good agreement with the phase distributions during the 11-year cycle of variations of the coronal hole areas and the rate of change of the sunspot area ΔS_p.

It is well known that when a comet is moving towards (or from) the Sun sharp fluctuations in its brightness (i.e., comet outbursts, as well as less significant variations of integral brightness) are often observed on the background of a uniform change in the comet brightness. The observed correlations with solar activity (Richter, 1954; Dobrovolskii, 1961) and the existence of a 27-day recurrence of comet outbursts (Vsehsviatskii, 1966) made it possible to conclude that comet outburst activity is related to the solar wind. More recently Flammer *et al.* (1986) have shown that the large and rapid variations of the brightness of Comet P/Halley observed between 11 and 8 AU are strongly correlated to its encounter with fast solar wind streams originating from a southern coronal hole. They argue that this could lead to electrostatic charging and levitation of fine dust grains lying on the surface, particularly on the night side; a process that is highly modulated by the speed of the solar wind (see also Mendis *et al.*, 1981).

Observations which have been analyzed by Andrienko and Vastchenko (1981) show a definite dependence of the comet outburst activity on heliocentric distance:

(1) The comet outburst intensity, determined by its amplitude, begins to grow from $r \approx 1.5$ AU, and at $r \approx 2.5$ AU a sharp jump in the burst amplitude is observed (Figure 1).

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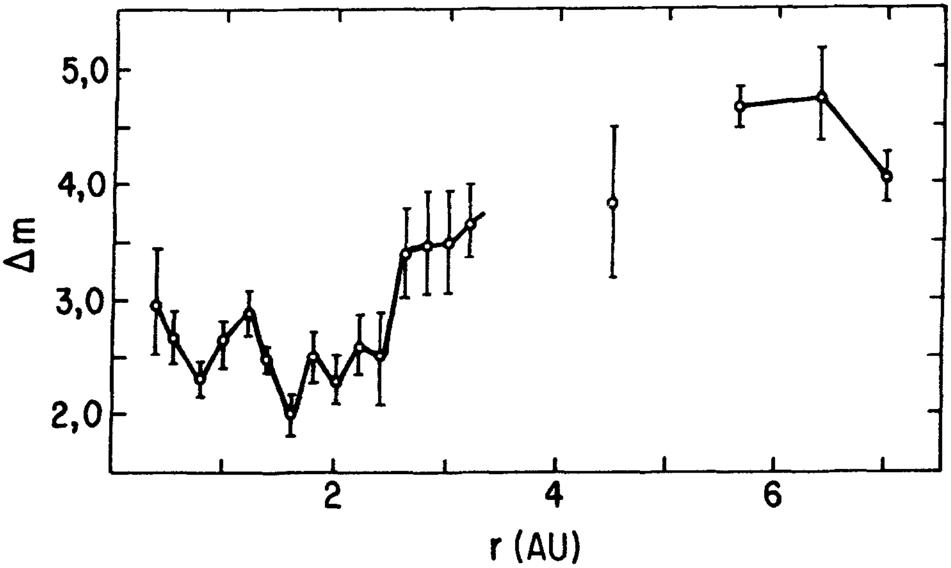

Fig. 1. The dependence of average comet outburst amplitudes m on the heliocentric distance r (Andrienko and Vastchenko, 1981)

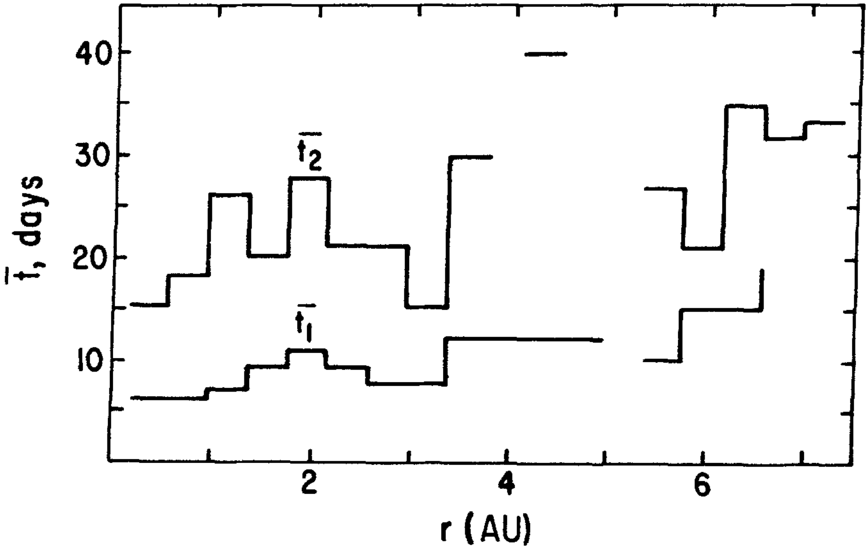

Fig. 2. The dependences of average durations of a leading $\bar{t}_1$ and trailing $\bar{t}_2$ comet outburst fronts on the heliocentric distance r.

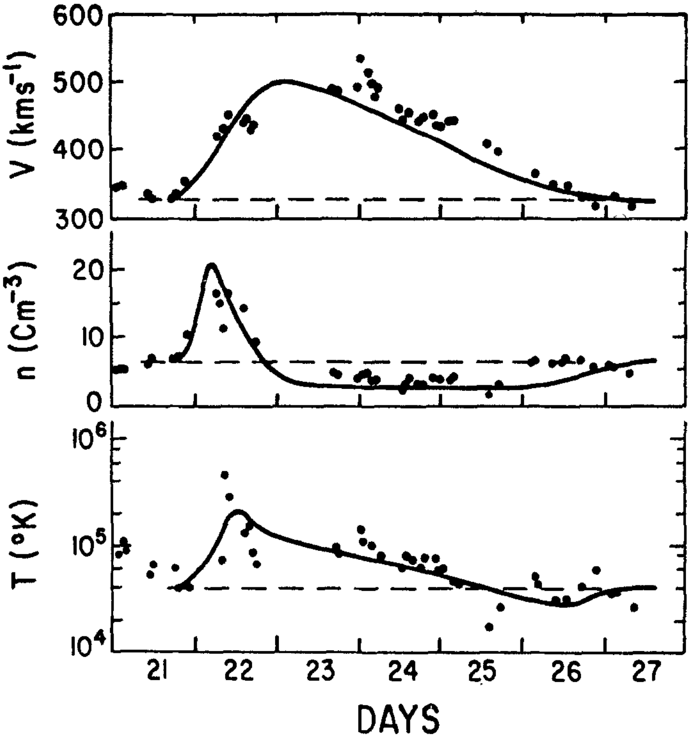

Fig. 3. The solar wind parameters (V, n, T) variations measured on Vela (Hundhausen, 1973a).

(2) The increase of comet brightness lasts on the average for 7–8 days and the decrease occurs over a time scale that is 2 or 3 times longer. These time intervals tend to be longer with increasing heliocentric distance (Figure 2).

(3) The comets with high brightness are characterized by maximum outburst recurrence frequences. Such comets are usually moving at great distances from the Sun and their outbursts have a high intensity.

At the same time, it is known from observational data of the solar wind parameters obtained by Pioneer 10 and 11, Voyager 1 and 2, and from comparison of these parameters with measurements on the Earth's orbit (Vela 3, IMP-7, 8, etc. (Gosling *et al.*, 1976; Smith and Wolf, 1979; Gasis, 1983) that the solar wind at distances from 1 AU up to 5–6 AU has a large-scale structure determined by corotating shock fronts which appear due to interaction of high and low speed streams.

The aim of this paper is to compare the dependence of the comet outburst activity on heliocentric distance with the solar wind large-scale structure in order to find the solar wind effects responsible for the comet outburst activity.

The existence of velocity waves in the solar wind which are evolving while moving away from the Sun has been established by direct measurements (see Figure 3). Observations at the Earth's orbit show that the solar wind stream having a mean velocity of the order of 450 km s^{-1} is characterized by velocity variations with an amplitude ~ 200 km s^{-1}. Within every wave the wind velocity rapidly increases up to its maximum value and then decreases more slowly to its background magnitude. These variations are due to interaction between the high- and low-speed streams. This interaction develops in such a way that a velocity disturbance while moving from the solar corona up to 1 AU does not always evolve into a discontinuity as occurs when interplanetary shock waves are being formed during solar flares. According to theoretical models (Eviator *et al.*, 1970; Hundhausen, 1973a, b; Hundhausen and Gosling, 1976; Dryer *et al.*, 1978), the high-speed stream evolution includes a continuous steepening of the profile with increasing heliocentric distance and a formation of two shock fronts (direct and reverse) at the leading edge of the wave beyond are Earth's orbit.

These high speed streams eventually assume the configuration of a rotating large-scale spiral structure. Inside the corotating interaction regions compression effects are dominant: the magnetic field, plasma density and fluctuation level sharply increase. Inside the quiet regions rarefaction effects prevail – the magnetic field, solar wind density and fluctuation level being extremely low. The formation of shock fronts takes place at heliocentric distances of the order of 2–3 AU, while the distance between the fronts increases with r (Gosling *et al.*, 1976; Smith and Wolfe, 1979). The wave amplitude decreases with r but more slowly than the sound velocity. As a result, the Mach number increases. This leads to a greater sharpness of the large-scale solar wind structure at great heliocentric distances ($r \sim 5-7$ AU) than near the Earth's orbit (Gosling *et al.*, 1976; Hundhausen and Gosling, 1976).

A series of compatible observations of velocity waves on IMP-7 and Pioneer 10, 11 confirmed the conception of rapidly evolving velocity waves with an increasing steepness. Observations on Pioneer 10, 11 show the existence of two sharp jumps of velocity at the leading edge of the wave which are identified with direct and reverse shock fronts (Hundhausen and Gosling, 1976).

Let us now compare the observed distribution of the comet outburst activity on the heliocentric distance described in items 1–3 with the large-scale structure of solar flares evolving with radial distance.

One may suppose that the sharp increase in comet outburst activity at the distance of about 2.5 AU (Figure 1) is due to the transformation of the velocity wave into a shock discontinuity. The further increase of mean amplitudes of the comet brightness variations may be connected with the increase of density on the leading edge of the wave, which is located between two shock fronts moving apart with the increase of the heliocentric distance or with the increase of Mach number. It must also be noted that at larger heliocentric distances the solar wind could penetrate on to the surface, with practically no impedance by a protective atmosphere (e.g., see Flammer *et al.*, 1986).

Let us now compare the characteristic times for both processes – the increasing of comet brightness and the evolution of solar wind velocity waves. Solar wind parameters observed on Vela near the Earth's orbit (e.g., see Hundhausen, 1973a) are presented in Figure 2. One can see that the characteristic time for the solar wind velocity waves is of the order of the week. The period of about a week in variations of the solar wind velocity V_{sw} and of the K_p-index is rather typical. This conclusion is confirmed by results obtained with the help of the Welch method of estimation of the density power spectrum which has been applied to velocity data obtained on IMP beginning from 1979 and to K_p-index data obtained on the geomagnetic station 'Moscow' during the period from 1979 up to 1981 (Figure 4) It is possible that different variabilities with a characteristic time of about a week, which are clearly revealed in variations of different geophysical parameters registered on the Earth (in the K_p-index and in the cosmic ray intensity (Cowling, 1956; Basilevskaya *et al.*, 1974; Pochtarev *et al.*, 1979; Vernova, 1983), are presumably caused by the solar wind velocity waves.

It should be noted that the characteristic times for the solar wind velocity waves and for the increase of the comet brightness are rather close. According to Andrienko and Vastchenko (1981) the average duration of the leading (t_1) and trailing (t_2) shock fronts of high-speed streams as well as the duration of comet outbursts depend on the heliocentric distance (Figure 2). The values of t_1 and t_2 as well as $(t_1 - t_2)$ are approximately doubled when r increases from 0.5–0.6 AU to 5–7 AU.

It is possible to estimate the similar values t_1 and t_2 for the solar wind velocity waves using data obtained on Pioneer XII (Jurbenko, 1981) ($r \approx 0.7$ AU) and on Pioneer X ($r \approx 4.5$ AU) (Hundhausen and Gosling, 1976). The characteristic wave transit time obtained from the data (which is the average of 20 events from September 1981 to January 1982, when Pioneer XII was near the Sun–Earth line, and determined by the sum $(t_1 + t_2)$) is of the order of 7 days. The characteristic time obtained by data of Pioneer X (Gosling *et al.*, 1976) is on the order of 11 days on the average. Thus while moving away from the Sun $r = 0.7$ AU up to $r = 4.5$ AU the value $(t_1 + t_2)$ increases a factor of 1.8.

The estimates of the high-velocity stream width (or the wave width) obtained with the help of a model from Gosling *et al.* (1976) and Hundhausen and Gosling (1976) give the value of $l \approx 0.6$ AU at $r \approx 1$ AU and $l = 1.2$ AU at $r = 6$ AU; i.e., the estimates also show that the characteristic wave transit time (which is proportional to the stream width) is approximately doubled when r changes from 1 to 6 AU. Thus besides the closeness of characteristic times for the solar wind corotating waves (ϵ) and for the comet outbursts (t) one may note the similar behavior of these parameters with the increase of the heliocentric distance; i.e., they increase by about a factor of 2, while r changes from 0.5–0.7 to 5–7 AU.

Hence, the nature of dependence of the comet outburst activity variations with the heliocentric distance appears to be in good agreement with the evolution of solar wind velocity waves with heliocentric distance.

In their turn the origin and temporal structure of these waves are due to non-stationary processes in the solar atmosphere. There is an observation that attracts our attention. In the periodic structure of the rate of change of the solar activity expressed in daily differences of the sunspot areas ΔS_p, there exists a component having the period of about 7–8 days (Vernova *et al.*, 1983). This component is

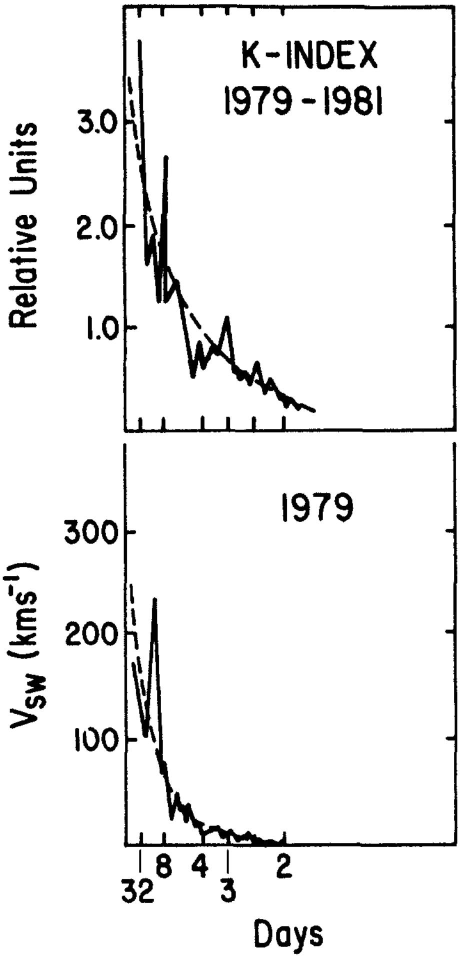

Fig. 4. Estimates of the power density spectrum using the Welch method (*Solar Geophysical Data*, NOAA Environmental Data Service). The initial data has been divided into 64-day intervals and then the given spectra have been averaged.

connected not with the sunspot distribution over the solar disc but rather with their evolution in time. This is probably connected with the fact that the evolution of the active regions (the increase of the area and the magnetic field of the spot up to their maximum values) occurs during the period of about 5–10 days depending on the lifetime of the spot (Cowling, 1956).

Convincing statistical relations between geo-effective fluxes and active regions on the Sun are well known. Lately the location of geo-effective sources on the surface of the Sun is considered to be in the coronal holes, which are characterized by an open magnetic field configuration. An investigation by Kovalenko and Molodich (1977) shows that the non-radially expanding flux geometry inside the coronal holes necessary for high-velocity stream formation is most probably realized in the vicinity of active regions. This fact is obviously the reason why the characteristic time of variations of temporal structures in the solar wind, the variations in the geomagnetic activity, and the comet outburst activity are similar.

The observed typical behavior of coronal holes and solar and comet activities during 11-year cycles may serve as a confirmation of the relations mentioned above. Such characteristics of comet activity as the number of outbursts, their amplitudes, the total number of comets and the number of brightest comets have a two-peaked distribution during the 11-year cycle of solar activity, the peaks coinciding with the rising and falling phases of the cycle (Dobrovolskii, 1961; Andrienko and Vastchenko, 1981). (See, for example, the curve 'd' in Figure 5, which gives the 11-year cycle phase distribution of outbursts for Comet Schwassmann–Wachmann I, the comet for which largest number of outburst observations are available.)

It is seen from Figure 5 that the coronal holes areas (the curve 'b') and the amplitude of change of sunspot areas ΔS_p (the curve 'a') have similar phase distributions.

Thus the observed dependences of the comet brightness curves and of different peculiarities of the solar activity on the 11-year cycle, which are connected with the solar wind streams, also serve as an argument in favor of a conclusion that the evolving solar wind streams play a crucial role in the comet outburst activity.

It should be noted that concrete mechanisms suggested earlier, which took into consideration the solar wind fluxes and interplanetary shock waves (Dobrovolskii, 1961; Eviator *et al.*, 1970) could not explain the whole complex of observed comet outburst activity peculiarities. In particular, they failed to take into account the spatial and temporal characteristics of comet outbursts determined by solar wind fluxes. See, however, the more recent work of Mendis *et al.* (1981) and Flammer *et al.* (1986).

An early mechanism connecting the comet outbursts with interplanetary shock waves is suggested in Eviator *et al.* (1970). The interplanetary shock waves generated by solar bursts are considered to be an agent transmitting the energy necessary for a comet dust cloud disturbance. The increase in comet brightness occurs according to this model due to the fact that in the vicinity of a dense cloud high albedo Platt particles appear, which are accelerated to high velocities during their interaction with the shock front, and reach distances of about several thousand kilometers from the core, thus increasing the comet's reflecting capacity and consequently its brightness.

However, this mechanism is subject to difficulties. First, the interplanetary shock waves generated by solar flares damp while moving off the Sun (Hundhausen, 1973a, b; Dryer *et al.*, 1978) but the intensity of the comet outbursts increases with r, as seen from observational data. Second, the solar flare is a short-time process, therefore it cannot cause recurrent bursts of brightness so typical of comet outburst activity, because the shock front does not participate in corotation. These difficulties are eliminated if we suppose that the evolving solar wind velocity waves rotating

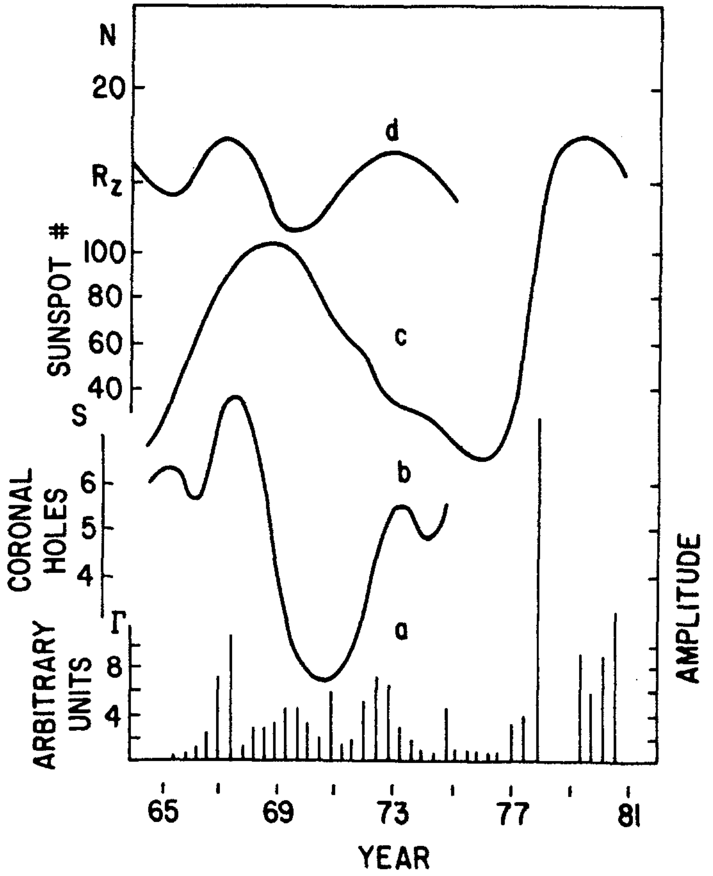

Fig. 5. The comparison of variations of some solar activity characteristics (Vernova *et al.*, 1983) with a distribution of the number of brightness outbursts for Comet Schwassmann–Wachmann I during the 11-year solar cycle. (a) The amplitude (in relative units) of the daily change of the sunspot area ΔS_p. Every reading (a vertical line on the figure) gives the amplitude in the intensity spectrum of ΔS_p obtained with the help of the Welch method using a temporal base of 62 days. (b) The total yearly area of coronal holes as a percentage of the area of the solar disc (Broussard *et al.*, 1978). (c) The sunspot number R_z. (d) The dependence of the average number of brightness outbursts (Andrienko and Vastchenko, 1981) for Comet Schwassmann–Wachmann I on the phase of solar activity in the 11-year cycle.

together with a high-speed flux are responsible for the energy transport necessary for a comet disturbance. As has been mentioned above, a specific feature of such a long-lived, large-scale structure of the solar wind is just the fact that this structure reveals itself most distinctly at large heliocentric distances. Moreover, the characteristic time scale in the corotating shock wave is about 7–8 days. In such a case the observed increase in comet brightness during the time of about a week on the average would indicate (for the mechanism suggested in Eviator *et al.* (1970)) a growth of Platt particle concentration around the comet core during the whole period of the gas-dynamic interaction between the comet and the shock fronts.

The present analysis alternately shows that the large-scale structure of the solar wind which is associated with corotating shock fronts of high-speed streams may be responsible for the comet outbursts activity. This is supported by the recent work of Flammer *et al.* (1986).

In summary, the following conclusions are reached: the comet outburst activity dependence on the heliocentric distance is in good accordance with the behavior of the solar wind velocity waves with heliocentric distance. The characteristic times for these waves (7–8 days at $r = 1$ AU) and comet brightness outbursts are close, and both vary with heliocentric distance in the same way. The cometary outburst activity also shows a good correlation with the phase distributions of the total area of coronal holes and the rate of change of sunspot area ΔS_p during the 11-year cycle.

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