ENERGY SOURCE OF THE SOLAR WIND

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Abstract. A direct transfer of energy from photospheric activity to the solar wind by means of electric currents is discussed. Currents are assumed to flow in quiescent prominences which occasionally erupt and give rise to expanding loop-like structures in the corona, as observed from Skylab. Due to expansion, the legs of the loops are transformed into coronal rays which carry currents from the photosphere to the outer parts of the corona or interplanetary medium and then back again to the photosphere. It is proposed that energy is transferred from photospheric activity to the solar wind in the following ways: (1) as kinetic energy of the ejected loop matter; (2) as electric power directly fed into the extended loops; and (3) as torsional waves produced by fluctuations in the loop currents.

1. Electric Current Models of Cosmic Plasma Phenomena

A model of a magnetized plasma can be based either on a magnetic field description or on an electric current description. The study of these alternative approaches (Alfvén, 1968, 1979a) shows that the current description is necessary for the understanding of the formation of double layers, explosive phenomena, and the transfer of energy from one region to another. A systematic construction of current models has already led to models of prominences and solar flares (Alfvén and Carlqvist, 1967; Carlqvist, 1969, 1979), magnetic substorms (Boström, 1974; Akasofu, 1977), the transfer of energy from the Sunward magnetospheric convection to auroral particles via a double layer or mirror effect electric field (Alfvén, 1977; Fälthammar, 1977, 1979; Lennartsson, 1977, 1978), a model of the Io–Jupiter electric circuit (Cloutier *et al.*, 1978), the Jovian magnetosphere (Smith, 1979), and the folding umbrella phenomenon in comets (Mendis, 1978).

Recently it has been shown how a current model of the solar wind–magnetosphere interaction can account for the transfer of energy from the solar wind to the magnetosphere (Alfvén, 1979b).

2. Model of Solar Wind Acceleration

In its interaction with the magnetosphere the solar wind acts as a generator, while losing momentum and energy to support dissipative electric current systems. We suggest that the reverse process – i.e., transfer of momentum and energy to the solar wind plasma by means of electric currents generated by photospheric activity – can explain how the solar wind becomes accelerated. We base our model on the current model of

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solar prominences and solar flares. If photospheric motion in the presence of magnetic fields produces voltage differences between two points of intersection of a magnetic field line with the photosphere, a current starts to flow along this field line. Due to drift motions caused by crossed electric and magnetic fields, matter from the corona is sucked in by this current so that a prominence is formed (Alfvén, 1961; Marklund, 1979). In such a prominence there may be a semi-permanent equilibrium between gravitation and electromagnetic forces (quiescent prominence) or an exploding double layer may be formed giving rise to a solar flare. However, there is also a third option: viz., the magnetostatic pressure of the prominence current is so large that it cannot be balanced by gravitation. In this case we have an eruptive prominence in which matter is ejected from the Sun. Such eruptive prominences have been studied by means of Earth-bound instruments for several decades. More recently, Skylab photographs (Figure 1(a)) have revealed that eruptive prominences may often give rise to expanding loop-like structures far out in the corona (Gosling *et al.*, 1974; Hildner *et al.*, 1975). The loops move with speeds ranging from about 200 to more than 1100 km s^{-1} and have been traced out to six solar radii. Ultimately, the lower parts of the loops are transformed into rays projecting almost radially from the Sun (Figure 1(b)). Models of expanding coronal loops based on electromagnetic driving forces have been presented by Mouschovias and Poland (1978) and Anzer (1978).

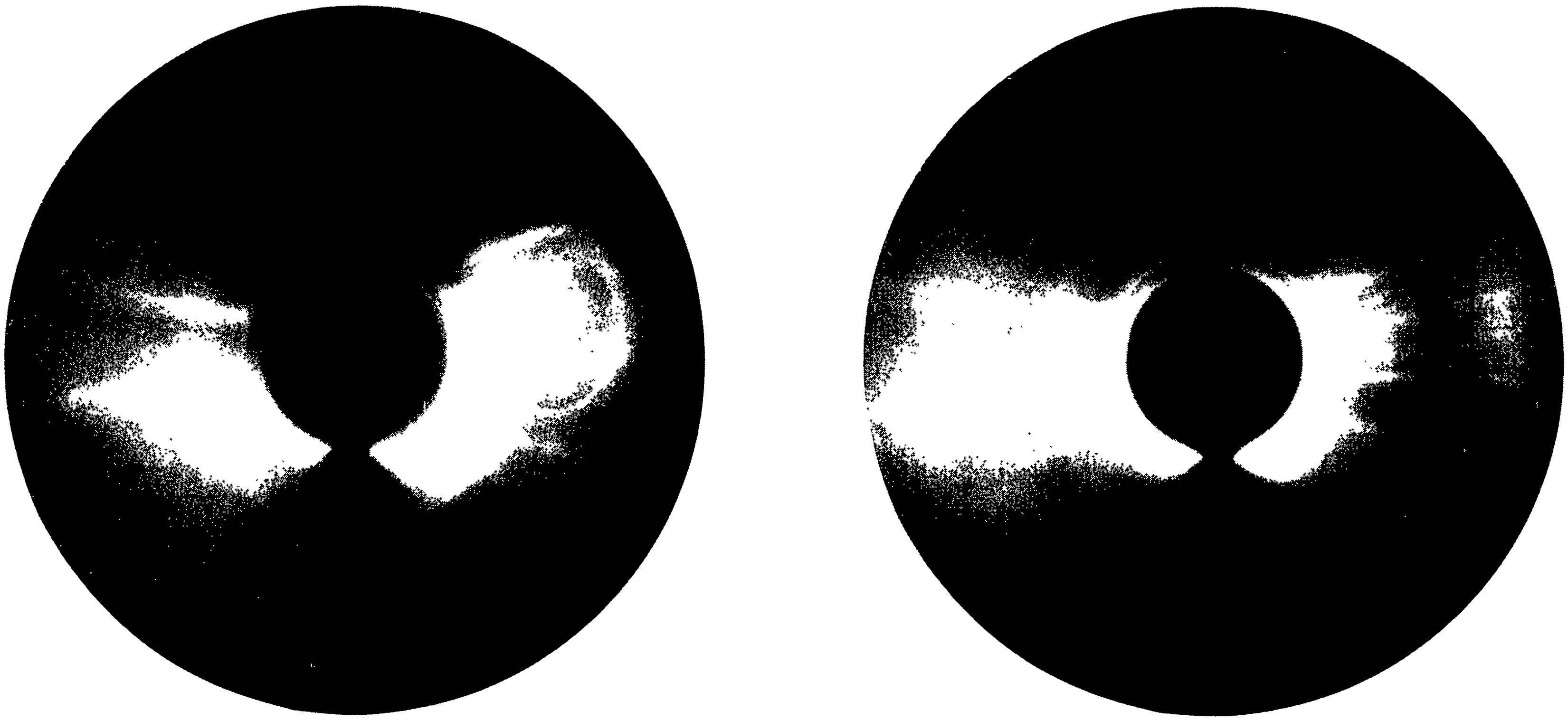
In the electric current picture the final state of an eruptive prominence is characterized by a current flowing from the photosphere to the outer parts of the corona or interplanetary medium along a more or less radial magnetic flux tube and returning via another (Figure 2(a)). Hence, we have a circuit delivering energy directly from the photospheric activity to the plasma far outside the photosphere. This is the reverse of the direct transport of energy from the solar wind to the magnetosphere by several magnetospheric current circuits (Alfvén, 1979b). Of these circuits, the front current (shock front) circuit (Figure 2(b)) is most similar in structure to the solar loop circuit discussed here. We suggest that the eruptive prominences leading to extended coronal current loops constitute the main source of solar wind kinetic and thermal power amounting to a few times 10^{20} W.

3. Comparison with Observations

This model may explain the following observational results:

1. Solar eclipse photographs treated by the 'image-enhancement technique' (Martinez, 1978) show that the Sun is surrounded by a large number of almost radial filaments (coronal streamers), visible out to ten solar radii (Figure 3). These photographs, together with the Skylab pictures, seem to demonstrate the existence of a large number of circuits transferring solar activity energy to the solar wind. Half of the filaments should carry current out from the Sun, half back towards the Sun.

2. Like the currents in the auroral zone, the currents along the magnetic field lines are expected to be shielded from the surrounding plasma by strong electric fields



(a) (b)

Fig. 1. A mass ejection from the Sun photographed by means of the white light coronagraph on board Skylab on 10 August, 1973 (Gosling *et al.*, 1974). The Sun is obscured by an occulting disk having an effective radius corresponding to 1.5 solar radii. North is up and west is to the right. (a) The expanding coronal loop at 1448 UT having an apparent speed of more than 400 km s^{-1}. (b) The state a few hours later at 1918 UT when the legs of the loop appear as almost radial rays.

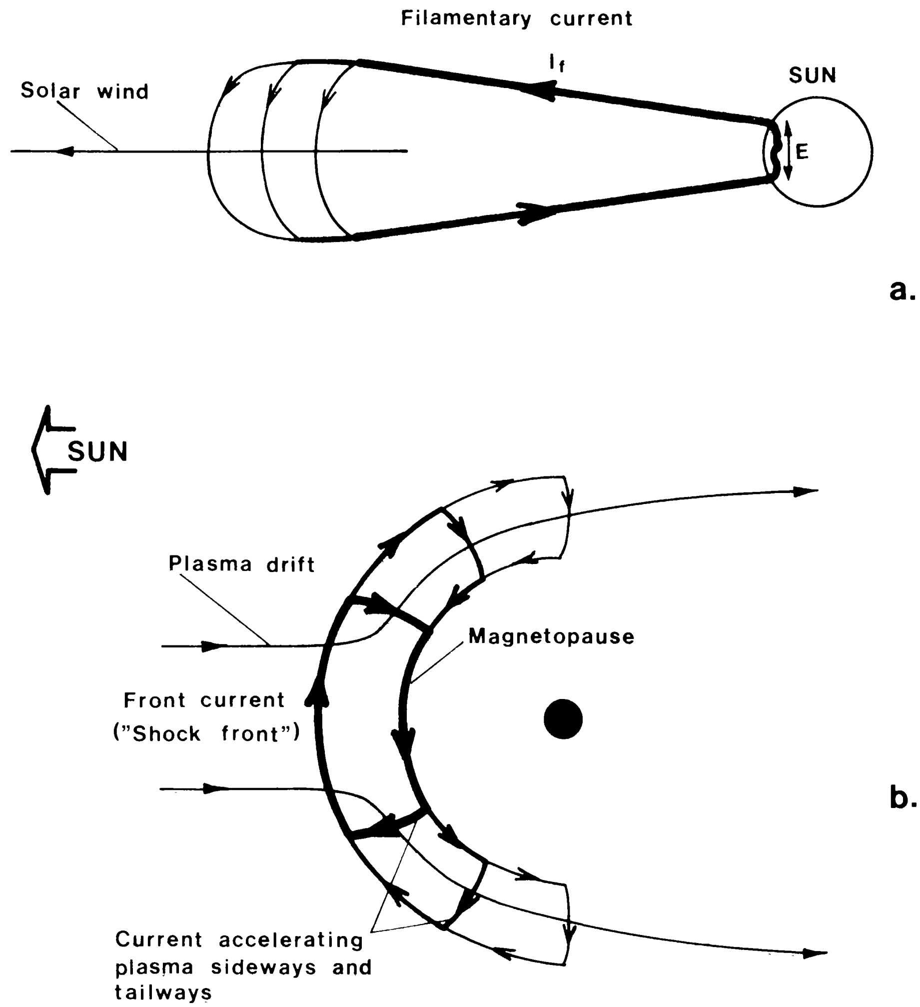


Fig. 2. (a) Schematic picture of an extended coronal current loop. The current, I_f, flows from the photosphere to the outer parts of the corona or interplanetary medium along a more or less radial magnetic flux tube and then back again along another. Due to the electromotive force E, a power I_fE is developed in the circuit. It is suggested that a set of such circuits constitute the main power source of the solar wind. (b) Schematic picture of the front (shock front) current circuit outside the magnetosphere of the Earth (Alfvén, 1979b). The front current decelerates the solar wind in front of the magnetosphere. Currents connecting the front current with the magnetosphere accelerate the plasma sideways and tailways. The currents close through the magnetopause.

('cable formation') (Block, 1969; Carlqvist and Boström, 1970; Mozer *et al.*, 1977; Alfvén, 1979a). A variation of the current produces torsional hydromagnetic waves. Hence, a considerable part of the transferred energy is used to produce such waves. This may explain why torsional hydromagnetic waves dominate in the solar wind.

3. Whereas the electric currents in normal prominences close in the lower corona, the regions in which energy transfer to the solar wind occurs are characterized by a different pattern. This may explain the correlation between coronal holes and the emission of solar wind.

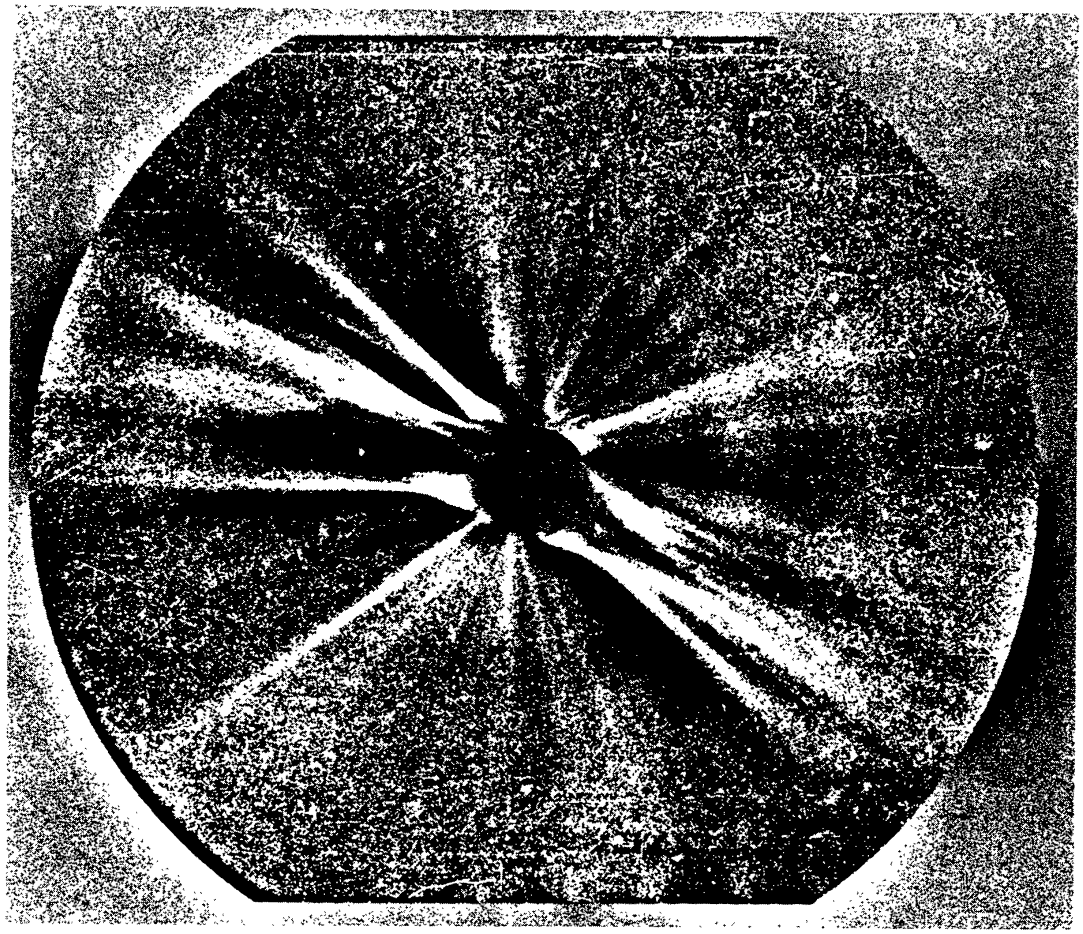


Fig. 3. Coronal streamers reaching out beyond 12 solar radii from the centre of the Sun. South is up and east is to the right. The lunar mask has a radius of 1.3 solar radii. Through special image-enhancement techniques (Martinez, 1978) the streamers have been made more clearly visible as compared to the original photograph secured during the total solar eclipse 30 June, 1973. It is suggested that large electric currents flow in and out along the streamers and transfer solar activity energy to the solar wind.

4. Energy Balance

According to the model proposed here the solar wind gets power from photospheric activity in the following ways:

1. Rising prominences are directly ejected into the surrounding space. According to Gosling *et al.* (1974) the energy of an expanding coronal loop is of the order 10^{30}–10^{31} erg = 10^{23}–10^{24} J. Since the loops are observed to occur, on average, once every third day they can only account for a small fraction of the total power delivered to the solar wind.

2. Currents $I = \sum I_f$ flowing up and down along almost radial filaments transfer a power $P = IE$, where E is the electromotive force produced by photospheric motions. For these motions to constitute the main power source of the solar wind, P

must be of the order of 10^{20} W. With a reasonable value of the electromotive force, $E \approx 10^8$–10^9 V (cf. Stenflo, 1969), the sum of the filamentary currents then has to be $I \approx 10^{11}$–10^{12} A. In order to estimate the filamentary currents we start from the current of a quiescent prominence which is expected to be in the range $I_p \approx 10^{11}$–10^{12} A (cf. Anzer and Tandberg–Hanssen, 1970). As the prominence erupts and forms an expanding coronal loop, the current decreases. Most of the magnetic energy stored in the prominence is then used in the expansion. If the current-induced magnetic field through the loop is taken to be constant and if, further, the loop expands out to ten solar radii, the prominence current will decrease by about two orders of magnitude. Hence, the current in a radial filament should be $I_f \approx 10^9$–10^{10} A immediately after expansion. Consequently, a total number of $N = I/I_f \approx 10^{2 \pm 1}$ current filaments is required to account for most of the power of the solar wind. It is possible that only a small fraction of these filaments are visible on the Skylab photographs.

3. Fluctuations in I produce hydromagnetic torsional waves which may contribute to the acceleration of the solar wind.

A check of this model can be obtained by careful study of the evolution of erupting prominences. The material for such an analysis may be available from Skylab observations.

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References

Akasofu, S.-I.: 1977, in *Physics of Magnetospheric Substorms* (Astrophys. and Space Science Library, Vol. 47), Chap. 7, D. Reidel Publ. Co., Dordrecht, Holland.
Alfvén, H.: 1961, *Arkiv Fysik* **19**, 375.
Alfvén, H.: 1968, *Ann. Geophys.* **24**, 1.
Alfvén, H.: 1977, *Rev. Geophys. Space Phys.* **15**, 271.
Alfvén, H.: 1979a, 'Plasma in Laboratory and Space', TRITA-EPP-79-12, Dept of Plasma Phys., Royal Inst. of Tech., Stockholm, Sweden (to be published in *J. Phys. Suppl. Coll.* **7**, 1979).
Alfvén, H. 1979b, in B. Battrick (ed.), *Proc. Magnetospheric Boundary Layers Conf., Alpbach* (ESA Special Publ. SP-148), p. 91.
Alfvén, H. and Carlqvist, P.: 1967, *Solar Phys.* **1**, 220.
Anzer, U.: 1978, *Solar Phys.* **57**, 111.
Anzer, U. and Tandberg-Hanssen, E.: 1970, *Solar Phys.* **11**, 61.
Block, L. P.: 1969, 'Some Phenomena in the Polar Ionosphere', Report No. 69–30, Depts of Electron and Plasma Phys., Royal Inst. of Tech., Stockholm, Sweden. (Paper presented at the Ninth Int. Conf. on Phenomena in Ionized Gases, Bucharest, Rumania, September 1969.)
Boström, R.: 1974, in B. McCormack (ed.), *Magnetospheric Physics*, D. Reidel Publ. Co., Dordrecht, Holland, p. 45.
Carlqvist, P.: 1969, *Solar Phys.* **7**, 377.
Carlqvist, P.: 1979, *Solar Phys.* **63**, 353.
Carlqvist, P. and Boström, R.: 1970, *J. Geophys. Res.* **75**, 7140.

Cloutier, P. A., Daniell, Jr., R. E., Dessler, A. J. and Hill, T. W.: 1978, *Astrophys. Space Sci.* **55**, 93.
Fälthammar, C.-G.: 1977, *Rev. Geophys. Space Phys.* **15**, 457.
Fälthammar, C.-G.: 1979, in *Int. Workshop on Selected Topics of Magnetospheric Physics, Tokyo*, p. 350.
Gosling, J. T., Hildner, E., MacQueen, R. M., Munro, R. H., Poland, A. I. and Ross, C. L.: 1974, *J. Geophys. Res.* **79**, 4581.
Hildner, E., Gosling, J. T., MacQueen, R. M., Munro, R. H., Poland, A. I. and Ross, C. L.: 1975, *Solar Phys.* **42**, 163.
Lennartsson, W.: 1977, *Astrophys. Space Sci.* **51**, 461.
Lennartsson, W.: 1978, 'On the Parallel Electric Field Associated with Magnetic Mirroring of Auroral Electrons – Some Basic Physical Properties'. TRITA-EPP-78-08, Dept of Plasma Phys., Royal Inst. of Tech., Stockholm, Sweden.
Marklund, G.: 1979, *Nature* **277**, 370.
Martinez, J.: 1978, *Sky and Telescope* **56**, 92.
Mendis, D. A.: 1978, *The Moon and the Planets* **18**, 361.
Mouschovias, T. Ch. and Poland, A. I.: 1978, *Astrophys. J.* **220**, 675.
Mozer, F. S., Carlson, C. N., Hudson, M. K., Torbert, R. B., Parady, B., Yatteau, J. and Kelley, M. C.: 1977, *Phys. Rev. Letters* **38**, 292.
Smith, E.: 1979, in B. Battrick (ed.), *Proc. Magnetospheric Boundary Layers Conf., Alpbach* (ESA Special Publ. SP-148), p. 221.
Stenflo, J. O.: 1969, *Solar Phys.* **8**, 115.