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V. S. KOMELKOV

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ASTRONOMY

V. S. KOMELKOV

ON ONE POSSIBLE MECHANISM OF EJECTIONS ON THE SUN

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The reality of the existence of magnetohydrodynamic vortices (MHD vortices) generated by the Sun has been proved by direct measurements of magnetic fields in the region of sunspots, which have, in the main, a bipolar structure ([1]–[3]). The latter arises as a result of the emergence of toroidal magnetohydrodynamic vortices from the depths to the surface of the Sun ([2], [3]). It is natural to suppose that ejections occurring on the Sun have a magnetohydrodynamic nature, but are associated not with disturbances of spot fields, but with the action of short-lived MHD vortices, whose development proceeds as rapidly as that of the accompanying ejections of the prominence and flare type.

Two types of toroidal MHD vortices are possible: with inner walls far separated from one another, when $D/2d \gg 1$ (Fig. 1a), and with closed inner walls, when $D/2d \simeq 1$. The former are characterized by quasi-equilibrium and slow floating upward, usually at large angles α to the surface of the Sun. The latter are substantially nonequilibrium and, as model experiments have shown, are deformed, stretching along the z axis (Fig. 1b), increasing their inductance. The vortices need not necessarily arise in the depths of the Sun. Their appearance is possible wherever, as a result of the interlacing of current cords or of instabilities inherent in plasma columns (pinches), regions with high current densities and increased magnetic pressures arise.

Experimental investigations of vortices of the second type and of the plasma jets produced by them have made it possible to establish a number of their specific properties, which may be summarized briefly as follows:

1. The structure of vortices of the type indicated in Fig. 1b does not change depending on the kind of gas (air, hydrogen, argon), if the discharge power is sufficiently large. In weak vortices the outer plasma coaxial breaks up into separate current filaments.

Fig. 1

Figure 1: Fig. 1

2. No influence was found on the structure of the jet from preliminary ionization and gas pressure in the range 10^{-3} mm Hg-1 atm. (density from 10^{-10} to 10^{-3} g/cm^3), nor from currents in the discharge varying from 10^3 to 10^6 A.

3. In addition to the field H_φ, produced by the longitudinal current of the cord, inside the plasma coaxial there is a field H_z, formed by the twisting of part of the longitudinal current into a spiral. Upon emergence into a medium of lower density, the diameter of the spiral increases sharply. Usually the fields H_φ and H_z near the current cord have the same order of magnitude. In the experiments their maximum reached 10^2-10^4 oersted.

4. The plasma of the current cord, compressed between the crossed fields H_φ and H_z, possesses high stability, the limit of which was not exceeded over the entire range of investigated times ($5 \cdot 10^{-6}$-$2 \cdot 10^{-4}$ sec.). The elongation of the jet is accompanied not by its destruction, but by the separation of plasmoids, which are independent MHD vortices of the same structure and continue the same cycle of expansion, elongation, and division.

5. The longitudinal velocities of the jet exceed the transverse ones by several (3-5) times. In connection with this the jet acquires a fountain-like form. The absolute values of v_z in model experiments ranged from $4 \cdot 10^5$ to $1.5 \cdot 10^7$ cm/sec, depending on the gas pressure and the currents in the discharge.

6. The plasma coaxial and, in particular, the current cord emit a continuous spectrum. Nevertheless, the temperature of the external plasma coaxial does not exceed 3 eV, and that of the current cord 30 eV.

7. X-ray radiation from the current cord is observed, with hardness up to 200-250 keV, at a potential difference along the jet circumference of 10-20 kV. The acceleration of the electrons that produce the X-ray radiation occurs when the field H_z changes. The acceleration processes are favored by the pushing-out of matter from the inner cavity of the jet, especially near the current cord, where the plasma fluctuations are greater than anywhere else. According to optical and probe measurements, they have a frequency of the order of 1 MHz.

Fig. 1. *a*—an emerging m. g. v.: 1—the surface of the Sun; 2—a toroidal current vortex; I—the current of the toroid; H—the magnetic field of the toroid; D and d—the large and small diameters of the toroid. *b*—the structure of an m. g. v. stretching along the z axis: 1—current cord; 2—external plasma coaxial; I—the current flowing in the cord and plasma coaxial; H_φ and H_z—the azimuthal and longitudinal magnetic fields.

Fig. 2

Figure 2: Fig. 2

8. Fountaining jets easily penetrate magnetic fields. Experience shows that a jet with a current of 3-10 kA penetrates a longitudinal field up to 50 kOe.
9. The structure of the jet is very stable with respect to the geometric dimensions of the vortex, which in model experiments varied by more than an order of magnitude.

This noncriticality of the basic properties of the m. g. v. with respect to changes in scale, time, and currents by factors of 10^2-10^3 gives grounds to suppose that they are widely distributed and arise wherever plasma currents exist. In particular, m. g. v. may play an essential role on the Sun, not only in ejections, but also in floccular radiation, chromospheric flares, feeding of the corona, turbulent exchange, etc. Of course, the simple form discussed here does not exhaust the diversity found in nature. Toroidal vortices may be bent, twisted, or flattened, and then they will produce not a single jet, but something like a "palisade" of jets. In the presence of an external magnetic field, interaction of the jets with magnetic fields arises, especially in the case where their ascent occurs slowly.

The m. g. v. scheme undoubtedly requires further development and refinement as applied to astrophysical problems; however, it is suitable as a first approximation for the analysis of many processes. From the example of ejections of the type of active and eruptive prominences and flares, it is seen that there are no serious contradictions between the m. g. v. scheme and the observational facts.

Let us begin with the **external appearance**, although it is not the principal argument in favor of one hypothesis or another. All ejections, including slow prominences and bulges, according to the testimony of many authors(7–10), are extremely close in their form to fountain-like jets. Photographs of limb flares(10) and of some cases of eruptive prominences(7,8) agree, without substantial corrections, with the picture of an m. g. v. described above. It is necessary, however, to bear in mind that the emergence of an m. g. v. onto the surface the Sun cannot fail to be accompanied by the capture and entrainment of cold and dense solar plasma. The internal cavity of an m.g.v., filled with rarefied gas, glows weakly; therefore observers most often record not the vortex itself, but the masses entrained by it.

The diagram in Fig. 2a, b, c, d illustrates the phases of the rise of a jet which, in the end, turns into a chain of plasmoids leaving the solar atmosphere and carrying with it separate clumps of matter. It may also be applied to an entire class of so-called returning prominences, which, after rising, return to the Sun.

The power and magnetic pressure inside the vortex may vary within wide limits.

Fig. 2. Diagram of the emergence of an m.g.v. onto the surface of the Sun: **a, b, c** —sequence of rise; **d** —formation of a chain of plasmoids. **1** —surface of the Sun; I, H_φ, H_z —respectively the current, and the azimuthal and longitudinal fields of the m.g.v.

Therefore, in some cases, detachment of an m.g.v. from the cold mass of a prominence may occur without special disturbances, while in others it may occur with the formation of shock waves and flares. This circumstance makes it possible to explain why flares are always accompanied by prominences, but not every prominence produces a flare.

The ability, inherent in many active prominences, to renew themselves again and again in one and the same place of the sunspot agrees well with the property of an m.g.v. to break up into separate plasmoids—a property that may manifest itself equally both in the development of a plasma jet and in the emergence of a vortex onto the surface of the Sun (Fig. 2c, d). As for slower prominences, their formation may be associated with the capture of external magnetic fields that prevent the closing together of the inner walls of the vortex in the phase of its transition into a jet.

Magnetic fields. Diffusion of the field H_z of the m.g.v. into the external region occurs with skin times sufficiently large (11) to rule out the possibility of their registration in short-lived prominences and flares. Direct measurements of the intrinsic fields of an m.g.v. H_φ and H_z have a chance of success only when the vortex rises into the upper layers of the solar atmosphere, having freed itself from the shielding envelope. There are as yet no such measurements. Therefore only indirect conclusions are possible.

A. B. Severnyi and co-workers (9,10) established two characteristic facts associated with flares: 1) the preferential, although by no means obligatory, formation of flares in neutral (zero) regions of the magnetic field, and 2) redistribution and decay of magnetic-field gradients after flares. Both are explained within the framework of the m.g.v. scheme: first, by the fact that the rising vortex encounters the least opposition from the external magnetic field in the neutral region, and second, by the freeing of a certain cavity occupied by the m.g.v., whose dimensions are apparently commensurate with the dimensions of the zone of redistribution of the observed fields.

The velocities of ejections on the Sun are close to those observed in laborato-

plasma jets ($10^5 \div 5 \cdot 10^7$ cm/sec). It is significant that the MHD scheme makes it possible to explain the observed fact of the increase in the velocity of plasma jets during ejections, sometimes tenfold ($10^7 \div 10^8$ cm/sec), since the acceleration of clumps, especially frontal ones, continues in the jets throughout the entire lifetime of the internal magnetic fields, which gradually pass over into a force-free structure. Even after the jet breaks up into individual plasmoids, acceleration of the frontal clumps will take place owing to the braking of the MHD following behind them. The stretching of the jet and the acceleration of the plasma occur over the entire trajectory of the ejection.

Ejection time. The length of the jets in model experiments reached 10^2 cm, which, incidentally, was not the limit. If one introduces a geometrical factor of 10^7, then the time of solar ejections with a duration of $10^2 \div 10^4$ sec is quite well correlated with the measured (but not limiting) lifetime of plasma jets ($5 \cdot 10^{-6} \div 2 \cdot 10^{-4}$ sec.).

Radiation. The increasing and pulsating character of the glow of flares may be associated with the formation of shock waves when an MHD exits onto the surface of the Sun. Since the MHD is compressed in the subphotospheric region by external magnetic fields and by inertial forces created by the masses entrained, the gas-kinetic and magnetic pressure in its cavity exceeds the pressure of the surrounding medium. The appearance of individual plasmoids will each time be accompanied by new shock waves causing pulsations of light.

The spectra of prominences and flares give no grounds for assuming the presence in them of superhigh temperatures, which is entirely consistent with the properties of plasma jets. The correlation between them can also be extended further with respect to X-ray radiation, which, according to direct measurements ([12]), has in prominences and flares a hardness of hundreds of kiloelectronvolts. The appearance of electrons of such high energies is difficult to explain by anything other than acceleration processes similar to those observed by us in plasma jets.

The delay of X-ray radiation, characteristic of flares, by minutes and tens of minutes relative to the optical maximum follows from the non-simultaneity of shock-wave processes and of the most significant changes in the magnetic fields in the internal cavity of the jet.

There are as yet insufficient data for conclusions about the limiting attainable energies of ions and protons in such a peculiar accelerator as a flying MHD. However, model experiments, in which energies of hundreds of kiloelectronvolts were attained, indicate the possibility of generating relativistic particles in it as well.

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