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THE solar corona (the outermost portion of the Sun's atmosphere) is far hotter than the 'surface' (the photosphere). Recent observations of X-ray jets[1–4] (collimated flows of plasma at temperatures of a few million degrees) suggest that magnetic reconnection—the cutting of stressed magnetic field lines, which is associated with a violent release of energy, and their subsequent reconnection—may be responsible for heating the corona[5]. But the physical relationship between the X-ray jets, microflares (localized impulsive bursts whose total energy is below the level of the standard flares) and cooler Hα surges[6] (jets of gas at a temperature of about 10,000 K) has been unclear. In particular, it has been thought[7] that Hα surges and X-ray jets must arise from independent processes, on the grounds that reconnection would heat any plasma to X-ray-emitting temperatures. Here we present the results of magnetohydrodynamic simulations of the reconnection process, which show that X-ray jets and Hα surges can be ejected simultaneously from microflares[8,9]. This suggests that the total energy associated with the microflares is much greater than previously thought, and may be significant in heating the corona.

Many solar X-ray jets are known to be ejected from emerging flux regions[1–3]. This suggests that the magnetic energy of the emerging flux[10] is converted to the bulk kinetic and internal energy of the jets. How can this conversion take place? The model of Shibata *et al.*[11] is as follows: two separate magnetic field lines of emerging flux and of pre-existing coronal field come close together due to the rising motion of the emerging flux. By the effect of finite resistivity, they are cut and are reconnected with each other. The reconnection disconnects some of the highly stressed field lines in the emerging flux region and causes these field lines to fly outwards at one end as they try to straighten out. This whip-like motion accelerates (like a sling-shot) the plasma that lies on these field lines. At the same time, by Joule dissipation, magnetic energy is partly released as heat to increase the temperature of the plasma to a level when it emits X-rays. As a result, hot plasma is ejected from the reconnecting region, and may be observed as the X-ray jets.

Figures 1 and 2 show the results of numerical simulations of this model. The simulations are performed by solving the two-dimensional resistive magnetohydrodynamic (MHD) equations with uniform gravitational field. (See Shibata *et al.*[8] for detailed information.) For heat loss/gain, the effect of heat conduction and radiative cooling is neglected. The initial state of the simulation is a hydrostatic plasma layer of three regions: corona (10^6 K), chromosphere/photosphere (10^4 K), and convection zone (with convectively unstable stratification). Initially, the interface of corona and chromosphere is interpolated smoothly by the hyperbolic-tangent function. To simulate the emerging flux, we put a horizontal magnetic flux sheet in the convection zone. The emergence of the flux sheet is reproduced by simulating the magnetic buoyancy instability[12–14] (the Parker instability). To excite this instability, a small perturbation is initially imposed on the magnetic flux sheet within a finite horizontal domain. As for an initial coronal field, we studied two cases; (1) a uniform oblique field (with inclination angle of 45°; Fig. 1), and (2) an approximately uniform horizontal field (Fig. 2). Note that, in case (1), although there is initially a kink at the transition between the horizontal magnetic flux sheet and the oblique coronal field (Fig. 1), it has little effect on the dynamics because it is embedded in a dense gas which is not moved by the effect of the kink on the timescale of the simulations. The plasma is assumed to have anomalous resistivity[15–17], whose functional form is taken to be $\eta=0$ for $v_d<v_c$ and $\eta\propto(v_d/v_c-1)^2$ for $v_d\geqslant v_c$, where $v_d\equiv J/\rho$, is the non-dimensional (relative ion-electron) drift velocity, ρ is the non-dimensional mass density, J is the current density, and v_c is threshold above which anomalous resistivity sets in. The numerical code we use here has been thoroughly examined, and has been used for the study of the two-dimensional evolution of the Parker instability by previous authors[12–14].

In the simulation, as expected, the magnetic loops expand by the Parker instability (Fig. 1). The distance between the two footpoints of the expanding loops is ~4,000 km. When the top of the rising loops make contact with the coronal field, reconnec-

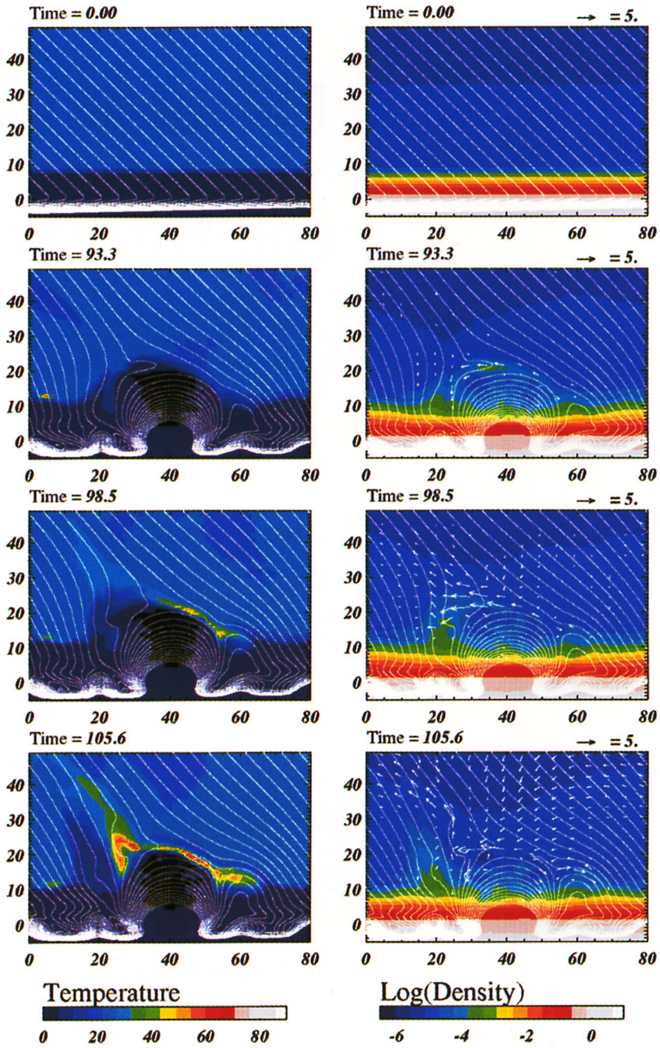

FIG. 1 Simulation of the reconnection of oblique field. The left-hand column shows temperature (T; colour map) in units of 10^4 K and magnetic field lines (**B**; lines). The right-hand column shows density ($\log_{10}\rho$; colour map) in units of 10^{-7} g cm^{-3}, magnetic field lines (**B**; lines), and velocity vectors (**v**; arrows). The times are in units of $\tau=H/C_s\approx 20$ s, and the length is in units of $H\approx 200$ km, where H and C_s are pressure scale height and sound speed in the photosphere/chromosphere, respectively. The parameters used in this simulation are as follows; initial coronal and chromospheric/photospheric temperature is 25 (which is somewhat low, but which has a weak effect on the result) and unity; vertical range of chromosphere/photosphere is 8 ($\approx$1,600 km);thickness of the chromosphere–corona interface is 0.5 ($\approx$100 km);plasma β (that is, ratio of gas pressure p to magnetic pressure $B^2/(8\pi)$) in the corona and in the horizontal magnetic sheet in the convection zone is 0.2 and 4.0, respectively; typical magnetic Reynolds number at the location of reconnection is ~300.

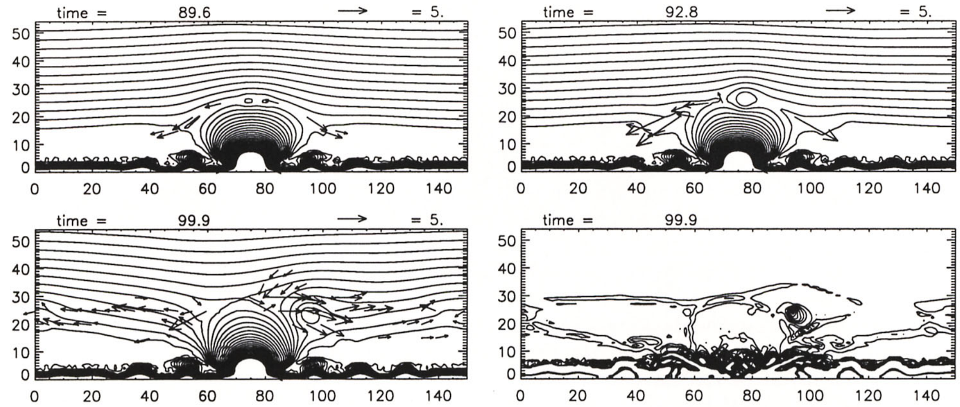

FIG. 2 Simulation of the reconnection of horizontal field. Panels show magnetic field lines **B** and velocity vectors **v** for $t = 89.6$, 92.8, 99.9 and current density J_y at $t = 99.9$. The units of times and lengths are the same as in Fig. 1. The scale of velocity vectors is shown as an arrow at the top right of each figure, whose length indicates 5 in units of C_s.

tion takes place between the two fields: the plasma at the interface is heated by Joule dissipation to X-ray temperature (~4–10 MK). At the same time, the field lines of emerging flux release their stress by straightening themselves out, accelerating hot plasma and creating a pair of hot jets (Fig. 1). One of the pair is ejected upward. The velocity of the hot jet reaches $\sim 100\ \mathrm{km\ s^{-1}}$, (which is approximately the Alfvèn speed that is realized when the magnetic energy is converted to the bulk kinetic energy) and the total bulk kinetic energy is $\sim 1.2 \times 10^{28}$ erg. These values are in good agreement with the typical observations of X-ray jets. Another interesting feature in this simulation is the high-temperature loops at the right side of the emerging flux in Fig. 1. This is the other product of the reconnection: while one of the pair of jets is ejected upward, the other goes down, colliding with the loops at the side of the emerging loops, and being compressed strongly there to form a very hot loop. This hot loop may account for some observations of a bright point (maybe unresolved bright loops) slightly away from the footpoint of the X-ray jets[2,3].

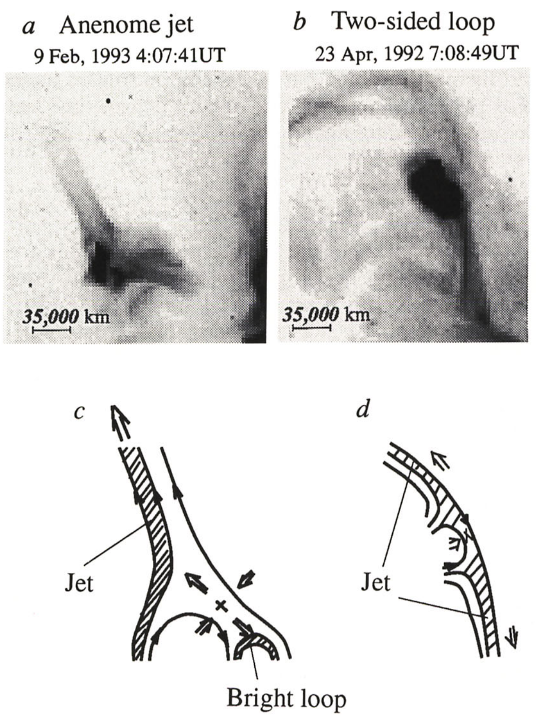

FIG. 3 Examples of two types of solar coronal X-ray jets observed by the Yohkoh soft X-ray telescope (after Shibata *et al.*[11]). In the anemone-jet (*a*), the active region at the footpoint of the jet looks like a sea-anemone. In the two-sided-loop type (*b*), a pair of jets appears at both sides of emerging flux along the nearly horizontal field. *c* and *d*, Are schematic pictures of models for each type (after Shibata *et al.*[11]).

In addition to these hot features, it is important that our simulation also reveals the whip-like motion of cool plasma (Fig. 1). The cool plasma in this motion is originally from the chromosphere, which is carried up with the expanding loops, ejected by the sling-shot effect (that is, acceleration by the tension force of disconnected field lines) due to the reconnection, and finally shows the whip-like motion. The velocity of this whip-like motion is a few tens of kilometres per second, and it may be observed as a cool jet, namely an Hα surge.

Figure 2 shows the results of our simulations in the case of horizontal field. In this case, multiple magnetic islands are created in the current sheet. Each island confines cool, dense, and high-pressure chromospheric plasma originally in the emerging loop. Soon after creation, the islands coalesce to a single large island (Fig. 2; $t = 92.8$), and the resulting large, cool island is ejected horizontally out of the current sheet. At the same time, the plasma near the neutral point is heated to X-ray-emitting high temperature, and is ejected to both sides of the neutral point, forming a pair of horizontal hot jets. The velocity of the jets is $\sim 100\ \mathrm{km\ s^{-1}}$. Though the geometry and dynamics in the horizontal-field case are somewhat different from those in the oblique-field case, we have found some common physical processes, such as the ejection of a cool jet (or blobs) and a pair of hot jets.

What are actual observations of X-ray jets on the Sun? Shibata *et al.*[11] found two types of interaction between emerging flux and coronal field, which result in ejection of X-ray jets. One is the anemone-jet type[18] (Fig. 3*a*), which occurs when emerging flux appears in a coronal hole where magnetic field is vertical or oblique (Fig. 3*c*). The other is the two-sided-loop type (Fig. 3*b*), which occurs when emerging flux appears in a quiet region where magnetic field is almost horizontal. Hot plasma is ejected along the coronal loops away from both sides of the emerging flux (Fig. 3*d*). The simulations shown in Figs 1 and 2 explain quite well these two observed types of interaction and their associated jets and loops. That is, the oblique-field case corresponds to the anemone-jet type, and the horizontal-field case corresponds to the two-sided-loop type.

It has long been thought that the cool Hα surges could not be explained by magnetic reconnection because reconnection would heat any cool plasma to X-ray temperatures. Consequently, it has generally been argued that surges require separate mechanism which accelerates the plasma without heating it at the same time. Our simulations now provide a possible physical picture of how magnetic reconnection can accelerate cool plasma (Hα surges) without much heating it. Our simulations also explain the coexistence of X-ray jets with Hα surges observed in some cases (ref. 1 and R. C. Canfield *et al.*, manuscript in preparation). Note also that our simulation has predicted a spatial offset of the Hα and X-ray jets, recently observed by Canfield *et al.* (manuscript in preparation). The cool magnetic island that is ejected horizontally in the horizontal-field case has not yet been observed, probably because of difficulties in resolving such fine structure. It will be interesting to search in future observations with high spatial resolution for ejection of this cool island.

Recently, Shimizu *et al.*[19] discovered many transient brightenings in active regions with the Yohkoh[20] soft X-ray telescope[21]. These transient brightenings correspond to spatially resolved microflares which have been often thought to be one of main mechanisms of the coronal heating[5]. Although the origin of these transient brightenings is still a puzzle, there is a possibility that they are the result of reconnections similar to those discussed above. The horizontal jets of the two-sided-loop case are not necessarily observed as jets, and instead they are more likely to be observed as transient loop brightenings if the horizontal field is a part of a coronal loop. Thus, our results may suggest that the jets and the loop brightenings are not physically independent but closely related. In relation to the coronal heating, it has been found that observed microflares do not possess enough energy to account for the coronal heating[22]. But the common physical origin of jets and loop brightenings strongly suggests the possibility of association of these two features, and hence that the relevant volume and the total energy of the jets and loop brightenings may be larger than those inferred from observations of loop brightenings. This suggests also that the estimate of the total energy in each loop brightening might be an underestimate.

The numerical simulations presented here should help the understanding of the physical relation between jets (both X-ray and Hα), loop brightenings and coronal heating, and further suggests the importance of magnetic reconnection[23,24] in solar coronal activity. □

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