Cosmic Magnetic Fields:
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X-ray jets and magnetic flux emergence in the Sun

Fernando Moreno-Insertis[1,2]

[1]Instituto de Astrofisica de Canarias, 38200 La Laguna (Tenerife), Spain
email: fmi@iac.es

[2]Dept of Astrophysics, Univ. La Laguna, Tenerife, Spain

Abstract. Magnetized plasma is emerging continually from the solar interior into the atmosphere. Magnetic flux emergence events and their consequences in the solar atmosphere are being observed with high space, time and spectral resolution by a large number of space missions in operation at present (e.g. SOHO, Hinode, Stereo, Rhessi). The collision of an emerging and a preexisting magnetic flux system in the solar atmosphere leads to the formation of current sheets and to field line reconnection. Reconnection under solar coronal conditions is an energetic event; for the field strengths, densities and speeds involved in the collision of emerging flux systems, the reconnection outflows lead to launching of high-speed (hundreds of km/s), high-temperature (10^7 K) plasma jets. Such jets are being observed with the X-Ray and EUV detectors of ongoing satellite missions. On the other hand, the spectacular increase in computational power in recent years permits to carry out three-dimensional numerical experiments of the time evolution of flux emerging systems and the launching of jets with a remarkable degree of detail.

In this review, observation and modeling of the solar X-Ray jets are discussed. A two-decade long computational effort to model the magnetic flux emergence events by different teams has led to numerical experiments which explain, even quantitatively, many of the observed features of the X-ray jets. The review points out that, although alternative mechanisms must be considered, flux emergence is a prime candidate to explain the launching of the solar jets.

Keywords. Sun: X-rays – Sun: flares – Sun: corona – Sun: atmosphere – magnetic fields – magnetohydrodynamics – methods: numerical

1. Introduction

A fundamental driver of the general dynamics of the solar atmosphere is the emergence of new magnetic flux from the solar interior. Episodes of magnetic flux emergence occur in the Sun on a bewildering variety of length- and timescales. Best known are those associated with large active regions or activity complexes which take place especially frequently toward the maximum of the solar activity cycle. When a large magnetic bipolar region or activity complex is formed on the surface, the simplest interpretation is that a bunch of magnetic flux ropes has emerged from the deep solar interior into the atmosphere (Zwaan 1978; Schrijver & Zwaan 2000). The global length scales of such magnetic complexes can be as large as 10^5 km, indicating that the associated flux ropes were formed in the main bulk of the convection zone (or at the bottom thereof) and have traversed it before appearing at the surface (Moreno-Insertis 1992, 1997). Going down from the largest scales, we find active regions in a continuum of sizes down to ephemeral active regions (Hagenaar *et al.* 2003, 2008). These appear at the center of meso- and supergranular cells; the two polarities of the region separate toward the boundaries of the cell, therefore reaching separations of order 10^4 km. At even smaller scales, recent high-resolution observations with the Hinode satellite have allowed to see flux emergence episodes in granules: Centeno *et al.* (2007) and Orozco Suárez *et al.* (2008) have clearly detected the emergence of magnetic tubes at the granular scale, with a length-scale of several hundreds of km. All of the foregoing indicates that turbulent convection in stars, in all its dominant scales, is at the root of the formation and fragmentation of the magnetic tubes that emerge at the surface. One should also expect flux emergence episodes on multiple scales to be a common occurrence in stars with magnetized convection in their envelope.

The emergence of magnetic flux from the interior causes important changes in the solar atmosphere, all the way from the photosphere to the corona. The corona is particularly affected since its structure and dynamics are dominated by the magnetic field. In the corona, two major types of change can occur following flux emergence. First, preexisting magnetic structures in equilibrium can become destabilized by the newly emerged magnetized plasma. Filament eruptions and coronal mass ejections may result from this kind of destabilization. Second, even when no large-scale destabilization takes place, *flaring* (possibly with ejection of collimated jets) can result from the flux emergence event (see Heyvaerts *et al.* 1977; Forbes & Priest 1984; Yokoyama & Shibata 1995; Shibata 1999): when the upcoming and preexisting magnetic systems get in contact, they press each other at a mutual interface. The magnetic field in general will be almost discontinuous across the interface: a concentrated current sheet is thus formed, which is a natural site for reconnection (Priest & Forbes 2000; Biskamp 2000). In the reconnection, field lines from either side of the interface are cut and new connections established, whereby the field lines from one side now become connected to those from the other side. This has profound implications for the structure of the corona. On the one hand, the general magnetic topology is modified. On the other, magnetic dissipation, which is proportional to the second derivatives of the field components, is important in the current sheet, given the large magnetic gradients. Magnetic energy is thus converted into heat at the reconnection site, and the plasma can become very hot, easily tens of 10^6 K. Further, according to the standard models of reconnection the plasma is ejected from the reconnection site with velocity of order the Alfven velocity, v_A. In the corona, v_A is high, say $v_A \gtrsim 100$ km s^{-1}. Hence, hot, X-ray emitting plasma is ejected with high speeds. Finally, the reconnection region is a natural site for the acceleration of microscopic particles (see references in Hannah & Fletcher 2006; Dalla & Browning 2008), which are then launched along the field lines both downward, toward the chromosphere, and also outward into more external regions of the corona or possibly into interplanetary space. Flux emergence is, therefore, a natural cause for the production of *flares* and their associated phenomena

The study of solar eruptions has received an important boost through the solar satellite missions with X-ray and EUV imaging and/or spectroscopic capabilities of the past ten years, like SOHO, YOHKOH, TRACE, RHESSI and Hinode. Of particular interest have been the observations of X-ray jets: these were discovered in the past decade using the soft X-ray telescope (SXT) onboard the Yohkoh satellite; a good summary and statistics of the properties of the jets deduced at the time was given by Shimojo *et al.* (1996). The Hinode mission, launched in September 2006, is monitoring these jets with a much higher spatial resolution in X-rays (close to 1 arcsec); it also has EUV spectroscopic capabilities through the EIS spectrometer. Particularly spectacular has been the observation of jets in coronal holes (see Cirtain *et al.* 2007), i.e., in the large coronal regions with field lines that extend out into the interplanetary medium. Fig. 1 shows an XRT image of a coronal hole in the polar regions of the Sun. In it, numerous sets of hot coronal loops are visible as bright features; also, a thin, elongated jet is visible toward the center of the figure. Detailed inspection reveals that many such jets have an inverted-Y shape and are flanked on one side by a compact set of hot loops (deep dark in the figure). A statistics of polar jets obtained in the first year of the mission contained interesting surprises: Savcheva

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Figure 1. Jet observed in a polar coronal hole by the X-Ray Telescope (XRT) onboard Hinode. The figure shows an image taken with XRT only a few months after the launch of the mission; a jet features prominently at the center of the image. A number of hot coronal loop systems appear in the coronal hole. Courtesy: Hinode mission / Monica Bobra.

et al. (2007) showed that there was a much higher number of jet occurrences (60 jets per day) than expected on the basis of the earlier data. Those authors also showed that the most probable outward velocities of the jets were between about 100 and 300 km s^{-1}. The histogram for jet lifetimes peaked at some 10 min; that for their sizes peaked at 8 Mm (width) and 50 Mm (height).

Following the abundant observational prompts, there has been a large amount of theoretical work trying to understand the generation and evolution of X-ray jets in the Sun, especially based on computer modeling. In the following, a summary of the theoretical and modeling effort is provided, with special emphasis in the most recent developments.

2. The theoretical understanding of the launching of X-ray jets in the Sun: 2D models

In the past twenty years a large effort was devoted to the two-dimensional modeling of emerging magnetic flux regions in and out of the solar interior (as exemplified by, for instance, Forbes & Priest 1984; Shibata *et al.* 1989, 1992; Nozawa *et al.* 1992; Yokoyama & Shibata 1995, 1996; Moreno-Insertis & Emonet 1996; Emonet & Moreno-Insertis 1998; Fan *et al.* 1998; Krall *et al.* 1998; Magara 2001; Miyagoshi & Yokoyama 2004; Nishizuka *et al.* 2008). The papers by Forbes & Priest (1984) and Yokoyama & Shibata (1995, 1996) were particularly illuminating for understanding the details of the ejection of X ray jets following flux emergence. The latter authors started with a magnetized sheet below the surface which was unstable to the *Parker instability*: bending the field lines in the vertical direction with, say, a sinusoidal shape of sufficiently large wavelength leads to excess evacuation at the tops and to the development of a buoyancy instability. In their calculations, the corona had a preexisting field either in the horizontal direction or inclined with some arbitrary angle. The rising top of the sheet, upon entering the atmosphere, bumps against the ambient coronal field. A current sheet is formed and reconnection ensues (see Fig. 2); the reconnected field lines are ejected as part of alfvenic outflows. Those impinge upon the surrounding matter, the plasma in the outflows goes through a fast shock and is diverted and launched along the field lines both downward, toward the surface, as well as outward into other coronal regions. The latter constitutes a hot, high-speed jet, which is a promising candidate to explain the actual jets observed in the Sun.

The model of Yokoyama & Shibata had a number of limitations, in part forced by the computing hardware available at the time. Their model had a rather dense corona (this allows to ameliorate the problem of the small timestep imposed by the high Alfven speed);

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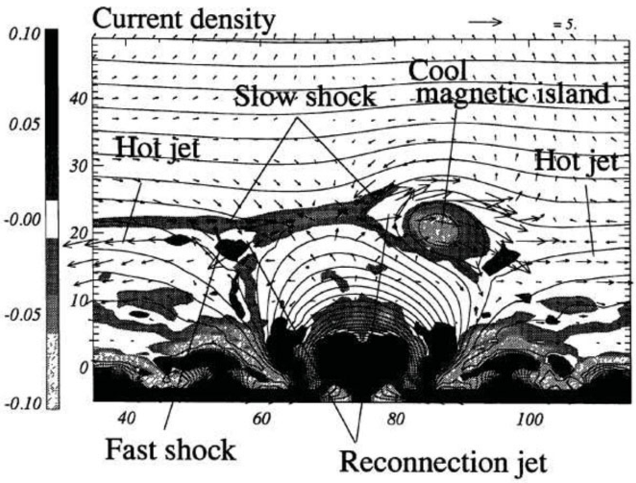

Figure 2. Two-dimensional model of reconnection and jet launching as a result of flux emergence from the solar interior. The emerged magnetized plasma collides with the overlying ambient coronal field and a current sheet is formed. Two hot jets are launched sideways along the coronal field lines. A thick plasmoid (cool island) is being formed in the current sheet. From Yokoyama & Shibata (1996)

also, the authors used a first-generation numerical scheme (Lax-Wendroff) which has the advantage of its simplicity, but can easily be fraught with high numerical diffusion. Yet, the results were an excellent first step toward a more complete modeling, possibly in three dimensions and with more sophisticated numerical tools.

3. Three-dimensional models

3.1. *General properties*

A new generation of more realistic, three-dimensional models of the launching of hot jets in the corona has been published in the past few years. Galsgaard *et al.* (2005, 2007), Archontis *et al.* (2005), Archontis & Török (2008) and Moreno-Insertis *et al.* (2008) have all provided detailed modeling of the reconnection phenomenon and the ensuing jet emission in 3D. Galsgaard *et al.* (2005, 2007) and Archontis *et al.* (2005) studied the results of reconnection between an emerging magnetic flux tube and a preexisting coronal field that points in the horizontal direction. These authors found the current sheet to have the shape of a concentrated, arch-like ribbon on top of the rising emerging plasma, as visible in Fig. 3. The jets are launched from the sides of the current sheet and the general geometry of sheet and jets is as shown in the right-hand panel. In the left panel, the color map corresponds to the plasma velocities; the jet is seen to have velocities of about 100 km s^{-1}. The temperature in the jet was typically several times 10^6 K. Galsgaard *et al.* (2007) studied the dependence of the results of the experiment on the mutual orientation of the magnetic field in the emerging and preexisting systems. The actual rate of rise of the current sheet is seen to be widely independent of the mutual orientation; reconnection is passive in these experiments and adapts to the dynamics imposed by the emergence process. Instead, the actual *reconnection rate* and the global change of connectivity between the ambient corona and the emerging system do depend sensitively on the mutual orientation. For initially almost antiparallel systems (the most favorable case for reconnection), some 30 min after emerging at the surface approximately 70% of

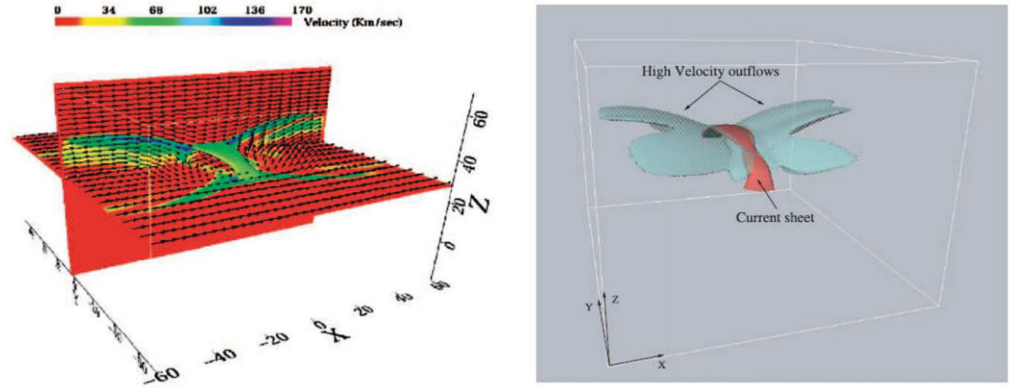

Figure 3. Structure of the current sheet and jet in a 3D experiment of flux emergence. From Archontis *et al.* (2005).

the initial flux in the upcoming system had changed connectivity and was now linked to the corona. In turn, in the least favorable case (magnetic field vectors close to parallel), very little reconnection occurs and the two systems remain virtually unconnected along the duration of the experiments.

Detailed conclusions concerning the actual reconnection process were provided by Archontis *et al.* (2005). The experiments revealed fully three-dimensional reconnection taking place across the current sheet. For instance, the reconnection occurred even though no prominent null points were apparent in the sheet. Also, in line with theoretical expectations (Pontin *et al.* 2005; Priest 2003; Priest *et al.* 2003) the reconnection in those experiments was shown to be a continuous process, instead of a one-off event, like in the classical 2D theory. In the 3D case, by pursuing a given field line in time one could see that it changed connectivity for as long as it was traversing the current sheet.

3.2. *Jets in coronal holes: theory and observation*

Of particular interest are the jets observed in coronal holes, for which there are now abundant, high-quality observational data, as explained in Sec. 1. The magnetic field in coronal holes links directly the Sun to the heliosphere, so the consequences of the violent reconnection and jet-launching in them can be felt directly in the interplanetary medium. A particular difficulty is the low density in the corona: 10^8 atoms cm^{-3} are expected there (Wilhelm 2006; Wilhelm *et al.* 2002), yielding typical Alfven velocities of order 1000 km s^{-1}, thus imposing very strict limits to the advance in time in the numerical experiments. In fact, the experiments described in the last section (3.1) were done with coronal density at least one or two orders of magnitude above that value (even higher densities were used for those of Sec. 2). The first 3D experiment of X-ray jets that included low coronal-hole densities was carried out by Moreno-Insertis *et al.* (2008) as part of a project aiming at comparing SOHO and Hinode data with 3D modeling. The results are summarized in the following.

Moreno-Insertis *et al.* (2008) start by using observational data of a coronal hole jet obtained with SOHO/MDI (magnetogram), Hinode/XRT (X-ray images) and Hinode/EIS (spectroscopic data). The jet appeared coinciding with a flux emergence episode at the surface. The 4-panel mosaic on the left in Fig. 4 shows the results of the analysis. The subpanel at the top left shows the XRT data in the form of a difference image (Open/Ti_poly). The jet appears as an intense (i.e., dark) feature around coordinates (−25, −110). Next to it, slightly below and to the right, a roundish dark feature

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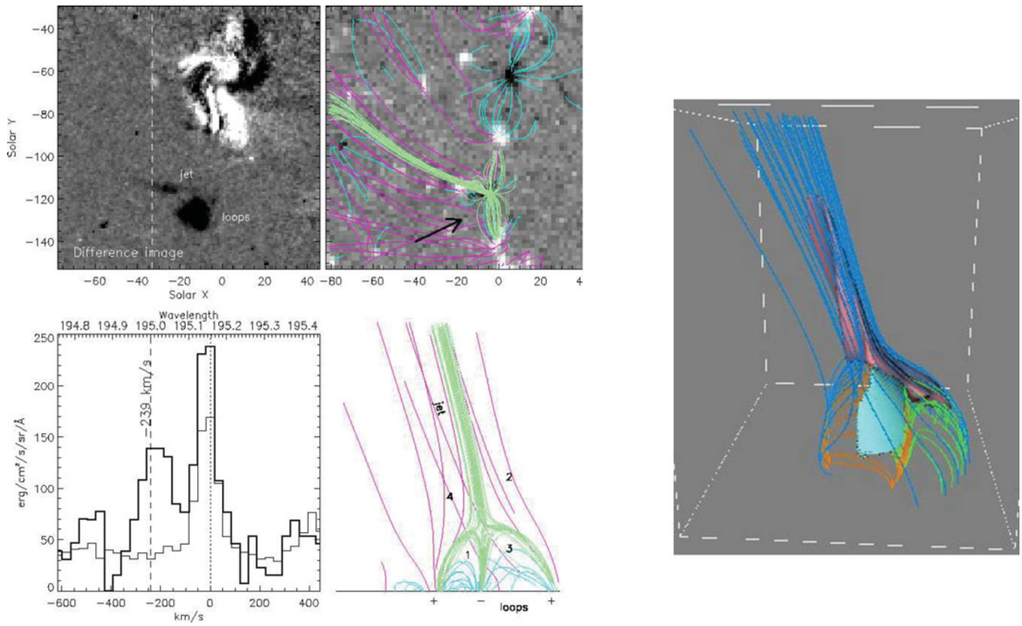

Figure 4. Left: Mosaic of observational results for a jet event occurred on 10th March 2007. The mosaic combines X-ray images from Hinode XRT, EUV spectroscopic data from Hinode EIS and magnetograms from SOHO MDI. Right: 3D perspective of a jet event obtained in the 3D numerical experiment of Moreno-Insertis *et al.* (2008)

corresponds to a set of hot coronal loops. In the subpanel immediately to the right, the result of carrying out a force-free magnetic field extrapolation on MDI magnetogram data of that same region is presented (the gray scale on the surface corresponds to the signed MDI magnetic flux measurement). A bunch of open fieldlines is seen stemming from the hot loop region and traversing the domain where the jet is located. The vertical perspective of the field line configuration, as seen from the direction indicated by the arrow, is given in the subpanel right below. Finally, the velocity values obtained on the basis of EIS spectra are given in the bottom-left subpanel. The prominent maximum at 240 km s^{-1} corresponds to the jet.

The numerical experiments in the paper by Moreno-Insertis *et al.* (2008) match the observational data remarkably well, both those just mentioned as well as the statistical analysis in the paper by Savcheva *et al.* (2007) discussed at the end of Sec. 1. In the experiments, the emergence of a twisted flux tube from below the photosphere leads to the formation of a current sheet, the start of reconnection, and the launching of a fast, hot jet. Fig. 5 contains a velocity (left) and temperature (right) map on a vertical cut around the time of peak jet activity. The jet clearly has the appearance of an *anemone* jet, in the notation of Yokoyama & Shibata (1996). Maximum temperatures and velocities are reached at the reconnection site itself (400 km $s^{-1}$and $3\,10^7$ K, respectively). In the jet, 200 km $s^{-1}$and 10^7 K are reached.

The field line configuration is worth noticing: below the reconnection site, two dome-shaped volumes are visible. The left dome contains the emerging material whose magnetic field is being brought up to reconnect with the overlying coronal system. The right dome contains hot, reconnected coronal loops. This configuration is strongly reminiscent of the field line extrapolation from observed surface data of Fig. 4 (bottom-right panel in the mosaic). To facilitate the comparison, Fig. 4 (right) contains a 3D view of the field lines

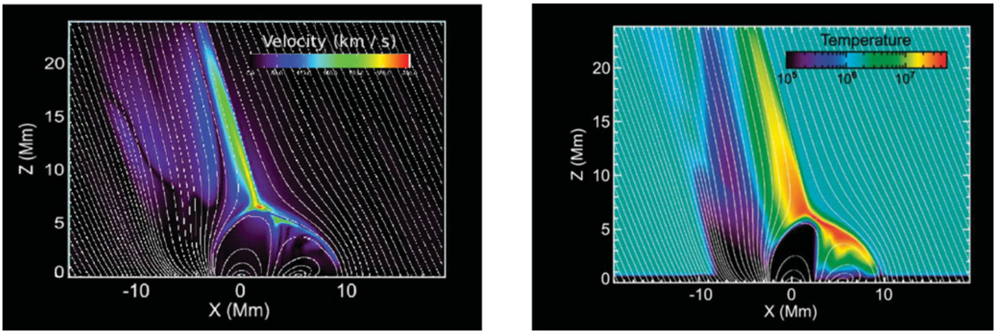

Figure 5. Velocity and temperature maps in a vertical cut of the three-dimensional experiment of Moreno-Insertis *et al.* (2008) around the time of peak jet activity

around the current-sheet. An isosurface of the current intensity is given in light blue as well as an isosurface of the temperature (pink) for $T = 6.5\ 10^6$ K. The similarity in the geometry and topology between the extrapolation and the simulation is apparent. A further result is the *drift* of the jet seen in the experiments: if Fig. 5 were a movie, we would see the position of the jet shift toward the right as time advances. This is associated with the gradual loss of plasma and magnetic flux from the emerged dome and the corresponding growth of the reconnected-loop dome. As a final note, the values of size, duration, ejection velocity and drift velocity of the jet in this experiment fall well within the ranges of variation of the jet parameters published by Savcheva *et al.* (2007).

4. Discussion and outlook

The study of X-ray jets, both observationally and theoretically, is undergoing rapid progress at present. The impressive series of solar space missions of the past 10 years have revealed that fast, hot jets are highly frequent in the Sun, especially in coronal holes, and have permitted to obtain a good idea of their main features. In this review an overview of results from jet models that occur as a consequence of emergence of magnetic regions from the solar interior has been provided. The most recent models include comparison with observational results obtained using X-ray, EUV and magnetogram data. An excellent match is obtained both in terms of field geometry and topology of the event as well as concerning values of physical quantities of the jet (duration, size, velocity, temperature, density and drift motion).

Additionally to the emergence of new magnetic flux, other mechanisms have been proposed that can cause the launching of jets like those observed by Hinode (Pariat *et al.* 2009; Patsourakos *et al.* 2008; Schmieder *et al.* 2008). Pariat *et al.* (2009) focus their attention on the helical structure and untwisting exhibited by a fraction of the observed jets. In their model, free energy is built up by twisting an initial dipole configuration that has an axisymmetric null-point + spine topology. If perfectly axisymmetric, reconnection would not be allowed in such a configuration. When finally the symmetry is broken, the energy is suddenly released, a burst is produced and a jet with obvious helical features is launched. The explanation of the twisting motions of some of the observed jets is a nice feature of this model. The match to the observed features in the jets perhaps needs to be improved, to reach the good level obtained by the flux emergence models.

Various important aspects of the jet phenomenon remain to be studied. A few of the 2D models mentioned in Sec. 2 took into account heat conduction. This is an important ingredient for the dynamics of any coronal phenomenon and, specifically, to study the so-called *evaporation* resulting from dumping thermal energy originating in the reconnection site down onto the dense chromospheric heights. To our knowledge, no 3D jet models up to date have included thermal conduction or optically thin cooling. A still larger step must be taken to properly include the thermodynamics of the low-atmospheric layers: models with proper treatment of the interaction between plasma and radiation field are needed for that. Fortunately, radiation-magnetohydrocodes dealing with all these aspects are already available, so a new generation of still more comprehensive jet models is likely to appear in the not too distant future.

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Discussion

JARDINE: Is the horizontal drift rate of the jets seen in coronal holes determined by the rate at which the reconnection site moves, rather than the velocity of the footpoints?

MORENO-INSERTIS: Yes, that is indeed the case. In some sense the footpoints play a passive role in the experiment and do not *move* much: as it changes connectivity, a given footpoint stops being part of the emerged *dome* and goes over either to be part of the set of hot reconnected loops or to be the root of one of the open field lines along which the jet hurries away. In doing so, the footpoint does not physically move. The reconnection site, on the other hand, is moving and changing shape as part of the process, and this causes the horizontal drift of the jet.

KHODACHENKO: As far as I can see, you use an assumption of a fully ionized hydrogen plasma in your numerical simulations. This is probably a good approximation in the corona, but in the chromosphere and especially in photosphere, solar plasma is known to be partially ionized. In photosphere $n_n/n_i \sim 10^4$, which completely changes the physics of magnetic field dynamics in the low solar atmosphere. Electric current dissipation rate is also thousands of times higher in the partially ionized plasmas, due to ion-neutral

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collisions. Could you somehow comment the validity of your model in the low solar atmosphere?

Moreno-Insertis: Complete ionization is not the only strong simplification of this type of models for the low atmosphere. All models discussed in this review (Sec. 2 and 3) disregard the interaction of the plasma with the radiation field. Like the partial ionization problem you correctly point out, the radiative cooling/heating may importantly affect the rising plasma especially in the photosphere. There are magnetic flux emergence models which already take into account either aspect like those by Arber *et al.* (2007), for the partial ionization, or Martínez-Sykora *et al.* (2008) and Tortosa-Andreu & Moreno-Insertis (2009) for the radiative aspects. However, to my knowledge no specific X-ray jet experiments have been carried out including those aspects so far.

de Gouveia Dal Pino: You have detected in the reconnection simulations continuous jets. What would the changes be in the initial conditions in order to see plasmons (or CMEs), or more intermittent ejections, since the same sort of reconnection phenomenon is expected to produce them?

Moreno-Insertis: In our previous jet experiments (see Archontis *et al.* 2005, 2006), we already saw the production of plasmoids which were ejected out of the current sheet toward the first part of the jet production process. We are investigating the possibility of intermittent behavior in the jets, but I cannot provide any conclusive reply on this at present.

Koutchmy: Two short questions: (a) Is gravity taken into account in your numerical simulation which means buoyancy is a driving force in the scenario proposed? (b) What about the interpretation of the apparent motions in transverse direction of the jet part(s)? Do field lines also move like in the case of an Alfven wave or a kink wave?

Moreno-Insertis: Gravity is certainly taken into account in our model: the emergence of the magnetized plasma is driven by the buoyancy force. The transverse motion of the jet is unlikely to be a phase motion associated with a wave. It rather seems to be due to the displacement and deformation of the reconnection site as more and more emerged flux is converted into hot coronal loops

Otmianowska-Mazur: The initial state. Do you apply the forced reconnection?

Moreno-Insertis: The reconnection appearing in the experiment is forced in the sense that the emerging plasma is pressing hard against the preexisting coronal field. That it does so is solely due to the magnetic forces that try to make the emerging material rise and expand in the corona and encounter some resistance in the ambient coronal medium. On a different score, the reconnection is facilitated by the hyperdiffusive resistivity we used in the model: it concentrates the diffusivity wherever there are large gradients and keeps the rest of the domain at a low-resistivity level, thus allowing for much larger Reynolds numbers than otherwise possible.