1. FINAL PUBLISHABLE SUMMARY REPORT

Summary description of the project objectives.

The project objectives were:

a) The acceleration mechanism of large-scale jets in the Sun.
b) The effect of the twist on the emergence of magnetic fields from the solar interior to the solar atmosphere and the formation of jets.
c) The onset of CME-like eruptions in emerging flux regions and their possible relationship to jets.
d) The relationship between CME-like eruptions and sigmoids.
e) Preparation of flux emergence experiments in three dimensions including thermo dynamical terms in the energy equation such as thermal conduction and partial ionization.
f) Preparation of the experimental/code set-up for the launching of jets from accretion disks around young stellar objects.

Description of the work performed since the beginning of the project.

a) We made an analysis of high cadence observations of solar jets observed in the Extreme Ultraviolet (EUV), at 304 ˚A, with the Atmospheric Imaging Assembly instrument aboard the Solar Dynamics Observatory (SDO). We investigated the temporal evolution of the jets by measuring the height of their leading edge as a function of time. Firstly, we assumed a ballistic motion for the jets and then a dynamical motion based on the actual velocity of the jets (without assuming a ballistic motion).
b) In the past few years, little attention has been given to the emergence of solar magnetic fields, which do not possess (or they have very small) twist. We performed experiments of emerging magnetic flux tubes, which were weakly twisted (i.e. at least four times less the twist needed for a flux tube to become kink unstable) or not twisted, through a highly stratified atmosphere. We studied the dynamics of the emergence of the magnetic fields and the onset and dynamics of jets, which were emitted in these regions. Furthermore, we studied the effect of the buoyant length of the emerging field (i.e. the parameter λ in our simulations) on the dynamics of the emergence and the onset of the jets.
c) We performed numerical simulations of twisted (but still not kink-unstable) magnetic flux tubes and their interaction with a pre-existing and oblique magnetic field in the corona. Based on our previous work on CME-like eruptions in emerging flux regions, we investigated the relationship between the erupting plasma and the jets formed by reconnection between emerging/erupting and pre-existing magnetic field due to reconnection. In cases with no ambient field, we also studied the distribution of current in small active regions produced by the emergence of a twisted flux tube.
d) We applied open boundary conditions in our simulations to study whether the eruptions produced in our experiments leave the numerical domain in a CME-like manner. We increased the size of the simulated active regions (up to 70 Mm) and the running time of the simulations (4-5 hours of solar time). We investigated the formation of sigmoids after/before the eruption(s) by studying the current density/temperature and plasma density distribution in the solar atmosphere.
e) We performed realistic (radiative MHD) experiments of flux emergence using the BiFROST code, including heat conduction, partial ionization and optically thin radiation. To perform these simulations, we used the parallel supercomputers (MHDcluster) at the University of St Andrews and at the University of Oslo.
f) We performed a series of three-dimensional numerical experiments (in collaboration with Dr. Titos Matsakos, University of Chicago, US) using the PLUTO code, to study the formation of jets driven by small-scale flux emergence and reconnection (e.g. internal or external with a pre-existing magnetic field) in accretion disks around young stellar objects.

Description of the results achieved so far.

a) We have found that the acceleration profiles of the jets suggest the influence of an upward driving force that weakens the decelerating effect of the solar gravitational field along the jet. A striking result is that this force is larger in the dynamical model, which suggests that the ballistic model does not properly determine the rising motion of the plasma jets. This force is highly likely to be associated with the magnetic tension of reconnected field-lines at the base of the emitting plasma jets. Another interesting result is that most of the jets that we observed energy to leave the corona and propagate into the outer space. Therefore, their contribution to the solar wind is questionable.

b) We have found that the emergence of a single weakly or non-twisted magnetic flux tube leads to the formation of two magnetic bipoles at the photosphere. Their interaction results in the formation of twisted magnetic fields in the photosphere/chromosphere and the recurrent emission of hot and high-speed jets (similar to EUV/X-ray jets observed in the Sun), which are confined by the outermost fieldlines that join the two bipoles. The decrease of the parameter λ initiates faster emergence above the solar surface and hotter/faster jets in the solar atmosphere.

c) We have found that (internal) reconnection of sheared fieldlines in the emerging flux region produces an erupting magnetic flux rope and a reconnection jet underneath it. The erupting plasma blows out the ambient field and, moreover, it unwinds as it is ejected into the outer solar atmosphere. The fast emission of the cool material that erupts together with the hot outflows due to external/internal reconnection forms a wider "blowout" jet. These jets have been repeatedly reported in observations.

d) We have found recurrent mini CME-like eruptions in a small active region (AR), which is formed by the *dynamical* emergence of a twisted flux tube. The eruptions are developed as a result of repeated formation and expulsion of new flux ropes due to continuous emergence and reconnection of sheared fieldlines along the polarity inversion line (PIL) of the AR. We find that each explosive eruption is followed by reformation of a sigmoidal structure and a subsequent "sigmoid-to-flare arcade" transformation in the AR. These results might have implications for recurrent CMEs and eruptive sigmoids/flares observations and theoretical studies. Also, we have found that active regions, the main sources of CMEs and flares, are born with substantial net currents, in agreement with recent observations.

e) We have found that convection-driven flux emergence leads to the formation of multi-scale magnetic loops at the solar atmosphere. The interaction of the magnetic loops leads to the formation of current sheets, which become fragmented due to the resistive tearing instability. The formation and ejection of plasmoids from the current sheets triggers the recurrent emission of X-ray jets and the powering of small flares (nano/micro-flares) that can heat the active corona.

f) We have found that a magnetic flux sheet, which becomes buoyantly unstable due to a density deficit at the accretion disk around a YSO, develops Ω-shaped magnetic loops. For high B-strength, the magnetic loops can erupt via a tether-cutting reconnection process (in a similar manner to solar CMEs but on a much smaller scale). We find reconnection jets underneath the erupting plasma. Interaction between the loop(s) and a pre-existing (poloidal) magnetic field can also lead to the onset of jets.

The potential impact of the final results and use.

The anticipated impact of the successful JET-CME project is mainly two-fold: in the scientific front, the project has profoundly contributed to our understanding of a) the emission of jets and the triggering of CME-like eruptions and b) the dynamic coupling between jets and eruptions. In the practical front, it contributes with the development and use of highly versatile numerical codes towards understanding the triggering and dynamics of solar eruptions. This contribution encompasses a greater societal impact because it brings the space-science community closer to optimizing space-weather forecasting. The project has demonstrated the optimal way to achieve this benefit, which is by jointly advancing physical understanding with computational innovation. Moreover, we have started to employ our well- tested solar techniques (i.e. experiments of magnetic flux emergence) in another astrophysical environment (i.e. YSO accretion disks), with the aim to study the emission of jets as a universal process. This has established new collaborations within the solar and astrophysics community and it has considerably contributed towards the development of a new area of research.