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**Laboratory Experiments to Simulate and Investigate**

**Paul Bellan  
CALIFORNIA INSTITUTE OF TECHNOLOGY**

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**05/12/2016  
Final Report**

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**14. ABSTRACT**  
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**15. SUBJECT TERMS**  
solar physics, plasma physics, eruptions from the solar corona, MHD instabilities, waves, heating, diagnostic methods, magnetohydrodynamics, whistler waves, MHD jets

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Final Report:  
"LABORATORY EXPERIMENTS TO  
SIMULATE AND INVESTIGATE THE  
PHYSICS UNDERLYING THE DYNAMICS  
OF MERGING SOLAR CORONA  
STRUCTURES"  
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Principal Investigator: Professor Paul M. Bellan  
Applied Physics and Materials Science  
California Institute of Technology  
Pasadena, CA 91125  
pbellan@caltech.edu  
626-395-4827

May 6, 2016

The solar corona is largely governed by the physics of plasmas and this physics has many different scales ranging from macroscopic MHD scales to microscopic particle orbit scales. There are also many different time scales ranging from steady-state equilibria to the very short periods of high frequency plasma waves. While these different space and time scales have been individually studied in the past, it is now realized that real-world physics typically involves substantial interaction between the different space and time scales. The dynamics of the solar corona is of particular interest because structures that are either static or have slowly built up to their present state can suddenly erupt and eject magnetized plasmas into interplanetary space while simultaneously spewing out energetic charged particles and radiating waves over a wide range of frequencies. Studying this complex behavior requires understanding equilibria, destabilization of equilibria, and transient phenomena having a great range of length and time scales.

Plasma equations such as magnetohydrodynamics, two fluid, or Vlasov have no intrinsic scale and so, in principle, phenomena occurring in the solar corona

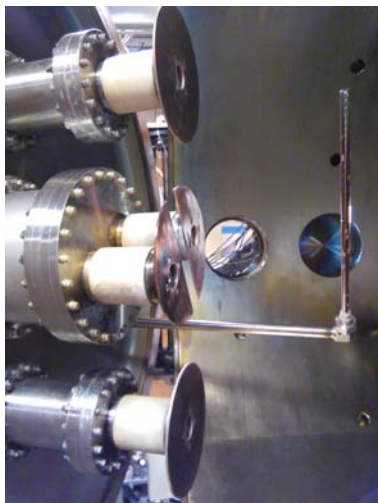


Figure 1: Electrode system used to make a pair of interacting MHD-driven plasma loops. Stalk on right is a magnetic probe array.

could also occur in laboratory experiments providing the appropriate boundary conditions are imposed. Such experiments are being implemented at Caltech. The experiments are not exact scale models but nevertheless provide useful qualitative insights because they are governed by the same dynamical relationships, have similar morphology, and often reveal the linkage between phenomena having widely separated length and time scales.

The laboratory experiments simulate coronal loop structures, MHD-driven jets, and manifest many of the MHD, microscopic, dynamical, wave and particle phenomena associated with solar physics. A typical electrode setup for making lab-scale versions of solar corona loops is shown in Fig. 1 while Fig.2 shows photos of actual plasma superimposed on the electrodes. During the last two years a new set of magnetic probes has been constructed that provides unprecedented space and time resolution so that the magnetic field, the current density, and the resulting MHD force vectors are measured in a three dimensional volume and then related to the observed motion. Figure 3 shows an example of the magnetic field measurements while Fig.4 shows measurements of the electric current density. These measurements allow direct calculation of the  $\mathbf{J} \times \mathbf{B}$  force and show that the plasma has bulk motion consistent with this force.

The research program has investigated MHD equilibria relevant to solar and space physics, dynamical behavior at the MHD scale (i.e., motion, deformation, and topological changes of the macroscopic structure such as expansion of a solar corona loop), MHD instabilities (e.g., kink and Rayleigh-Taylor instabilities), high frequency waves that are generated by transients associated with the instabilities (e.g., generation of whistler waves), particle energization (e.g., elec-

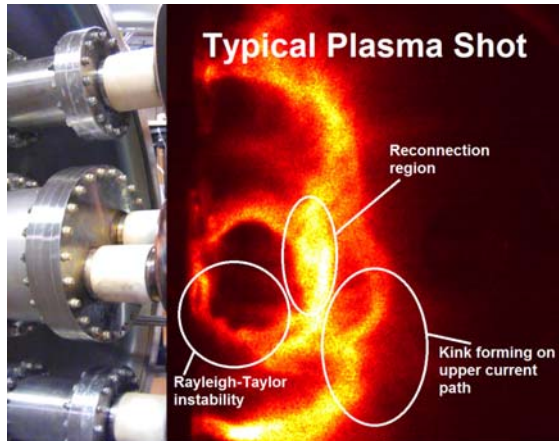


Figure 2: Photo of plasma superimposed on electrode structure.

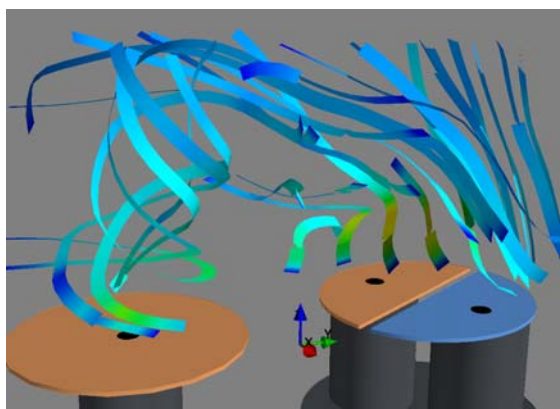


Figure 3: Experimentally measured magnetic field.

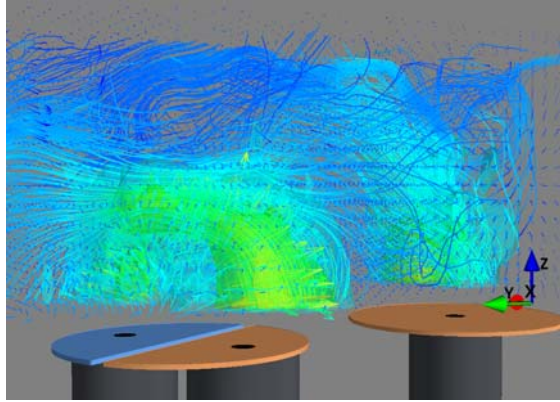


Figure 4: Experimentally measured current density.

tron and ion heating, changes in ionization state, emission of energetic photons), complex particle orbits in an electro-magnetic field (e.g., extension of adiabatic invariant concepts, stochastic heating, Hamiltonian concepts, relativistic particle motion in a circularly polarized wave), and new diagnostic techniques (e.g., coded aperture imaging, determining wave-vector  $\mathbf{k}(\omega)$  from single spacecraft measurements).

The results have been published in the scientific literature and presented at conferences. Fourteen papers have been published during 2011-2016 or are have been submitted (titles and journals are given in the list of references at the end of this report). Below are brief summaries of each paper. These summaries show how the research program has investigated behavior at many different length and time scales as well as the interaction between these varied scales.

1. Stenson & Bellan (2012) showed that the plasma coming from each foot-point of a coronal loop is actually a jet driven by MHD forces.
2. Bellan (2012) showed that the dispersion relations for magnetized warm plasma waves could be derived more efficiently by using current density rather than electric field as the fundamental wave quantity.
3. Moser & Bellan (2012) showed that the effective gravity produced by the lateral acceleration of a kink instability provides the environment for a fast growing Rayleigh-Taylor instability; thus there is a cascade from one type of MHD instability (kink) to another faster and finer-scale instability (Rayleigh-Taylor). This shows how one scale affects another.
4. Bellan (2013a) provided a new and simple derivation showing that the magnetic field of a whistler wave is circularly polarized even when the wave  $\mathbf{k}$ -vector is not parallel to the background magnetic field whereas the wave electric field is only circularly polarized for parallel propagation.

5. Bellan (2013b) showed that a relativistic electron interacting with a low amplitude circularly polarized electromagnetic wave (e.g., whistler) propagating in a magnetized plasma undergoes extremely strong pitch angle scattering.
6. Chaplin & Bellan (2013) described a fast trigger circuit for ignitron high power electric switch tubes such as used in our experiments. This trigger circuit uses IGBT devices
7. Bellan (2014) showed that fast non-MHD reconnection involves coupling between out-of-plane electric and magnetic fields and that the coupled equations are generalizations of the equations that produce whistler waves when the plasma is uniform. This shows that whistler physics is intimately related to fast reconnection.
8. Bellan *et al.* (2015) provided an overview of the experimental activities by the Bellan plasma group at Caltech. This paper was chosen to be a featured article by the Journal of Plasma Physics and given free distribution.
9. Bellan & Paccagnella (2015) described analytic Grad-Shafranov toroidal equilibria where the pressure on the magnetic axis is lower than the pressure external to the toroid so there is effectively a magnetic bubble. This is relevant to interplanetary magnetic clouds spawned by the eruptions of solar corona structures.
10. Perkins & Bellan (2015) analyzed orbit-averaged particle motion using Hamiltonian methods and showed how orbit-averaged quantities such as the flux enclosed by an orbit could be calculated from operations on the action integral.
11. Haw & Bellan (2015) described implementation of a coded aperture imaging system that provided high-speed images of a plasma jet without using lenses or mirrors.
12. Chai *et al.* (2016) described a set of interrelated experimental measurements that resolved the sequence of an MHD kink instability of a jet spawning a Rayleigh-Taylor instability that in turn spawned what is presumed to be a magnetic reconnection. Electron and ion heating as well of whistler wave radiation were observed in conjunction with the magnetic reconnection. The circular polarization of the whistler wave was observed. This paper was selected to be an Editor's Pick by the editor of the Physics of Plasmas. This paper illustrates a cascade of scales: MHD flow  $\Rightarrow$  MHD kink instability  $\Rightarrow$  MHD Rayleigh-Taylor instability  $\Rightarrow$  reconnection  $\Rightarrow$  whistler wave emission, particle energization.
13. Zhai & Bellan (2016) provided a semi-analytic model for the Rayleigh-Taylor instability resulting from the lateral acceleration of a cylindrical plasma such as a kinked jet or an accelerating coronal loop.



14. Bellan (2016) is a just-submitted manuscript to JGR-Space Physics showing how the wave-vector  $\mathbf{k}(\omega)$  of a traveling wave can be determined from single-spacecraft measurements of the wave magnetic field  $\mathbf{B}(t)$  and the wave current density  $\mathbf{J}(t)$ .

Paul Bellan and/or members of his group have attended and made presentations at the annual APS Division of Plasma Physics Meeting, the bi-annual High Energy Laboratory Astrophysics meeting, the AFOSR Space Science Program Review, the SHINE solar physics meeting, the International Astrophysics Conference, and the workshop “Complex plasma phenomena in the laboratory and in the universe”.

## References

- Bellan, P. M. 2012. Improved basis set for low frequency plasma waves. *Journal of Geophysical Research-Space Physics*, **117**. A12219.
- Bellan, P. M. 2013a. Circular polarization of obliquely propagating whistler wave magnetic field. *Physics of Plasmas*, **20**(8). 082113.
- Bellan, P. M. 2013b. Pitch angle scattering of an energetic magnetized particle by a circularly polarized electromagnetic wave. *Physics of Plasmas*, **20**(4). 042117.
- Bellan, P. M. 2014. Fast, purely growing collisionless reconnection as an eigenfunction problem related to but not involving linear whistler waves. *Physics of Plasmas*, **21**. 102108.
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- Bellan, P. M., Zhai, X., Chai, K. B., & Ha, B. N. 2015. Complex astrophysical experiments relating to jets, solar loops, and water ice dusty plasma. *Journal of Plasma Physics*, **81**. 495810502.
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- Chai, K.B., Zhai, X., & Bellan, P. M. 2016. Extreme ultra-violet burst, particle heating, and whistler wave emission in fast magnetic reconnection induced by kink-driven Rayleigh-Taylor instability. *Physics of Plasmas*, **23**. 032122.
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- Stenson, E. V., & Bellan, P. M. 2012. Magnetically Driven Flows in Arched Plasma Structures. *Physical Review Letters*, **109**(7). 075001.
- Zhai, X., & Bellan, P. M. 2016. A hybrid Rayleigh-Taylor-current-driven coupled instability in a magnetohydrodynamically collimated cylindrical plasma with lateral gravity. *Physics of Plasmas*, **23**. 032121.

1.

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The full name of the principal investigator on the grant or contract.

Paul Murray Bellan

**Program Manager**

The AFOSR Program Manager currently assigned to the award

Julie J. Moses

**Reporting Period Start Date**

08/01/2011

**Reporting Period End Date**

07/31/2016

**Abstract**

The research program has used laboratory experiments and theoretical models to investigate MHD equilibria relevant to solar and space physics, dynamical behavior at the MHD scale (i.e., motion, deformation, and topological changes of the macroscopic structure such as expansion of a solar corona loop), MHD instabilities (e.g., kink and Rayleigh-Taylor instabilities), high frequency waves that are generated by transients associated with the instabilities (e.g., generation of whistler waves), particle energization (e.g., electron and ion heating, changes in ionization state, emission of energetic photons), complex particle orbits in an electro-magnetic field (e.g., extension of adiabatic invariant concepts, stochastic heating, Hamiltonian concepts, relativistic particle motion in a circularly polarized wave), and new diagnostic techniques (e.g., coded aperture imaging, determining wave-vector  $k$  from single spacecraft measurements).

In one set of experiments a fast MHD-driven plasma jet undergoes a kink instability which causes the plasma to form a fast growing corkscrew end. The lateral acceleration associated with this growth produces an effective gravity that provides the environment for an even faster Rayleigh-Taylor instability. The Rayleigh-Taylor instability instigates what is believed to be a magnetic reconnection. Rapid particle heating and emission of whistler waves is observed in association with whistler emission.

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In another set of experiments a magnetic probe array has been used to map out the 3D magnetic field of a loop-like plasma with sufficient resolution to allow calculation of the current density  $J$  from the curl of the magnetic field.

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Bellan, P. M. 2013a. Circular polarization of obliquely propagating whistler wave magnetic field. *Physics of Plasmas*, 20(8). 082113.]

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**Change in AFOSR Program Manager, if any:**

Dr. Julie Moses has replaced Dr. Kent Miller

**Extensions granted or milestones slipped, if any:**

**AFOSR LRIR Number**

**LRIR Title**

**Reporting Period**

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**Program Officer**

**Research Objectives**

**Technical Summary**

**Funding Summary by Cost Category (by FY, \$K)**

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