* 1. **Final publishable summary report**

**Part 1. Executive summary**

The objectives of this project on “Nonlinear dynamics of the solar-terrestrial environment” are to advance our knowledge of the complex spatiotemporal dynamics of space plasmas, and their applications in solar-terrestrial relation, space weather, and other frontier problems in space science, and to strengthen the long-term EU-Brazil cooperation in space research. Two Tasks were formulated for this project. Task 1: Modeling Alfvén waves and intermittent turbulence in space plasmas, and Task 2: Observation of coherent structures and intermittent turbulence in space plasmas. The objectives and two Tasks for this project have been successfully executed. The scientific results of Task I were published in 8 papers and of Task II were published in 4 papers, all in international peer-reviewed journals. The results of this project were presented in 7 invited talks, 4 oral papers, and 4 poster papers in 15 international meetings. Under the coordination of Dr. N. Vilmer, the scientific representative of the project's coordinator, a mini-course with a series of 4 tutorial lectures were given by Dr. A. C.-L. Chian at Observatoire de Paris in 2011. Through the collaboration of Dr. Chian with Dr. J.-L. Bougeret of Observatoire de Paris and the WISER research & teaching network, a Special Session (SpS10) on the Dynamics of the Star-Planet Relation was organized at the General Assembly of the International Astronomical Union (IAU) in Beijing-China in 2012; two Public Forums at Peking University and Tsinghua University were organized as the public educational outreach activities of SpS10. Dr. Chian presented a Keynote Talk at the Joint Annual Meeting of the Solar-Terrestrial Centre of Excellence (STCE-2012) and Alfvén Workshop in Brussels-Belgium. Dr. Chian was one of the conveners of the 9th International Workshop on Nonlinear Waves and Chaos in Space Plasmas held in La Jolla-USA in 2013; a special issue of Nonlinear Processes in Geophysics will be co-edited by Dr. Chian. This project succeeded to establish an international scientific cooperation program on “Nonlinear dynamics in the solar-terrestrial environment” focused on three topics: 1) Alfvén waves and turbulence in solar and interstellar plasmas; 2) Computer modelling of solar physics phenomena; and 3) Analysis of observational solar-terrestrial data. This scientific program involves the partnership of the following institutions: 1) Europe: Observatoire de Paris-France, Observatoire Cote d’Azur-France, Ecole Normale Superieure/Paris-France, Ecole Polytechnique/Palaiseau-France, INRIA-France, LATMOS-France, Belgian Institute for Space Aeronomy-Belgium, Potsdam University-Germany, MPI for Plasma Physics/Greifswald-Germany, University of Calabria-Italy, Space Research Institute-Russia, Institute of Earthquake Prediction Theory and Mathematical Geophysics-Russia, NORDITA & University of Stockholm-Sweden, Uppsala University-Sweden, University of Zurich-Switzerland, Cambridge University-UK, Durham University-UK, St. Andrews University-UK; 2) Brazil: National Institute for Space Research (INPE), Institute of Aeronautical Technology (ITA), University of Sao Paulo (USP), University of Brasilia (UnB); 3) Chile: University of Chile, University of Concepcion; 3) USA: University of California at Berkeley, University of Texas at Austin; 4) China: Purple Mountain Observatory, Luoyang Normal University.

**Part 2. Summary description of project context and objectives**

 This project is closely related to the scientific activities targeted by CAWSES-II (Climate and Weather of the Sun-Earth System), an international program in 2009-2013 sponsored by SCOSTEP (Scientific Committee on Solar-Terrestrial Physics) of ICSU (the International Council of Scientific Unions), which was established to significantly enhance our understanding of the space environment and its impacts on life and society, by coordinating international activities in observations, modeling, and applications crucial to achieving this understanding (<http://www.cawses.org/CAWSES/Home.html>). To achieve this goal, CAWSES-II calls for the international scientific community to discover the important processes that connect changes at the solar surface with features in the geospace environment and ultimately with climate variability. These connections are key to understanding complex planetary environments, and the general elements that enable planets to sustain life. Scientific breakthroughs in all these areas require international collaboration across national boundaries and across disciplines.

 Solar variations such as solar flares, energetic particle bursts, coronal mass ejections, and high-speed solar wind streams directly alter space weather on short time scales. Electromagnetic radiation drives the ionosphere, while solar particulate outputs penetrate through space, interact with the magnetosphere and upper-middle atmospheres, and even produce disturbances at Earth’s surface. CAWSES-II stresses that the systems approach is crucial to understand and forecast space weather. The objective of this project is to perform modeling and observation of the nonlinear dynamics of the space environment, using the innovative methodology of complex systems approach, to meet the challenge of Task Group 3 of CAWSES-II: “*how short-term solar variability affects the geospace environment”*.

 This project aims to make significant and far-reaching contributions to advance our knowledge of the complex spatiotemporal dynamics of space plasmas, and their applications in solar-terrestrial relation, space weather, and other frontier problems in space science, and to strengthen the long-term EU-Brazil co-operation in space research.

 Principle aims of this project are to execute the following two tasks

***Task 1 - Modeling Alfvén waves and intermittent turbulence in space plasmas:*** to build a nonlinear dynamical model of Alfvén waves and intermittent turbulence in space plasmas based on numerical simulations.

***Task 2 - Observation of coherent structures and intermittent turbulence in space plasmas:*** to perform nonlinear analysis of coherent structures and intermittent turbulence in space plasmas based on *in-situ* and *remote* observational data and images.

 The Sun constantly releases energy into space through solar electromagnetic radiation and solar wind (Parker 2007). The absorption by the Earth of electromagnetic emissions such as heat and UV radiation from the Sun triggers photosynthesis and makes life possible; it also influences the circulation of currents in the atmosphere and oceans, as well as the formation of cloud, rain, snow and ice which are responsible for climate change (Labitzke 2007). Solar activity is controlled by the magnetic fields generated by its dynamo that exhibits solar cycles varying with an average cycle of eleven years (Brandenburg 2007). Solar and interplanetary radio emissions are electromagnetic signatures of the dynamical processes taking place in solar and interplanetary plasmas (Bougeret & Pick 2007).

 Space weather results from the Sun-Earth coupling caused by the variability of solar wind that induces the variability in geomagnetic activities (Lanzerotti 2007). The Sun-Earth system is driven far from equilibrium and is, therefore, dominated by waves, instabilities and turbulence, as evidenced by the intermittent and chaotic dynamics of solar cycles (Chian et al. 2006, 2010a). Intermittency is characterised by abrupt changes of the physical variables in space-time, with alternating periods of high- and low-level fluctuations. It displays multi-scale behaviour with power-law spectrum and non-Gaussian statistics in the probability distribution function of fluctuations. Chaos is characterised by aperiodic fluctuations in time and disordered patterns in space, and sensitive dependence on small changes in the initial conditions and system parameters (Lorenz 1963). Nonlinear dynamics of the Sun-Earth system are governed by coherent structures embedded in wave turbulence and fully-developed turbulence in fluids (atmosphere, ocean) and plasmas (solar interior, solar atmosphere, solar wind, planetary magnetosphere-ionosphere). Coherent structures such as Coronal Mass Ejections (CME), current sheets, and interplanetary Alfvén waves/turbulence are manifestations of intermittent turbulence processes operating in the space environment. CME triggers aurora and other electromagnetic disturbances on the Earth, discharging between 1,000 to 10,000 million kg of plasma from the Sun into space at speed up to 2,500 km/s (Cargill & Harra 2007). Large-amplitude interplanetary Alfvén waves are solar-wind drivers of geomagnetic activities such as High-Intensity Long-Duration Continuous Auroral Activities (HILDCAAs) (Tsurutani & Gonzalez 1987).

 The recent discovery of exoplanets in extrasolar systems have motivated the search for Earth-like exoplanets by targeting flaring stars where frequent CME-like events are expected (Chian et al. 2010a). The study of the solar-terrestrial environment that surrounds the Earth not only reveals the complex nature of the Sun-Earth relation, but also improves the understanding of our role in the universe (Kamide & Chian 2007). This project combines novel theoretical, observational and computational tools to investigate the fundamental processes that may advance significantly our ability to forecast space weather and search for exoplanets.

 To bring together an international group of high-quality scientists to develop the most innovative tools of complex systems and computation to study the nonlinear dynamics of the space environment, the Marie Curie International Incoming Fellow of this project, Dr. Abraham Chian, founded the research and training network **WISER** (World Institute for Space Environment Research, <http://www.cea.inpe.br/wiser>) in 2001. WISER operates as an international network of centers of excellence dedicated to promote collaboration in research and training in the earth-ocean-space environment, focusing on the study of the impact of space weather and space climate on the earth’s climate, environment and technology, as well as the prevention of natural disasters such as storms and earthquakes, with emphasis on theory, computer modeling, data analysis, and prediction (Moussas, Chian & Shaltout 2010). The mission of WISER is to “*linking nations for the peaceful use of the earth-ocean-space environment*”. Hundreds of space and earth scientists from leading academic and research institutions from over 30 countries are taking part in WISER activities. WISER has organised 12 workshops worldwide and 3 advanced schools in Brazil, Italy and Costa Rica, and published 12 special volumes of journals, including 3 volumes of *Space Science Reviews*, 6 volumes of *Nonlinear Processes in Geophysics,* and 3 volumes of *Advances in Space Research*. These WISER publications have contributed considerably to improve our understanding of the nonlinear dynamics in the space environment. In 2007, Dr. Chian co-edited with Dr. Kamide of Nagoya U. the *Handbook of the Solar-Terrestrial Environment*, which has become a leading reference book in space science as evidenced by the publication of a Chinese edition in 2010. This project continues to pursue the mission of WISER, in collaboration with space scientists at LESIA and in Europe, to extending the role of Europe in WISER research and training activities.

**Part 3. Description of the main S&T results/foregrounds**

**A. Foregrounds**

In collaboration with LESIA and WISER scientists, we applied the complex systems approach to model (Task 1) and observe (Task 2) the nonlinear dynamics of the solar-terrestrial environment.

**Task 1 - Modeling Alfvén waves and intermittent turbulence in space plasmas**

Alfvén waves and turbulence are the manifestation of short-term solar variability driven by dynamical solar activities such as solar flares, coronal mass ejections, and high-speed solar wind. The southward component of interplanetary Alfvén waves causes geomagnetic storms and substorms, such as the HILDCAAs events, through magnetic reconnection with the geomagnetic magnetic field (Tsurutani & Gonzalez 1987; Chian et al. 2006; D’Amicis, Bruno & Bavassano 2009). A better knowledge of the nonlinear dynamics of Alfvén waves in solar atmosphere and solar wind will improve space weather forecasting. Moreover, Alfvén waves play a vital role in stellar mass loss and drive stellar winds in certain types of stars and in the magnetic interaction between a host star and an exoplanet (Vidotto & Jatenco-Pereira 2006; Chian et al. 2010a).

***Nonlinear dynamics, chaos & turbulence***

Space environment is an intrinsically nonlinear dynamical system dominated by waves, instabilities, and turbulence (Chian et al. 2010a). A variety of nonlinear waves are found in space plasmas: solitons, double layers, vortices, shocks, electron and ion holes. Turbulence is a nonlinear phenomenon where multi-scale stochastic and deterministic chaotic processes coexist. A typical power density spectrum of turbulence shows power-law which is an indication of energy cascade (either direct or inverse) due to multi-scale interactions. In the direct cascade mechanism, energy is transferred from large to small scales, whereas in an indirect cascade mechanism energy is transferred from small to large scales. In general, turbulence in the space environment is intermittent, exhibiting spatiotemporal variations that switch randomly between bursting periods of large-amplitude fluctuations and quiescent periods of low-amplitude fluctuations. Such intermittent behavior becomes more pronounced at small scales. The statistical approach to turbulence shows that the probability distribution functions of fluctuations are of nearly Gaussian shape at large scales, but become non-Gaussian with sharp peaks and fat tails at small scales. This implies that extreme events, i.e., large-amplitude fluctuations, have a higher probability of occurrence than if they are normally distributed. Coherent structures are localized regions of turbulence where finite amplitude-phase correlation exists (He & Chian 2003, Chian et al. 2010b), with a typical lifetime longer than the background of stochastic fluctuations.

Turbulence can display chaotic behavior. Chaos in the Earth's atmosphere was discovered by Lorenz **(**1963**)** and has contributed greatly to the study of nonlinear wave-wave and nonlinear wave-particle interactions in a plasma turbulence. A chaotic system shows sensitive dependence on the system's initial conditions so that nearby orbits will diverge exponentially in time; it also demonstrates sensitive dependence on small variations of the system parameters. Order and chaos can coexist in a nonlinear dynamical system. The ordered state is described by a stable periodic orbit **(**regular attractor**),** and the chaotic state can be described by a chaotic attractor. The dynamical systems approach to turbulence provides a powerful technique to probe the nonlinear dynamics of the solar-terrestrial environment.

***Chaotic saddles & amplitude-phase synchronization***

Chaotic saddles are unstable coherent structures that form the skeleton of a chaotic attractor and can describe the transient dynamics that precedes the convergence of a dynamical system to an attractor. It has beenobserved in a variety of nonlinear systems ranging from fluid dynamics and chemistry to population dynamics and biology (Tél & Lai 2008). The tendency for a turbulence in pipe flows not to persist but decay to a laminar state if the observation time is long enough is explained by the turbulent state corresponding to a chaotic saddle; the boundary between the chaotic saddle (turbulence) and the laminar state is determined by the edge of chaos (Eckhardt et al. 2007).

Spatiotemporal chaos refers to the state of a spatially extended system which is chaotic in time and irregular in space. A spatiotemporal chaotic behaviour reflects permanent chaos when it is governed by a chaotic attractor, or transient chaos when it is governed by a chaotic saddle. Chaotic saddles play a key role in nonlinear waves and turbulence in fluids and plasmas (Rempel & Chian 2007; Rempel, Chian & Miranda 2007; Rempel, Miranda & Chian 2009; Chian et al. 2010b). As a control parameter is varied, the asymptotic solution of the system undergoes a transition from a laminar state characterised by regularity in space to a turbulent state characterised by spatiotemporal chaos. At the onset of permanent spatiotemporal chaos, the temporally chaotic attractor loses its stability and is converted to a temporally chaotic saddle, which couples to the pre-existing spatiotemporally chaotic saddle. The resulting time series of the on-off spatiotemporal intermittency displays random switching between laminar and bursting regimes, similar to the intermittent behaviour observed in solar cycles and in the Alfvén intermittent turbulence observed in the solar wind.

The study of phase synchronization in a system of coupled oscillators has improved our knowledge of a variety of nonlinear phenomena. Phase synchronization may explain the formation of nonlinear coherent structures such as solitons and vortices in turbulence. Tél & Lai (2008) relates transient chaos to spatially diffusive coupling, which prefers the neighbouring sites to synchronize. The concept of phase synchronization of coupled periodic oscillators has been generalized to coupled chaotic oscillators. He & Chian (2003) showed that the phase synchronisation resulting from multi-scale interactions induces strong energy bursts in a well-developed on-off spatiotemporal intermittency. At the onset of permanent spatiotemporal chaos, Rempel, Chian & Miranda (2007) and Rempel, Miranda & Chian (2009) showed that the time-averaged Fourier power spectrum of the temporally chaotic saddle is narrower than the spatiotemporally chaotic saddle, and the time-averaged Fourier power spectral entropy of the temporally chaotic saddle is lower than the spatiotemporally chaotic saddle. Chian et al. (2010b) demonstrated the duality of amplitude-phase synchronization due to multi-scale interactions in an on-off intermittency at the onset of permanent spatiotemporal chaos.

***Dynamical model of Alfvén waves and intermittent turbulence***

The transition from wave to turbulence via various routes to chaos has been studied by Chian et al. (2006, 2007) using a low-dimensional model of nonlinear Alfvén waves described by the stationary solutions of a driven-damped derivative nonlinear Schrödinger equation. The high-dimensional, spatiotemporal dynamics of nonlinear Alfvén waves has been studied by De Oliveira, Rizzato & Chian (1997), Krishan & Nocera (2003) and Nariyuki & Hada (2006). In this project, we extend the recent advances in the theory of spatiotemporal chaos of He & Chian (2003), Rempel & Chian (2007) and Chian et al. (2010b) to formulate a nonlinear dynamical model of Alfvén waves and turbulence. In particular, we examine the emergence of coherent structures (chaotic saddles) and the duality of amplitude-phase synchronisation in a spatiotemporal Alfvén intermittency, by solving numerically the derivative nonlinear Schrödinger equation in space and time. We will compute the correlation function, Shannon entropy of power-phase spectra, spectral average and the Kuramoto order parameter, and apply the Fourier-Lyapunov representation of Yamada & Ohkitani (1988) and Chian et al. (2010b) to determine the amplitude and phase dynamics of chaotic saddles in an Alfvén intermittent turbulence. In addition, we investigate the phenomenon of edge-of-chaos (Skufca et al. 2006; Eckhardt et al. 2007) in an Alfvén intermittent turbulence modelled by the derivative nonlinear Schrödinger equation, to analyse the nature of wave-turbulence transition in space plasmas.

**Task 2 - Observation of coherent structures and intermittent turbulence in space plasmas**

To complement the theoretical studies of Task 1, we joine efforts with LESIA and WISER scientists to perform observational studies of the nonlinear dynamics of the solar-terrestrial environment using *in-situ* and *remote sensing* data and image of space plasmas.

There is observational evidence of amplitude-phase synchronization in nonlinear wave interactions in the space plasma turbulence, as demonstrated in a series of papers by Chian and his collaborators (Koga et al. 2007; Chian & Miranda 2009; Miranda et al. 2010; Muñoz et al. 2010**)**. Koga, et al. (2007) used the Geotail magnetometer data, upstream and downstream of the Earth´s bow shock, to show that nonlinear wave interactions among scales are the origin of magnetic field intermittent turbulence in the solar wind. Chian & Miranda (2009) extended the nonlinear analysis of Koga et al. (2007) to the ACE and Cluster magnetometer data in the unshocked and shocked solar wind, at 1 AU and upstream of the Earth’s bow shock, respectively, and reported the first direct measurement of the amplitude-phase synchronization due to nonlinear multi-scale interactions in the ambient solar wind turbulence. Miranda et al. (2010) carried out a nonlinear coherence analysis of solar and interplanetary magnetic field based on the SOHO MDI image and ACE-Cluster data of an ICME-event in January 2005, and measured finite degrees of non-Gaussianity and phase coherence in the magnetic fluctuations in the solar active region and in the interplanetary shock associated with this ICME-event. These results provide evidence of the duality in the amplitude-phase synchronization related to multi-scale interactions in the magnetic field intermittent turbulence in a solar active region and in an interplanetary shock. Muñoz et al. (2010) used the plasma data of four Cluster spacecraft to detect current sheet and magnetic reconnection in the interplanetary shock of the ICME event of 21 January 2005.

We extend our previous observational studies of intermittent turbulence in solar and interplanetary plasmas using measurement of Cassini, Cluster, STEREO, Ulysses and other spacecraft. In collaboration with LESIA and WISER scientists, we compare and combine our approaches to improve the nonlinear analysis and interpretation of space data. We find out what kind of coherent structures are responsible for the solar and interplanetary intermittency. We build new nonlinear techniques to detect and characterize coherent structures and amplitude-phase synchronization in the space plasma turbulence. We applied the complex discrete wavelet analysis to compute the spectral power-phase Shannon entropy, and quantify the degree of amplitude-phase synchronization in coherent structures. This provided us a complete picture of the amplitude and phase dynamics of coherent structures in a space plasma turbulence.

During this project, dedicated efforts have been made to collaborate with scientistis from a number of European institutions including Observatoire de Paris-France, Ecole Normale Superieure/Paris-France, Ecole Polytechnique/Palaiseau-France, INRIA-France, LATMOS-France, Observatoire Cote d’Azur-France, the Institute of Earthquake Prediction Theory and Mathematical Geophysics of the Russian Academy of Sciences-Russia, IKI-Russia, the Belgian Institute for Space Aeronomy-Belgium, University of Potsdam-Germany, University of Calabria-Italy, Cambridge University-UK, Durham University-UK, St. Andrews University-UK, NORDITA and University of Stockholm-Sweden, and University of Zurich-Switzerland.

**B. Main S&T results**

***Achievements during the period***

1. **Publications**

As the result of this project, twelve papers have been published in international peer-reviewed journals. In addition, five papers have been submitted and three papers will be submitted. In all twenty papers listed below, the support of the Marie Curie International Incoming Fellowship by the European Commission and the kind hospitality of Paris Observatory has been acknowledged.

***Published***

1. E. L. Rempel, A. C.-L. Chian, A. Brandenburg. Lagrangian chaos in an ABC-forced nonlinear dynamo. Physica Scripta 86, 018405 (2012)

1. E. L. Rempel, A. C-L. Chian, A. Brandenburg, P. R. Munoz, S. C. Shadden. Coherent structures and the saturation of a nonlinear dynamo, Journal of Fluid Mechanics 729, 309-329 (2013)
2. R. A. Miranda, E. L. Rempel, A. C.-L. Chian, N. Seehafer, B. A. Toledo, P. R. Munoz. Lagrangian coherent structures at the onset of hyperchaos in the two-dimensional Navier-Stokes equations, Chaos 23, 033107 (2013)­­­­­­­­­­­­­­­­­
3. F. A. Asenjo, F. A. Borotto, A. C.-L. Chian, V. Munoz, J. A. Valdivia, E. L. Rempel. Self-modulation of nonlinear waves in a weakly magnetized relativistic electron-positron plasma with temperature. Physical Review E 85, 046406 (2012)
4. R. Lopez, V. Munoz, F. Asenjo, J. A. Valdivia, A. C.-L. Chian. Self-modulation of nonlinear Alfvén waves in a strongly magnetized relativistic electron-positron plasma, Physical Review E 88, 023105 (2013)
5. T. P. Chagas, B. A. Toledo, E. L. Rempel, A. C.-L. Chian, J. A. Valdivia. Optimal feedback control of the forced van der Pol system. Chaos, Solitons & Fractals 45, 1147–1156 (2012)
6. R. A. Miranda, E. L. Rempel, A. C.-L. Chian. Chaotic saddles in nonlinear modulational interactions in a plasma. Physics of Plasmas 19, 112303 (2012)
7. P. R. Munoz, J. J. Barroso, A. C.-L. Chian, E. L. Rempel. Edge state and crisis in the Pierce diode. Chaos 22, 033120 (2012)
8. A. C.-L. Chian, P. R. Munoz. Observation of magnetic reconnection at the turbulent leading edge of an interplanetary coronal mass ejection. In: Understanding solar activity: Advances and Challenges. Editors: C. Fang and M. Faurobert. EAS Publications Series 55, 327-334 (2012)
9. R. A. Miranda, A. C.-L. Chian, E. L. Rempel. Universal scaling laws for fully-developed magnetic field turbulence near and far upstream of the Earth's bow shock. Advances in Space Research 15, 1893-1901 (2013)
10. I. Zimovets, N. Vilmer, A. Chian, I. Shaykin, A. Struminsky. Spatially resolved observations of a band-splitting coronal type-II radio burst. Astronomy & Astrophysics 547, A6 (2012)
11. B. A. Toledo, A. C.-L. Chian, E. L. Rempel, R. A. Miranda, P. R. Munoz, J. A. Valdivia. Wavelet-based multifractal analysis of nonlinear time series: The earthquake-driven tsunami of 27 February 2010 in Chile, Physical Review E 87, 022821 (2013)

***Submitted***

1. V. Jatenco-Pereira, A. C.-L. Chian, N. Rubab. Alfvén waves in space and astrophysical dusty plasmas, Nonlinear Processes in Geophysics, submitted (2013)
2. J. A. Valdivia, V. Munoz, R. A. Lopez, F. A. Asenjo, F. A. Borotto, A. C.-L. Chian, E. L. Rempel. Large-amplitude wave propagation in relativistic electron-positron plasmas, Nonlinear Processes in Geophysics, submitted (2013)
3. D. Falceta-Goncalves, G. Kowal, E. Falgarone, A. C.-L. Chian. Turbulence in the interstellar medium, Nonlinear Processes in Geophysics, submitted (2013)
4. R. Chertovskih, A. C.-L. Chian, O. M. Podvigina, E. L. Rempel, V. A. Zheligovsky. Existence, uniqueness and analyticity of space-periodic solutions, to the regularised long-wave equation, Advances in Differential Equations, submitted (2013)
5. A. C.-L. Chian, P. R. Munoz, E. L. Rempel. Edge of chaos and genesis of turbulence, Physical Review E, submitted (2013)

***To be submitted***

1. A. C.-L. Chian, E. L. Rempel, A. Aulanier, B. Schmieder, S. C. Shadden, B. T. Welsch, A. R. Yeates. Detection of coherent structures in photospheric turbulent flows, Astrophysical Journal, to be submitted (2013)
2. A. C.-L. Chian, H. Q. Feng, T. D. Phan, P. R. Munoz, D. J. Wu. Turbulent magnetic reconnection at the trailing edge of a small-scale magnetic flux rope in the solar wind, Astronomy & Astrophysics, to be submitted (2013)
3. Y. Saiki, M. Yamada, A. C.-L. Chian, R. A. Miranda, E. L. Rempel. Reconstruction of chaotic saddles by unstable periodic orbits: Kuramoto-Sivashinsky equation, Chaos, to be submitted (2013)

To execute Task I of the project, we modelled the nonlinear dynamics of Alfven waves and intermittent turbulence in space and astrophysical plasmas, as well as the nonlinear dynamics of fluids and magnetohydrodynamics. Our results are presented in the following eight papers.

Paper 1, Rempel, Chian & Brandenburg (2012), has been selected as the 2012 Highlight Paper by the Editors of Physica Scripta of the Institute of Physics (IOP) - UK. In this paper, we studied the Lagrangian properties of the velocity field in a magnetized fluid using three-dimensional simulations of a helical magnetohydrodynamic dynamo in order to improve our understanding of the dynamics of solar magnetic field. We computed the attracting and repelling Lagrangian coherent structures (LCS), which are dynamic lines and surfaces in the velocity field that delineate particle transport in flows with chaotic streamlines and act as transport barriers. Two dynamo regimes are explored, one with a robust coherent mean magnetic field and the other with intermittent bursts of magnetic energy. The LCS and the statistics of the finite-time Lyapunov exponents indicate that the stirring/mixing properties of the velocity field decay as a linear function of magnetic energy. We also discussed the relevance of this study to the solar dynamo problem.

In paper 2, Rempel et al. (2003), we used Eulerian and Lagrangian tools to detect coherent structures in the velocity and magnetic fields of a mean-field dynamo, produced by direct numerical simulations of the three-dimensional compressible magnetohydrodynamic equations with an isotropic helical forcing and moderate Reynolds number. Two distinct stages of the dynamo were studied: the kinematic stage, where a seed magnetic field undergoes exponential growth; and the saturated regime. It is shown that the Lagrangian analysis detects structures with greater detail, in addition to providing information on the chaotic mixing properties of the flow and the magnetic fields. The traditional way of detecting Lagrangian coherent structures using finite-time Lyapunov exponents is compared with a recently developed method called function M. The latter is shown to produce clearer pictures which readily permit the identification of hyperbolic regions in the magnetic field, where chaotic transport/dispersion of magnetic field lines is highly enhanced.

In Paper 3, Miranda et al. (2013), we studied a transition to hyperchaos in the two-dimensional incompressible Navier-Stokes equations with periodic boundary conditions and an external forcing term. Bifurcation diagrams are constructed by varying the Reynolds number, and a transition to hyperchaos (HC) is identified. Before the onset of HC, there is coexistence of two chaotic attractors and a hyperchaotic saddle. After the transition to HC, the two chaotic attractors merge with the hyperchaotic saddle, generating random switching between chaos and hyperchaos, which is responsible for intermittent bursts in the time series of energy and enstrophy. The chaotic mixing properties of the flow are characterized by detecting Lagrangian coherent structures. After the transition to HC, the flow displays complex Lagrangian patterns and an increase in the level of Lagrangian chaoticity during the bursty periods that can be predicted statistically by the hyperchaotic saddle prior to HC transition.

In Paper 4, Asenjo et al. (2012), we formulated a nonlinear theory for the self-modulation of a circularly polarized electromagnetic wave in a relativistic hot weakly magnetized plasma, which can be applied to Alfven waves. The case of parallel propagation along an ambient magnetic field is considered. A nonlinear Schroedinger equation is derived for the complex wave amplitude of a self-modulated wave packet. We showed that the maximum growth rate of the modulational instability decreases as the temperature of the pair plasma increases. Depending on the initial conditions, the unstable wave envelope can evolve nonlinearly to either periodic wave trains or solitary waves. This theory has application to solar-terrestrial plasmas and high-energy astrophysics, where electrons and positrons are found.

In Paper 5, Lopez et al. (2013), we studied the self-modulation of a circularly polarized Alfven wave in a strongly magnetized relativistic electron-positron plasma with finite temperature. This nonlinear wave corresponds to an exact solution of the equations, with a dispersion relation that has two branches. For a large magnetic field, the Alfven branch has two different zones, which we call the normal dispersion zone (where *dω/dk >* 0) and the anomalous dispersion zone (where *dω/dk <* 0). A nonlinear Schroedinger equation is derived in the normal dispersion zone of the Alfven wave, where the wave envelope can evolve as a periodic wave train or as a solitary wave, depending on the initial condition. The maximum growth rate of the modulational instability decreases as the temperature is increased. We also studied the Alfven wave propagation in the anomalous dispersion zone, where a nonlinear wave equation is obtained. However, in this zone the wave envelope can evolve only as a periodic wave train.

In Paper 6, Chagas et al. (2012), we investigated a feedback control strategy for chaotic systems using the forced van der Pol system as an example. The van der Pol equation serves as a simplified model of solar dynamo and is capable of reproducing the qualitative temporal behavior of sunspot cycles. Our strategy is to regard chaos control as an optimization problem, where the maximum magnitude Floquet multiplier of a target unstable periodic orbit (UPO) is used as a cost function that needs to be minimized. Thus, the method obtains the optimal control gain in terms of the stability of the target UPO. This strategy was recently proposed for the proportional feedback control (PFC) method. We extended to the highly popular delayed feedback control (DFC) method. Since the DFC method treats the system as a delay-differential equation whose phase space is infinite-dimensional, the characteristic multipliers are found through a truncation in the number of delayed states. Control of a target UPO is achieved for several values of the forcing amplitude. We compared the DFC and PFC methods in terms of stability of the controlled orbit, steady state error and control effort.

In Paper 7, Miranda, Rempel & Chian (2012), we studied numerically a nonlinear model of modulational processes in the subsonic regime involving a linearly unstable wave and two linearly damped waves with different damping rates in a plasma. We computed the maximum Lyapunov exponent as a function of the damping rates in a two-parameter space, and identified shrimp-shaped self-similar structures in the parameter space. By varying the damping rate of the low-frequency wave, we constructed bifurcation diagrams and focused on a saddle-node bifurcation and an interior crisis associated with a periodic window. We detected chaotic saddles and their stable and unstable manifolds, and demonstrated how the connection between two chaotic saddles via coupling unstable periodic orbits can result in a crisis-induced intermittency. The relevance of this work for the understanding of modulational processes observed in plasmas and fluids was discussed.

In Paper 8, Munoz et al. (2012), we studied the chaotic dynamics of the Pierce diode, a simple spatially extended system for collisionless bounded plasmas, focusing on the concept of edge of chaos, the boundary that separates transient from asymptotic dynamics. Pierce diode is used to model double layers that can explain the propagation of relativistic electron beams in the presence of a strong parallel electric field in space plasmas. We fully characterized an interior crisis at the end of a periodic window, thereby showing direct evidence of the collision between a chaotic attractor, a chaotic saddle, and the edge of chaos, formed by a period-3 unstable periodic orbit and its stable manifold. The edge of chaos persists after the interior crisis, when the global attractor of the system increases its size in the phase space. In this paper, we focused on a periodic window in the parameter space, where typical phenomena such as chaotic transients and interior crisis are observed. In general, chaotic transients arise due to the presence of a surrounding chaotic saddle, and the ensuing interior crisis triggered by the collision between a chaotic attractor and a mediating unstable periodic orbit (UPO). Our results show that the mediating UPO coincides with the edge state that lies in the boundary defined by the edge of chaos. For the first time the interior crisis in the classical Pierce diode is fully characterized. Our results and the methodology developed herein can be used for the characterization of chaotic transitions in other spatially extended systems such as intermittent turbulence in space and astrophysical plasmas.

To execute Task II of the project, we performed nonlinear analysis of coherent structures and intermittent turbulence in solar and interplanetary plasmas using data and image of spacecraft and ground-based instruments. In addition, we carried out a nonlinear analysis of ocean turbulence in relation to a tsunami event driven by an earthquake using tidal-gauge data.

In Paper 9, Chian & Munoz (2012), we analyzed in-situ data of solar wind turbulence. Magnetic Cloud Boundary Layer (MCBL) is formed by the interaction between a magnetic cloud ejected by the Sun and the ambient solar wind, which may be linked to the outer loops of an Interplanetary Coronal Mass Ejection (ICME) and often display the properties of magnetic reconnection. We studied the relation between current sheets, turbulence, and magnetic reconnection at the leading edge of an ICME intercepted by the four Cluster spacecraft in the solar wind, upstream of the Earth’s bow shock, on 2005 January 21. We obtained the observational evidence of a fully-developed magnetic turbulence in the vicinity of two current sheets at the leading edge of ICME. Each current sheet shows the signatures of magnetic reconnections with oppositely propagating Alfven waves and jets. The current density of bifurcated current sheets is computed by the curlometer technique using multi-spacecraft data.

In Paper 10, Miranda, Chian & Rempel (2012), we analyzed the multifractal scaling of the modulus of the interplanetary magnetic field near and far upstream of the Earth’s bow shock, measured by Cluster and ACE, respectively, from 1 to 3 February 2002. The maximum order of the structure function is carefully estimated for each time series using two different techniques, to ensure the validity of our high-order statistics. The first technique consists of plotting the integrand of the p-th order structure function, and the second technique is a quantitative method which relies on the power-law scaling of the extreme events. We compared the scaling exponents computed from the structure functions of magnetic field differences with the predictions obtained by the She–Leveque model of intermittency in anisotropic magnetohydrodynamic turbulence. Our results show a good agreement between the model and the observations near and far upstream of the Earth’s bow shock, rendering support for the modelling of universal scaling laws based on the Kolmogorov phenomenology in the presence of sheet-like dissipative structures.

In Paper 11, Zimovets et al. (2012), we investigated the origin of coronal type-II radio bursts and the nature of their band-splitting which are still not fully understood, although a number of scenarios have been proposed for their interpretation. This is largely due to the lack of detailed spatially resolved observations of type-II burst sources and of their relations to magnetoplasma structure dynamics in parental active regions. To make progress in solving this problem on the basis of one extremely well observed solar eruptive event, we studied the relative dynamics of multi-thermal eruptive plasmas, observed in detail by the Atmospheric Imaging Assembly onboard the Solar Dynamics Observatory and of the harmonic type-II burst sources, observed by the Nancay Radioheliograph at ten frequencies from 445 to 151 MHz, for the 3 November 2010 event arising from an active region behind the east solar limb. Special attention is given to the band-splitting of the burst. Analysis is supplemented by investigation of coronal hard X-ray (HXR) sources observed by the Reuven Ramaty High-Energy Solar Spectroscopic Imager. We found that the flare impulsive phase was accompanied by the formation of adouble coronal HXR source, whose upper part coincided with the hot (*T* ≈ 10 MK) eruptive plasma blob. The leading edge (LE) of th**e** eruptive plasmas (*T* ≈ 1 − 2 MK) moved upward from the flare region with the speed of *v* ≈ 900 − 1400 km s−1. The type II burst source initially appeared just above the LE apex and moved with the same speed and in the same direction. After ≈ 20 s it started to move about twice faster, but still in the same direction. At any given moment the low frequency component (LFC) source of the splitted type-II burst was situated above the high frequency component (HFC) source, which in turn was situated above the LE. We also found that at a given frequency the HFC source was located slightly closer to the photosphere than the LFC source. Based on the set of established observational facts we concluded that the shock wave, which could be responsible for the observed type-II radio burst, was initially driven by the multi-temperature eruptive plasmas, but later transformed to a freely propagating blast shock wave. The most preferable interpretation of the type-II burst splitting is that its LFC is emitted at the upstream region of the shock, whereas the HFC is emitted at the downstream region of the shock. The shock wave in this case could be subcritical.

In Paper 12, Toledo et al. (2013), we studied general multifractal properties of tidal gauge and long-wave time series which show a well defined transition between two states, as is the case of sea level when a tsunami arrives. We adopted a method based on discrete wavelets, called wavelet leaders, which has been successfully used in a wide range of applications from image analysis to biomedical signals. First, we analyzed an empirical time series of tidal gauge from the tsunami event of 27 February 2010 in Chile. Then, we studied a numerical solution of the driven-damped regularized long-wave equation (RLWE) which displays on-off intermittency. Both time series are characterized by a sudden change between two sharply distinct dynamical states. Our analysis suggests a correspondence between the pre- and post-tsunami states (ocean background) and the on-state in the RLWE, and also between the tsunami state (disturbed ocean) and the off-state in the RLWE. A qualitative similarity in their singularity spectra is observed, and since the RLWE is used to model shallow water dynamics, this result could imply an underlying dynamical similarity.

1. **Presentation in scientific meetings**

The grant from this project has been used by Dr. Chian to attend the following fifteen meetings and present papers based on the scientific results of this project.

1. Symposium 286 of the International Astronomical Union (IAU) on “Comparative magnetic minima: Characterizing quiet times in the Sun and stars”, Mendoza, Argentina, October 3-7, 2011

Poster paper: A. C.-L. Chian, A. Brandenburg, M. R. E. Proctor, E. L. Rempel. Solar grand minima and on-off intermittent dynamo.

1. 4th French-Chinese Meeting on Solar Physics, Nice, France, November 15-18, 2011

Oral paper: A. C.-L. Chian, P. R. Munoz. Observation of magnetic reconnection at the turbulent leading edge of an interplanetary coronal mass ejection.

1. American Geophysical Union (AGU) Fall Meeting, San Francisco, USA, December 5-9, 2011

Oral paper: A. C.-L. Chian, P. R. Munoz, R. A. Miranda. Magnetic reconnection and turbulence
at the leading edge of an ICME.

1. European Geophysical Union (EGU) General Assembly, Vienna, Austria, April 22-27, 2012

Oral paper: A. C.-L. Chian, A. Brandenburg,, M. R. E. Proctor, E. L. Rempel. On-off intermittency and Lagrangian coherent structures in solar dynamo.

1. Annual Meeting of the Solar-Terrestrial Centre of Excellence (STCE-2012) and Alfven Workshop on “Alfven Waves and Turbulence in Solar-Terrestrial Plasmas”, organized by Dr. Yuriy Voitenko and Dr. Andrea Verdini on 25 May 2012 at the Belgium Institute for Space Aeronomy (BIRA) in Brussels, Belgium

Invited talk: A. C.-L. Chian. Multifractal turbulence and magnetic reconnection at the leading edge of an interplanetary CME

1. Joint 39th European Physical Society Conference on Plasma Physics & 16th International Congress on Plasma Physics, Stockholm, Sweden, July 2-6, 2012

Poster paper: F. A. Asenjo, F. a. Borotto, A. C.-L. Chian, V. Munoz, J. A. Valdivia, E. L. Rempel. Envelope solitons in a weakly magnetized electron-positron plasma with relativistic temperatures.

1. International Astronomical Union (IAU) General Assembly, Beijing, China, August 19-31, 2012

Invited talk: A. C.-L. Chian, A. Brandenburg, P. R. Munoz, R. A. Miranda, E. L. Rempel. Nonlinear dynamics of the star-planet relations.

1. American Geophysical Union (AGU) Fall Meeting, San Francisco, USA, December 5-9, 2012

Poster paper: A. C.-L. Chian, E. L. Rempel, B. T. Welsch, A. R. Yeates. Lagrangian coherent structures in the solar magnetoconvective turbulence.

1. 9th International Workshop on Nonlinear Waves and Chaos in Space Plasmas, La Jolla, USA, March 4-8, 2013

Invited talk: A. C.-L. Chian. Lagrangian coherent structures in solar plasma turbulence.

1. 8th European Workshop on Collisionless Shocks, Institut d'Astrophysique de Paris (IAP), Paris, France, June 4-7, 2013

Invited talk: A. C.-L. Chian, Turbulence and amplitude-phase synchronization at coronal, interplanetary and planetary shocks.

1. IAU Symposium 300 on Nature of prominences and their role in space weather, Paris, France, June 10-16, 2013

Poster paper: A. C.-L. Chian, N. Vilmer, I. Zimovets. Magnetic reconnection at the leading edge of a solar erupting loop and an ICME.

1. 12th Scientific Assembly of the IAGA, Merida, Mexico, August 25-31, 2013

Oral paper: A. C.-L. Chian, H. Q. Feng, P. R. Munoz, T. D. Phan, D. J. Wu. Cluster observation of magnetic reconnection at the turbulent boundary layers of interplanetary magnetic flux ropes.

1. Workshop on the Physics of Positron-Electron Plasmas (PPEP 2013), IPP-Greifswald, Germany, October 10, 2013

Invited powerpoint presentation: A. C.-L. Chian. Nonlinear processes in electron-positron plasmas.

1. Workshop on Mechanics of the Magnetospheric System and Effects on the Polar Regions, Torres del Paine, Chile, October 27 - November 1, 2013

Invited talk: A. C.-L. Chian. Turbulent magnetic reconnection at the leading edge of an ICME.

1. Brazilian Meeting on Plasma Physics, Brasilia, Brazil, December 2-5, 2013

Invited talk: A. C.-L. Chian. Turbulent magnetic reconnection at the boundary layers of a coronal mass ejection.

1. **Visitors**

During this period, Dr. Chian received 6 visitors for scientific collaboration at Observatoire de Paris:

1. Dr. Hongqi Zhang from National Astronomical Observatory, China, from 9 to 13 April 2012
2. Dr. Yoshitaka Saiki from Hokkaido University, Japan, from 1 to 19 June 2012
3. Dr. Gaetano Zimbardo from University of Calabria, Italy, 25 October 2012
4. Dr. Olga Podvigina and Dr. Vladimir Zheligovsky from Observatoire Cote d’Azur, France and the Institute of Earthquake Prediction Theory and Mathematical Geophysics of the Russian Academy of Sciences, Russia, from 5 to 9 November 2012
5. Dr. Diego Falceta-Goncalves from University of Sao Paulo, Brazil, from 18 March to 16 April 2013

***Project management during the period***

1. **List of project meetings, dates and venues**
2. ***Mini-Course at Observatoire de Paris***

Under Dr. N. Vilmer’s coordination, Dr. Chian presented a mini-course at Observatoire de Paris on “Nonlinear dynamics of the stellar-planetary environment”, attended by many researchers and students from Division of Solar Physics and Division of Plasma Physics of Observatoire de Paris and other academic and research organizations in Paris. The aim of this mini-course was to introduce the innovative concepts and techniques of complex systems to space physicists and astrophysicists. This mini-course consisted of four tutorial lectures:

* Lecture 1: 23/09/2011: A cosmic vision of Poincare and Lagrange
* Lecture 2: 14/10/2011: Alfven waves and turbulence
* Lecture 3: 07/11/2011**:** Langmuir waves and turbulence
* Lecture 4: 25/11/2011**:** Drift waves and turbulence
1. ***Special Session and Public Forums at the IAU General Assembly***

Dr. Chian organized in collaboration with Dr. J.-L. Bougeret of Observatoire de Paris, Dr. X. Feng of CSSAR/Academy of Sciences-China and Dr. M. Opher of Boston University-USA, a Special Session SpS10 on “Dynamics of the star-planet relations” at the General Assembly of the International Astronomical Union (IAU) in Beijing, China, in 27-31 August 2012. This Special Session aimed to foster cross-disciplinary studies of Heliophysics and Asterophysics: the physics of the sun and stars and their environment in the interstellar medium. It raises the question: What can the knowledge we gained in heliophysics bring to the quest for understanding extra-solar systems and the fundamental physical processes in the Asterospheres. And, in return, what can the studies of other stellar systems in our galaxy bring to our understanding of our own stellar system, the Heliosphere. It reviewed the state-of-the-art of the theoretical, numerical modeling, and space-borne and ground-based observational studies of the dynamics of Sun-Earth relation, Sun-planet relation, and extrasolar star-exoplanet relation, and identified the key problems in these fields to be addressed by astronomy, astrophysics, and space physics communities in the coming years. This Special Session consisted of the following seven sessions:

* Session 1: Overview of the star-planet relations
* Session 2: Fundamental processes in the stellar-planetary environment
* Session 3: Stellar-solar variability
* Session 4: Sun-Earth relations
* Session 5: Star-planet relations
* Session 6: Heliosphere and asterospheres
* Session 7: Perspectives of the star-planet relations

The Special Session SpS10 organized a Public Forum on “The sun-planet relations” at Peking University and a Public Forum on “The star-planet relations” at Tsinghua University, each attended by around 100 students and professors. A request has been made to the Senior Editor of Space Science Reviews to publish a special volume on “Dynamics of the star-planet relations” containing six invited review papers from the Special Session SpS10. Dr. Chian and Dr. J.-L. Bougeret of Observatoire de Paris will be Guest-Editors of this special volume, jointly with Dr. M. Opher and Dr. X. Feng; and will be in charge of writing a review paper on “Overview of the dynamics of the star-planet relations”.

The organization of the Special Session SpS10 and two Public Forums was carried out in collaboration with a number of European and international participants of the WISER (World Institute for Space Environment Research) research and teaching network founded and coordinated by Dr. Chian.

|  |  |
| --- | --- |
| 1. ***STCE Workshop***

Dr. Chian was a Keynote Speaker at the Annual Meeting of the Solar-Terrestrial Centre of Excellence (STCE-2012) and Alfven Workshop on “Alfven Waves and Turbulence in Solar-Terrestrial Plasmas”, organized by Dr. Yuriy Voitenko and Dr. Andrea Verdini on 25 May 2012 at the Belgium Institute for Space Aeronomy (BIRA) in Brussels, Belgium. The goal of this workshop was to review last year’s achievements and coordination of research by the STCE institutes ([Royal Observatory of Belgium-ROB](http://www.observatoire.be/), [Royal Meteorological Institute-RMI](http://www.meteo.be/meteo/view/), [Belgian Institute for Space Aeronomy-BIRA/IASB](http://www.aeronomie.be/%22%20%5Ct%20%22_blank)), developed in collaboration with European and international partners. This workshop focused on Alfvén waves observed in space plasmas which are mostly in a turbulent state. Dr. Chian and Dr. G. Gogoberidze of University of Calabria – Italy, both Marie Curie International Incoming Fellows, gave invited talks on “[Multifractal turbulence and magnetic reconnection at the leading edge of an interplanetary CME](http://www.spaceweather.eu/en/repository/download?id=Chia-1338554866.&file=Chian.pdf)” and “[Testing theoretical models of MHD turbulence by solar wind data](http://www.spaceweather.eu/en/repository/download?id=Gogoberidz-1338554744.&file=Gogoberidze.pdf)”, respectively. This Workshop is closely related to the development of R&D activities of Space Weather in STCE and Europe.1. ***9th International Workshop on Nonlinear Waves and Chaos in Space Plasmas***

Dr. Chian is one of the conveners of the International Workshop on Nonlinear Waves and Chaos in Space Plasmas held in La Jolla-USA, from 4 to 8 March 2013. This is one of the major workshops on nonlinear processes in space plasmas in the world and was attended by over thirty scientists including many from Europe. Dr. Chian is one of the Handling Editors of a special issue of *Nonlinear Processes in Geophysics*, a joint EGU/AGU journal, to be published containing papers from this workshop.***Project planning and status***This project succeeded to establish a long-term scientific cooperation on “nonlinear dynamics in the solar-terrestrial environment” involving Dr. Chian and his WISER team in Brazil and collaborators in Europe and worldwide. In particular, the following research topics have been identified by this project: 1. ***Alfven waves and turbulence in solar and interstellar plasmas:*** *To apply the dynamical systems approach to study the spatiotemporal dynamics of shear and kinetic Alfvén waves and turbulence in solar photosphere, solar atmosphere, solar wind, and interstellar medium, based on numerical solutions of nonlinear wave equations, and investigate the implications for acceleration and heating of solar and interstellar plasmas by Alfvén waves and turbulence.*

This topic will be studied through the collaboration of the following scientists:* Dr. F. Asenjo, University of Texas at Austin, USA
* Dr. F. Borotto, University of Concepcion, Chile
* Dr. A. Chian, Observatoire de Paris, France & INPE, Brazil
* Dr. D. Falceta-Goncalves, St. Andrews University, UK & USP, Brazil
* Dr. E. Falgarone, Ecole Normale Superieure/Paris, France
* Dr. V. Jatenco, University of Sao Paulo, Brazil
* Dr. B. Lembege, LATMOS, France
* Dr. V. Munoz, University of Chile, Chile
* Dr. E. Rempel, Institute of Aeronautical Technology, Brazil
* Dr. J. Valdivia, University of Chile, Chile
* Dr. Y. Voitenko, Belgium Institute for Space Aeronomy, Belgium
* Dr. D. Wu, Purple Mountain Observatory, China
1. ***Computer modelling of solar physics phenomena:*** *To perform 3D computer modelling of Lagrangian coherent structures and compressible magnetoconvective turbulence in an intermittent solar dynamo and in coronal mass ejections driven by a turbulent dynamo.*

This topic will be studied through the collaboration of the following scientists:* Dr. G. Aulanier, Observatoire de Paris, France
* Dr. A. Brandenburg, Nordita & Stockholm University, Sweden
* Dr. A. Chian, Observatoire de Paris & INPE, Brazil
* Dr. R. Miranda, University of Brasilia, Brazil
* Dr. P. Munoz, Institute of Aeronautical Technology, Brazil
* Dr. E. Rempel, Institute of Aeronautical Technology, Brazil
* Dr. N. Seehafer, Potsdam University, Germany
* Dr. S. Shadden, University of California at Berkeley, USA
* Dr. A. Yeates, Durham University, UK
1. ***Analysis of observational solar-terrestrial data:*** *To use spacecraft and ground-based data for studying coherent structures, magnetic reconnection and turbulence in solar and interplanetary plasmas, photospheric flows in quiet and active regions*

This topic will be studied through the collaboration of the following scientists:* Dr. A. Chian, Observatoire de Paris & INPE, Brazil
* Dr. H. Feng, Luoyang Normal University, China
* Dr. T. Phan, University of California at Berkeley, USA
* Dr. A. Retino, Ecole Polytechnique/Paliseau, France
* Dr. F. Sahraoui, Ecole Polytechnique/Palaiseau, France
* Dr. B. Schmieder, Observatoire de Paris, France
* Dr. L. Sorriso-Valvo, University of Calabria, Italy
* Dr. A. Vaivads, Uppsala University, Sweden
* Dr. N. Vilmer, Observatoire de Paris, France
* Dr. B. Welsch, University of California at Berkeley, USA
* Dr. G. Zimbardo, University of Calabria, Italy
* Dr. I. Zimovets, Space Research Institute-IKI, Russia
 |  |
|  |  |  |
|  |  |

**Part 4. The potential impact (including the socio-economic impact and the wider societal implications of the project so far) and the main dissemination activities and exploitation of results**

***Potential for creating long term collaborations and mutually beneficial co-operation between Europe and the Third Country***

This project has created long-term collaboration between Europe and Brazil in Solar-Terrestrial and Space Weather research. Dr. Chian’s home institution, the National Institute for Space Research (INPE) in São José dos Campos – Brazil, is the leading space organization in the southern hemisphere with a permanent staff of over one thousand employees. A Space Weather and Climate Program has been implemented recently at INPE to study events from their initiation on the Sun to their impacts on the Earth, including their effects on space-borne and ground-based technological systems. This program is built on existing capabilities at INPE, which include scientists with a long tradition and excellence in the observation, analysis and modeling of solar and solar-terrestrial phenomena and an array of geophysical instruments that spans all over Brazil from the north to south of the magnetic dip equator. Its scientific activities focus on the solar-planetary relations, the equatorial electrojet, the South Atlantic Magnetic Anomaly, and the ionospheric irregularities. The technological, economic and social importance of such activities was recognized by the Brazilian government. New ground instruments have been installed to extend the capability to provide space weather observations, accurate forecasts of space weather conditions, and timely hazard alerts. This space weather program is now operational.

This project succeeded to establish an international scientific cooperation program on “Nonlinear dynamics in the solar-terrestrial environment” focused on three topics: 1) Alfvén waves and turbulence in solar and interstellar plasmas; 2) Computer modelling of solar physics phenomena; and 3) Analysis of observational solar-terrestrial data. This scientific program involves the partnership of the following institutions: 1) Europe: Observatoire de Paris-France, Observatoire Cote d’Azur-France, Ecole Normale Superieure/Paris-France, Ecole Polytechnique/Palaiseau-France, INRIA-France, LATMOS-France, Belgian Institute for Space Aeronomy-Belgium, Potsdam University-Germany, MPI for Plasma Physics/Greifswald-Germany, University of Calabria-Italy, Space Research Institute-Russia, Institute of Earthquake Prediction Theory and Mathematical Geophysics-Russia, NORDITA & University of Stockholm-Sweden, Uppsala University-Sweden, University of Zurich-Switzerland, Cambridge University-UK, Durham University-UK, St. Andrews University-UK; 2) Brazil: National Institute for Space Research (INPE), Institute of Aeronautical Technology (ITA), University of Sao Paulo (USP), University of Brasilia (UnB); 3) Chile: University of Chile, University of Concepcion; 3) USA: University of California at Berkeley, University of Texas at Austin; 4) China: Purple Mountain Observatory, Luoyang Normal University.

***Contribution to European excellence and European competitiveness***

This project has increased the competitiveness of Europe and its international position in Solar-Terrestrial research and Space Weather research, in particular, it has strengthened the participation of Europe in CAWSES-II (Climate and Weather of the Sun-Earth System), an international program in 2009-2013 sponsored by SCOSTEP (Scientific Committee on Solar-Terrestrial Physics) of ICSU (the International Council of Scientific Unions), which was established to significantly enhance our understanding of the space environment and its impacts on life and society (<http://www.cawses.org/CAWSES/Home.html>). The two tasks executed in this project, “*Modeling Alfvén waves and intermittent turbulence in space plasmas*” and “O*bservation of coherent structures and intermittent turbulence in space plasmas*”, have contributed considerably to the mission of CAWSES-II to discover the important processes that connect changes at the solar surface with features in the geospace environment and ultimately with climate variability.

The research on the “*Nonlinear dynamics in the solar-terrestrial environment*” carried out in this project has enhanced the activities of Space Weather developed at LESIA and Paris Observatory, and the ESA SSA (Space Situational Awareness) program (<http://www.esa.int/SPECIALS/SSA/index.html>) which was established to support Europe's independent utilization of, and access to, space through the provision of timely and accurate information, data and services regarding the space environment, and in particular regarding hazards to infrastructure in orbit and on the ground. The SSA program will, ultimately, enable Europe to autonomously detect, predict and assess the risk to life and property due to remnant man-made space objects, re-entries, in-orbit explosions and release events, in-orbit collisions, disruption of missions and satellite-based service capabilities, potential impacts of Near Earth Objects, and the effects of Space Weather phenomena on space- and ground-based infrastructure.  The connections of LESIA-WISER with several research groups in Belgium involved in the Space Weather area of the SSA program (SWE) have been used to reinforce this project, to the benefit of the ESA SSA program as a whole.

***Benefit of the mobility to the European Research Area***

This project has allowed Dr. Chian, who is the founder and director of the international research and training network WISER (World Institute for Space Environment Research, <http://www.cea.inpe.br/wiser>), to come from Brazil to France to work with LESIA scientists which will facilitate the the participation of LESIA in future WISER activities to jointly promote international co-operation in space environment & space weather research and training in Europe, Brazil and worldwide.

**Part 5. The address of the project public website, if applicable as well as relevant contact details.**

This project will be continued in the coming years by the WISER network and based on the WISER website: [www.cea.inpe.br/wiser](http://www.cea.inpe.br/wiser), which will be updated in the near future.

Dr. Chian, the founder and coordinator of WISER, will be in charge of the future activities of this project whose contact details are:

Professor Abraham Chian

National Institute for Space Research (INPE)

P. O. Box 515

Av. Astronautas 1758

12227-010 Sao Jose dos Campos-SP

Brazil

Tel: +55 12 3208-6785

Fax: +55 12 3208-7898

E-mail: abraham.chian@gmail.com

**REFERENCES**

 [Abramenko, V. I](http://apps.isiknowledge.com/OneClickSearch.do?product=UA&search_mode=OneClickSearch&db_id=&SID=2BJbIPlFcbheNpkDFGl&field=AU&value=Abramenko%20VI&ut=000186432700044&pos=1)., [Yurchyshyn, V. B](http://apps.isiknowledge.com/OneClickSearch.do?product=UA&search_mode=OneClickSearch&db_id=&SID=2BJbIPlFcbheNpkDFGl&field=AU&value=Yurchyshyn%20VB&ut=000186432700044&pos=2)., [Wang, H](http://apps.isiknowledge.com/OneClickSearch.do?product=UA&search_mode=OneClickSearch&db_id=&SID=2BJbIPlFcbheNpkDFGl&field=AU&value=Wang%20H&ut=000186432700044&pos=3)., [Spirock, T. J](http://apps.isiknowledge.com/OneClickSearch.do?product=UA&search_mode=OneClickSearch&db_id=&SID=2BJbIPlFcbheNpkDFGl&field=AU&value=Spirock%20TJ&ut=000186432700044&pos=4)., [Goode, P. R](http://apps.isiknowledge.com/OneClickSearch.do?product=UA&search_mode=OneClickSearch&db_id=&SID=2BJbIPlFcbheNpkDFGl&field=AU&value=Goode%20PR&ut=000186432700044&pos=5). *Astrophys. J.* 597, 1135, 2003.

Alexandrova , O., *Nonlinear Proc. Geophys.*, **15**, 95, 2008.

Alexandrova, O., Saur, J. *Geophys. Res. Lett.* **35**, L15102, 2008.

Alexandrova, O., Saur, J., Lacombe, C.. Mangeney, A., Mitchell, J., Schwartz, S. J., Robert, P. *Phys. Rev. Lett.* **103**, 165003, 2009.

Arnold, L. *Random Dynamical Systems*. Springer, New York , 1998.

Bohr, T., Jansen, M. H., Paladin, G. Vulpiani, A. *Dynamical Systems Approach to Turbulence*. Cambridge University Press, Cambridge, 1998.

Bougeret, J.-L., Pick, M. Solar radio emissions. In: Kamide, Y., Chian, A. C.-L. (Eds.) *Handbook of the Solar-Terrestrial Environment*, Springer, Berlin, 2007.

Bougeret, J.-L. et al. *Space Sci. Rev.* **136**, 487, 2008.

Brandenburg, A. The solar interior – Radial structure, rotation, solar activity cycle. In: Kamide, Y., Chian, A. C.-L. (Eds.) *Handbook of the Solar-Terrestrial Environment*, Springer, Berlin, 2007.

Briand, C. *Nonlinear Proc. Geophys.*16, 319, 2009.

Bruno, R., Carbone, V. *Living Rev. Solar Phys*. **2**, 2005. (Available at <http://solarphysics.livingreviews.org>)

Cargill, P. J., Harra, L. K. Coronal mass ejection. In: Kamide, Y., Chian, A. C.-L. (Eds.) *Handbook of the Solar-Terrestrial Environment*, Springer, Berlin, 2007.

Chen, P. F., Wu, S. T., Shibata, K., Fang, C. *Astrophys. J. Lett*. **572**, L99, 2002.

Chen, P. F. *Astophys. J. Lett*. **698**, L112, 2009.

Chian, A. C.-L.,Kamide, Y., Rempel, E. L., Santana, W. M*. J. Geophys. Res. – Space Phys*. **111**, A07S03, 2006.

Chian, A. C.-L., Kamide, Y. An overview of the solar-terrestrial environment. In: Kamide, Y., Chian, A. C.-L. (Eds.) *Handbook of the Solar-Terrestrial Environment*, Springer, Berlin, 2007.

Chian, A. C.-L. et al. *Nonlinear Proc. Geophys* **14**, 17, 2007.

Chian, A. C.-L., Miranda, R. A. *Ann. Geophys*. **27**, 1789, 2009.

Chian, A. C.-L., Han, M., Miranda, R. A., Shu, C., Valdivia, J. A. *Adv. Space Res*. **46**, 572-584, 2010a

Chian, A. C.-L., Miranda, E. A., Rempel, E. L., Saiki, Y., Yamada, M. *Phys. Rev. Lett*. 104, 254102, 2010b

D’Amicis, R., Bruno, R., Bavassano, B*. J. Atmos. Solar-Terr. Phys*. **71**, 1014, 2009.

De Oliveira, L. P. L., Rizzato, F. B., Chian, A. C.-L. *J. Plasma Phys*. **58**, 441, 1997.

Dauphin, C., Vilmer, N., Anastasiadis, *Astron. Astrophys.* **468**, 273, 2007.

Eckhardt, B., Schneider, T. M., Hof, B., Westerweel, J. *Annu. Rev. Fluid Mech*. **39**, 447, 2007.

He, K. F., Chian, A. C.-L. *Phys. Rev. Lett*. **91**, 034102, 2003.

Henri, P., Briand, C., Mangeney, A., Bale, S. D., Califano, F., Goetz, K., Kaiser, M.. *J. Geophys. Res. – Space Phys.* **114**, A03103, 2009.

Heinzel, P., Schmieder, B., Farnik, F., Schwartz, P., Labrosse, N., Kotrc, P., Anzer, U., Molodij, G., Berlicki, A., DeLuca, E. E., Golub, L., Watanabe, T., Berger, T., *Astrophys. J.* **686**, 1383, 2008.

Issautier, K. et al. *Geophys. Res. Lett.* **35**, L19101, 2008.

Kamide, Y., Chian, A. C.-L. *Handbook of the Solar-Terrestrial Environment*. Springer, Berlin, 2007.

Koga, D., Chian, A. C.-L., Miranda, R. M., Rempel, E. L. Phys. Rev. E **75**, 046401, 2007.

Krishan, V., Nocera, L. *Phys. Lett. A*, **315**, 389, 2003.

Labitzke, K. Effects of the solar cycle on the earth’s atmosphere. In: Kamide, Y., Chian, A. C.-L. (Eds.) *Handbook of the Solar-Terrestrial Environment*, Springer, Berlin, 2007.

Lai, Y.-C., Liu, Z., Billings. L., Schwartz, I. B. *Phys. Rev. E* **67**, 026210, 2003.

Lai, Y.-C., Park, K., Rajagopalan, L. *Eur. Phys. J. B*. **69**, 65, 2009.

Lanzerotti, L. J. Space weather. In: Kamide, Y., Chian, A. C.-L. (Eds.) *Handbook of the Solar-Terrestrial Environment*, Springer, Berlin, 2007.

Le Chat, G., Issautier, K., Meyer-Vernet, N., Zouganelis, I., Maksimovic, M., Moncuquet, M. *Phys. Plasmas* **16**, 102903, 2009.

Lorenz, E. N. *J. Atmos. Sci*., **20**, 130, 1963.

Miranda, R. A., Chian, A. C.-L. et al. In: Kosovichev, A. G., Andrei, A. H., Rozelot, J.-P. (Eds.) *Solar and Stella Variability: Impacts on Earth and Planets*. IAU SYMPOSIA 264, 363, 2010.

Moussas, X., Chian, A.C.-L., Shaltout, M. *Adv. Space Sci.* **46**, 363, 2010.

Muñoz, P. R., Chian, A. C.-L., Miranda, R. A., Yamada, M. In: Kosovichev, A. G., Andrei, A. H., Rozelot, J.-P. (Eds.) *Solar and Stellar Variability: Impacts on Earth and Planets*. IAU SYMPOSIA 264, 369, 2010.

Nariyuki, Y., Hada, T. *Nonlinear Proc. Geophys*. **13**, 425, 2006.

Ott, E. *Chaos in Dynamical Systems*. Cambridge University Press, Cambridge, 2002.

Parker, E. N. Solar wind. In: Kamide, Y., Chian, A. C.-L. (Eds.) *Handbook of the Solar-Terrestrial Environment*, Springer, Berlin, 2007.

Perez, J. C., Boldyrev, S. *Astrophys. J. Lett.* **672**, L61, 2008.

Rempel, E. L., Santana, W. M., Chian, A. C.-L. *Phys. Plasmas* **13**, 032308, 2006.

Rempel, E. L., Chian, A. C.-L**.** *Phys. Rev. Lett*. **98**, 014101, 2007.

Rempel, E. L., Chian, A. C.-L., Koga, D., Miranda, R. A., Santana, W. M. *Int. J. Bifurcation & Chaos* **18**, 1697, 2008.

Rempel, E. L., Miranda, R. A., Chian, A. C.-L. *Phys. Fluids* **21**, 074105, 2009.

Rempel, E. L., Proctor, M. R., Chian, A. C.-L. *Monthly Not. Royal Astron. Soc*. **400**, 409, 2009.

Roberts, A. J. *Physica A* **387**, 12, 2008.

Sakao T. et al. *Science* **318**, 1585, 2007.

Schekochihin, A. A., Cowley, S. C., Dorland, W., Hammett, G. W., Howes, G. G., Quataert, E., Tatsuno, T. *Astrophys. J.* *Supp. Ser.* **182**, 310, 2009.

Schmieder, B., Mandrini, C. H., Demoulin, P., Aulanier, G., Li, H., Berlicki, A. *Adv. Space Res*. **39**, 1840, 2007.

Skufca, J. D., Yorke, J. A., Eckhardt, B. *Phys. Rev. Lett*., **96**, 174101, 2006.

Tél, T., Lai, Y.-C. *Phys. Rep*. **460**, 245, 2008.

Tsurutani, B. T., Gonzelez, W. D. *Planet. Space Sci.* **35**, 405, 1987.

Vidotto, A. A., Jatenco-Pereira, V. *Astrophys. J*. **639**, 416, 2006.