Proposal for an International Team on
Partially Ionized Plasmas in Astrophysics (PIPA)

Team members
Igor Alexeev, Lomonosov Moscow State University, Rusia
José Luis Ballester, Universitat de les Illes Balears, Spain **(Team Leader)**
Manuel Collados, Instituto de Astrofísica de Canarias, Spain
Turlough Downes, Dublin City University, Ireland
Nikolai Erkaev, Institute of Computational Modelling, Rusia
Holly Gilbert, NASA, United States of America
Maxim Khodachenko, Space Research Institute, Austria
Elena Khomenko, Instituto de Astrofísica de Canarias, Spain
Ramón Oliver, Universitat de les Illes Balears, Spain
Enrique Vázquez-Semadeni. Instituto de Astronomia, México
Mark Wardle, Macquarie University, Australia
Teimuraz Zaqarashvili, Space Research Institute, Austria

Abstract
We propose to set up an International Team spanning a wide range of expertise in order to expand our understanding of the role of partially ionized plasmas (from now on, PIP) in Astrophysics. The Team consists of 12 members, coming from 9 different Institutions in 7 different countries. Each member of the team is an expert in PIP, working in different astrophysical environments, and whose research interests offer a combination of data analysis and interpretation, spectro-polarimetry, waves and instabilities in magnetized plasmas, solar system planets, exoplanets atmospheres and magnetospheres, interstellar medium, accretion disks, and numerical simulations. The primary goals of the team are to exchange ideas, establish collaborative links and develop joint strategies for tackling current problems related with solar and astrophysical PIP. Therefore, we will meet at ISSI to discuss the latest developments in these fields, to interpret existing ground- and space-based observations, and decide modelling strategies to be carried out between the meetings. **The expected outcome of the proposed research will be a better understanding of the different astrophysical environments in which PIP play a significant role, and the establishment of scientific links between different astrophysical communities.**

Scientific Rationale, goals and timeliness
Plasma pervades the Universe at all scales. In general, the study of plasmas beyond the Earth's atmosphere is called Plasma Astrophysics, and includes many different astrophysical environments such as the sun, the heliosphere, magnetospheres of the Earth and the planets, the interstellar medium, accretion disks, exoplanet atmospheres, stars and astrospheres, exoplanetary ionospheres, etc. In these environments, the ionization level varies from almost no ionization in cold regions to fully ionized in hot regions which, at the same time, leads to a wide range of parameters being relevant to astrophysical plasmas. Furthermore, in some cases the plasma is influenced by, or coupled to, embedded dust, giving rise to dusty plasmas. While a non-ideal Magnetohydrodynamics (MHD for short) approach is relatively infrequent in the solar physics community, during recent years the study of PIP has become a hot topic because solar structures such as spicules, prominences, as well as layers of the solar atmosphere (photosphere and chromosphere) are made of partially ionized plasmas. On the other hand, considerable developments have taken place in the study of partially ionized plasmas applied to the physics of the interstellar medium, the formation of protostellar discs, planetary magnetospheres/ionospheres, exoplanets atmospheres and hot hydrogen coronas, etc. In the following, the above mentioned topics are briefly described:

1.- Solar Physics: Coupling between ions and neutrals in magnetized plasmas is fundamentally important to many aspects of heliophysics. Usually, the ideal MHD approximation is used to study the dynamical processes taking place in magnetized solar plasmas from the photosphere to the corona. However, in some layers and structures of the solar atmosphere, the effects of partial ionization are of particular importance. For instance, in the lower solar atmosphere where the tempearture is relatively cool, the degree of ionization is very small. This fact, together with the decrease in the collision frequency with height, produces conditions under which the assumptions supporting the ideal MHD approximation are not valid. **Therefore, in these layers other additional effects such as the Hall effect and ambipolar diffusion must be taken into account, and could produce interesting effects related, for instance, to chromospheric heating (Khomenko & Collados, 2012; Zaqarahvili et al. 2013)**. Furthermore, it has been also shown that the single-fluid MHD approximation fails in some circumstances, therefore multi-fluid MHD must be adopted (Zaqarashvili et al. 2011). Another region in the solar atmosphere where ion-neutral coupling needs to be considered is in the physics of solar prominences, where cross-field diffusion of neutrals may play a critical role in determining the cross-field structure and mass variation of prominences (Gilbert et al. 2002: Gilbert et al. 2007). Because mass variation is intimately connected to prominence structure and dynamics, the following important question must be raised: **what role, if any, do ion-neutral interactions play in vertical flows, which are commonly seen in quiescent prominences?** Recently, high-resolution observations made by the HINODE satellite (Berger et al. 2008, 2010, 2011) have revealed a lot of dynamical processes taking place in limb prominences. Most of these dynamical features have been interpreted and modeled (Ryutova et al. 2010; Hillier et al. 2011, 2012) in terms of different instabilities (Rayleigh-Taylor, Kelvin-Helmholtz, etc.) which develop in the prominence plasma considered as fully ionized. However, because of low temperature, prominence plasmas are PIP, with physical properties similar to those of chromosphere, **and the study of thermal, Rayleigh-Taylor and Kelvin-Helmholtz instabilities in PIP has been already started (Soler et al. 2012; Soler et al. 2012; Díaz et al. 2012) with the aim of determining the modifications in the instabilities thresholds and growth rates produced by partial ionization effects.**

2.- Electrodynamics of planetary magnetospheres. Implications for Exoplanets: Prominent among the key questions regarding exoplanets is the problem of their interaction with the solar/stellar wind, including the self-consistent structure of the magnetospheric currents system and the impact of solar/stellar radiation and plasma flows on the near-planetary plasma and planetary atmosphere environments. Hydrodynamic expansion of an exoplanetary upper atmosphere (at close-orbit), heated by stellar X-ray/EUV (XUV) radiation with the consequent photo-ionization of the expanding atmospheric gas (Tian et al. 2005, Penz et al. 2008) leads to the formation of an extended, essentially dynamical planetary ionosphere/plasmasphere. **The interaction of the expanding planetary partially ionized plasma envelopes with the intrinsic planetary magnetic fields and the stellar winds lead to the development of a new type of magnetosphere, not typical for solar system planets (Khodachenko et al. 2012).** Of crucial importance in this scenario appears to be the formation of plasma magnetodisks around the close-orbit exoplanets resulting from the planetary rotation and hydrodynamic escape of the partially ionized upper atmospheric material (Khodachenko et al., 2012).

3.-Astrophysical PIP: Fluids constituting molecular clouds are mainly made up of neutral material which does not interact with magnetic fields. However, neutrals are not the only constituent of molecular clouds since there are also several types of charged species which do interact with magnetic fields. Furthermore, the charged fraction also interacts with the neutral material through collisions. These multiple interactions produce many different physical effects which may have a strong influence on star formation and molecular cloud turbulence. **In this context, recent studies about the presence of Kelvin-Helmlhotz instability in weakly ionized plasmas such as those of molecular clouds, or about multifluid MHD turbulence have been performed (Jones and Downes, 2011, 2012; Downes and O'Sullivan, 2009, 2011; Downes, 2012).** Another example can be found in the formation of dense cores in molecular

clouds induced by MHD waves. Because of the low ionization fraction, neutrals and charged particles are weakly coupled and **ambipolar diffussion plays an important role in the formation process (Van Loo et al. 2008)**. The Hall effect has been also studied in this context by considering a self-similar model of the collapse of rotating isothermal molecular cloud cores with both Hall and ambipolar diffusion. The similarity solutions point out the profound influence of the Hall effect on the dynamics of collapse affecting the size of the protoplanetary disc and the protostellar accretion rate (Braiding and Wardle, 2012) and, **finally, the influence of magnetic fields and ambipolar diffusion on the formation and evolution of Giant Molecular Clouds and in the evolution of the star formation rate have also been studied (Vázquez-Semadeni et al. 2005a; Vázquez-Semadeni et al. 2005b;Vázquez-Semadeni et al. 2011).** All these studies are of high relevance and high impact to a broad range of fields of study within astrophysics.

However, in spite of all the progress achieved during past years in the study of PIP in different astrophysical environments, many unsolved questions still remain, **and the promotion of interaction among these different fields of research is the main goal of this ISSI proposal. In this respect, this proposal is focused on two key topics identified by the Team members and which will be addressed during the team meetings.**

Topics

1.- General

Nowadays, numerical simulations are routinely used to study the behaviour of PIP in different astrophysical environments. This is a very general topic of common interest for the different PIP above considered and, on the other hand, some of the proposed Team members have a great expertise in this field. For these reasons, the general topic to be addressed is:

Formulation of the multi-fluid plasma description appropriate for different astrophysical situations and the best way to implement it in numerical codes: Numerical schemes used to simulate the behaviour of astrophysical plasmas are often based on the single-fluid approximation. Recently, 1D and 3D numerical schemes for the treatment of multifluid plasmas, paying special attention to diffusive processes producing stability issues, have been introduced. The main goal of this general topic would be to discuss these new numerical approaches for the treatment of multifluid plasmas and to arrive to a wide consensus about its implementation in different astrophysical environments.

2.- Specific

The following specific topic tries to address some of the questions stated in the above ***Scientific Rationale***, which are of wide interest for different astrophysical areas where PIP are dominant, and in which the Team members have a proven expertise.

The Effects of Multifluid Physics on the Dynamics of PIP. Applications to Astrophysical Environments: MHD waves and Instabilities are ubiquitous in fully and partially ionized space plasmas, therefore, it is of great importance to understand the effects that the consideration of multifluid physics would have on MHD waves and Instabilities in PIP. In particular, the use of single-fluid approximation versus multifluid approaches in different astrophysical environments, the importance of ambipolar diffusion and Hall effect, and the modifications of instability thresholds and growth rates would be discussed. This topic is of great importance in solar plasmas, molecular clouds, the thermally unstable interstellar atomic medium and star formation. On the other hand, and in the exoplanetary context, the different interactions of the partially ionized plasma species with the planetary magnetic field and each other, play a crucial role in the processes of electric current generation and energy dissipation resulting in additional heating.

Correct and self-consistent modelling of these processes in the dynamical environments of expanding magnetized and partially ionized plasmaspheres, would be considered.

These topics call for a collaborative, multi-disciplinary approach, such as our Team proposes. The project is especially timely because of the current interest of this topic and the availability for the team members of space-borne and ground-based observatories, which can provide with breakthrough discoveries in this field, as well as the access to state-of-the-art computing facilities for numerical simulations. The present proposal offers a timely opportunity to make significant progress in the modelling of PIP, thanks to the collaboration of world experts in the areas mentioned above.

Expected output

The research carried out by the participants in response to the strategy that will be adopted at the end of the first meeting will lead to the publication of several papers in refereed journals, as well as presentations at conferences. The conclusions from our coordinated work will be finalized at the last meeting and presented in a review paper on this topic written by the team members. At present, the team members have published more than 100 papers on related topics.

Added value provided by ISSI

The present call for proposals is a great opportunity to generate fruitful inter-disciplinary collaborations among experts of different fields and different countries, with the aim of achieving a better understanding of the role played by partially ionized plasmas in Astrophysics. ISSI provides the ideal framework for coordinating state-of-the-art theory, observations and data analysis: its stimulating research environment and excellent research facilities, together with its convenient geographical location, will help us to carry out this project. The impetus given to the Team by ISSI will extend beyond the duration of this particular project, consolidating existing collaborations and fostering new ones. The visibility brought to the International Team selected by ISSI will also be an advantage for obtaining observing time on world-class observatories and presenting the results of our work at major conferences.

Expertise of participants

*Igor I. Alexeev is expert in the modelling of the interactions between solar wind and planetary magnetospheres.
*José Luis Ballester brings expertise in MHD waves and Instabilities in solar PIP.
*Manuel Collados brings expertise in observational techniques as well as in MHD plasma processes in the solar atmosphere.
*Turlough Downes is expert in supercomputation, multifluid physics and instabilities in PIP.
*Nikolai V. Erkaev brings key expertise in exoplanets atmospheres and numerical simulations.
*Holly R. Gilbert expertise is in the analysis and interpretation of multi-wavelength observations for investigating the physics of the solar corona and chromosphere.
*Maxim Khodachenko is expert in and Space plasma physics, in particular Exoplanets, kinetic theories and planetary magnetospheres.
*Elena Khomenko is expert in numerical simulations of plasma processes in the solar atmosphere.
*Ramón Oliver is expert in solar observations and MHD processes in the solar atmosphere
*Enrique Vázquez is expert in the physics of the interstellar medium and star formation
*Mark Wardle is expert in MHD, turbulence, physics of accretion discs and instabilities in astrophysical plasmas
*T. Zaqarashvili has invaluable expertise in plasma physics processes applied to different astrophysical environments

Schedule

Two meetings are planned, each of duration 4.5 days. The first meeting could take place at the end of 2013, and the second one in the second half of 2014. This will give enough time to

achieve the goals defined at the end of the first meeting. Two young scientists are planned to be attending each meeting, within the 20% of allocated man-weeks. The website hosted by ISSI will be an important way of coordinating and keeping track of Team's activity

Support requested

The proposed meetings will require one or two meeting rooms with video-projection facility, a printer, and Internet access for participants who will bring their own laptops. Financial support for accommodation and per diem for all participants, and travel expenses for the team leader, are requested from ISSI. The participants will seek alternative sources of funding to cover the remaining expenses.

References

Berger, T. E., ApJ, 676, L89, 2008
Berger, T. E., ApJ, 716, 1288, 2010
Berger, T. E. et al. Nature, 472, 197, 2011
Braiding, C. R. and Wardle, M., MNRAS, 427, 3188, 2012
Díaz, A. J. et al. ApJ, 754, 41, 2012
Downes, T. and O'Sullivan, S., ApJ, 730, 12, 2011
Downes, T.P., MNRAS, 425, 2277, 2012
Gilbert, H. R., et al., Ap. J., 577, 464, 2002
Gilbert, H. R., et al., Ap. J., 671, 978, 2007
Hillier, A. et al., ApJ, 736, L1, 2011
Hillier et al., ApJ, 746, 120, 2012
Jones, A. C. and Downes, T. P., MNRAS, 418, 390, 2011
Jones, A. C. and Downes, T. P., MNRAS, 420, 817, 2012
Khodachenko, M. et al., ApJ, 744, 70, 2012
Khomenko, E. and Collados, M., ApJ, 747, 87, 2012
Möstl, U. V. et al., Icarus, 216, 476, 2011
Penz, T. et al., Planet. and Space Sci., 56, 1260, 2008
Ryutova, M. et al., Solar Physics, 267, 75, 2010
Soler, R. et al., A&A, 540, A7, 2012
Soler, R. et al. ApJ, 749, 163, 2012
Tian, F. et al., ApJ, 621, 1049, 2005
Van Loo, S. et al., A&A, 484, 275, 2008
Vázquez-Semadeni et al., ApJ 618, 344, 2005a
Vázquez-Semadeni et al., ApJ 630, L49, 2005b,
Vázquez-Semadeni et al., MNRAS, 414, 2511, 2011
Zaqarashvili et al. 2011, A&A, 529, A82
Zaqarashvili et al. 2013, A&A, 549, A113

Appendix A: Curriculum Vitae of Participants

Igor I. Alexeev

Citizenship: Russia

Education:
Predoctoral study (1964 - 1967) in Physical Institute of Academy of Science, Moscow
Ph.D. (1971) , Doctor of Sci. (1998) - Lomonosov Moscow State University Skobeltsyn Institute of Nuclear Physics (MSU SINP) in speciality: Physics of plasma. interplanetary space.

Employment:
2010 - present Head of the Planetary Magnetospheres Laboratory, MSU SINP
2010 –present Professor of Cosmic Ray Physics, MSU SINP
1973-2010 Head of the Applied Mathematics Laboratory, MSU SINP
1971- 1973 – Senior Research Sci,, MSU SINP

Specialization: Space plasma physics, Astrophysics, Applied Mathematics, Electrodynamics, Physics of Magnetosphere. Publications: Book: 1; Papers in Refereed Journals and books: 101; Presentations: 162

Research Interests: The solar wind - magnetosphere interaction. A finite conductivity solution flow past the magnetosphere for the magnetic field in the magnetosheath in kinematic approach have been constructed. The planet magnetosphere modelling (Mercury, Earth, Jupiter and Saturn). Auroral particle acceleration and thin current sheet formation.

Awards: 2010 – S.V. Vervov silver medal, SINP MSU, 2011 – M.V. Lomonosow gold medal, MSU.

Research projects and grants: In cooperation with University of Michigan, Virginia Technical University, Goddard Space Flight Center serve as Principal Investigator from Russian side in grants NASA and NSF in 1995 - 2007. Also serve as Russian PI in the cooperation with KTH Stockholm (Sweden Royal Academia grants in 2003-2007. Serve as PI in 6 three years (1995 – present) Research grants from Russian Foundation of Basic Research (RFBR): During 1995 – till now to take part in other 11 RFBR Grants as participant. Serve as Russian PI in FP7 grant 2011-2015 IMPEx # 262863

Selected International Publications:

*Alexeev, I. I., et al., Paraboloid model of Mercury's magnetosphere, *J. Geophys. Res.*, **113**, A12210, doi:10.1029/2008JA013368, 2008.
*Alexeev, I. I., et al., Mercury's magnetospheric magnetic field after the first two MESSENGER flybys, Icarus, 209, 23-39, 2010,
*Khodachenko, M.L., Alexeev, I.I., et al., Magnetospheres of "Hot Jupiters": The importance of magnetodisks for shaping of magnetospheric obstacle, Astrophysical Journal, **744**, 1, 70, 2012.

José Luis Ballester (Team Leader)

Nationality
Spanish

Current Position
Professor of Astronomy and Astrophysics. Universitat Illes Balears (Spain)

Research Topics:
Dynamics of solar prominences; Structure, support and equilibrium of solar prominences; Equilibrium of magnetic flux tubes; MHD waves in coronal structures; Partial ionization effects in the Solar Atmosphere

Research Grants: PI in more than twenty National Research Projects. Participant and PI in several International Research Projects (NATO, INTAS, etc).

Publications
145 papers in journals included in the SCI.

Selected relevant papers for the proposal
* Forteza, P.; Oliver, R.; Ballester, J.L. Time damping of non-adiabatic MHD waves in an unbounded partially ionised prominence plasma. Astronomy and Astrophysics, 492, 223-231, 2008.
*Soler, R., Oliver, R., Ballester J. L. Magnetohydrodynamic Waves in a Partially Ionized Filament Thread. The Astrophysical Journal, 669, 1553-1562, 2009
* Soler, R.; Oliver, R.; Ballester, J. L. Resonantly Damped Kink Magnetohydrodynamic Waves in a Partially Ionized Filament Thread. The Astrophysical Journal, 707, 662-670, 2009
* Soler, R., Díaz, A. J., Ballester, J. L., Goossens, M. Kelvin-Helmholtz instability in partially ionized compressible plasmas. The Astrophysical Journal, 749, 163, 2012
*Díaz, A. J., Soler, R., Ballester, J. L. Rayleigh-Taylor instability in partially ionized compressible plasmas. The Astrophysical Journal, 754, 41, 2012
*Soler, R., Díaz, A. J., Ballester, J. L., Goossens, M. Effect of partial ionization on wave propagation in solar magnetic flux tubes. Astronomy and Astrophysics, 551, A86, 2013

Books
***Dynamics and Structure of Solar Prominences.** Editors: J. L. Ballester & E. R. Priest Servicio de Publicaciones de la Universidad de las Islas Baleares (1988), 182 pages. ISBN 84-7632-033-7
***INTAS Workshop on MHD waves in Astrophysical Plasmas.** Editors: J. L. Ballester & B. Roberts. Servicio de Publicaciones de la Universidad de las Islas Baleares (2001), 186 pages. ISBN 84-7632-68-4
***SOHO 13 - Waves, Oscillations and small-scale transient events in the Solar Atmosphere: A joint view from SOHO and TRACE.** Editors: R. Erdelyi, J. L. Ballester & B. Fleck. ESA SP- 547 (2004). ISBN 92-9092-858-1

Conferences
Attended more than 80 International Conferences. 26 Invited Reviews in International Conferences

Manuel Collados

Present position
Associate Professor at University of La Laguna, Researcher at Instituto de Astrofísica Canarias, La Laguna (Spain)

Academic Record
Feb/1983: Assistant Professor at University of La Laguna
June/1987: Ph.D. thesis in Physics
Feb/1989-Present: Associate Professor at University of La Laguna

Merits
2007-2012: President of EAST "European Association of Solar Telescopes"
2008-2011: Co-ordinator of the EU-funded Collaborative Project "EST: The European Solar Telescope"
2013-2017 Co-ordinator of the EU Integrated Infrastructures Initiative "High-Resolution Solar Physics Network: SOLARNET"

Fields of Interest
Magnetohydrodynamics, MHD equilibrium, MHD wave propagation
Chromospheric heating, partial ionization
Polarimetry, observations

Relevant Publications
*Khomenko, E.; Collados, M. "Heating of the Magnetized Solar Chromosphere by Partial Ionization Effects", Astrophys. J., 747, 87 (2012)
*Collados, M., Bettonvil, F. et al. "European Solar Telescope: project status", in "Ground-based and Airborne Telescopes III". Edited by Stepp, Larry M.; Gilmozzi, Roberto; Hall, Helen J. Proceedings of the SPIE, 7733, 77330 (2010)
*Beck, C.; Khomenko, E.; Rezaei, R.; Collados, M., "The energy of waves in the photosphere and lower chromosphere. I. Velocity statistics", Astron. Astrophys., 507, 453 (2009)
*Khomenko, E., Kosovichev, A., Collados, M.; Parchevsky, K., Olshevsky, V. "Theoretical Modeling of Propagation of Magnetoacoustic Waves in Magnetic Regions Below Sunspots", Astrophys. J., 694, 411 (2009)
*Khomenko, E., Collados, M. "Magnetohydrostatic Sunspot Models from Deep Subphotospheric to Chromospheric Layers" Astrophys. J., 689, 1379 (2008)
*Centeno, R.; Trujillo Bueno, J.; Uitenbroek, H.; Collados, M. "The Influence of Coronal EUV Irradiance on the Emission in the He I 10830 Å and D3 Multiplets", Astrophys. J., 677, 742 (2008)
*Khomenko, E., Centeno, R., Collados, M., Trujillo Bueno, J. "Channeling 5 Minute Photospheric Oscillations into the Solar Outer Atmosphere through Small-Scale Vertical Magnetic Flux Tubes", Astrophys. J., 676, L85 (2008)
*Khomenko, E., Collados, M., Felipe, T. "Nonlinear Numerical Simulations of Magneto-Acoustic Wave Propagation in Small-Scale Flux Tubes" Solar Phys., 251, 589 (2008)
*Martínez González, M. J.; Collados, M.; Ruiz Cobo, B.; Beck, C. "Internetwork magnetic field distribution from simultaneous 1.56 μm and 630 nm observations", Astron. Astrophys., 477, 953 (2008)
*Martínez González, M. J.; Collados, M.; Ruiz Cobo, B.; Solanki, S. K. "Low-lying magnetic loops in the solar internetwork", Astron. Astrophys., 469, 39 (2007)

Turlough Downes

Position
Senior Lecturer, School of Mathematical Sciences, Dublin City University (DCU).

Relevant Research funding
Over my career I have been awarded a total of 12.7 million euro on projects in which I was either PI or co-PI. Some particular awards of relevance to this proposal are:
PRACE supercomputing awards: Two awards from PRACE (the EU Research Infrastructure for Advanced Computing in Europe): 4.3 million core hours on Europe's most advanced supercomputers in 2009, and 14.3 million core hours on JUGENE in 2011.
Science Foundation Ireland: awarded €178,000 as PI to investigate stellar jet launching using multifluid MHD simulations. This project is now inactive and final results are in preparation for submission for 3 papers.
JETSET EU FP6 Project: From March, 2004 until March, 2009 I coordinated the scientific effort in simulations of stellar outflows across the 11 participating European institutions. Two post-doctoral research assistants and two PhD students worked directly with this workpackage and I was partly responsible for their mentoring and supervision.

Mentoring and Supervision
Current PhD Students: Mr Wayne O'Keeffe
Completed PhD Students: Dr Aoife Jones (2011), Dr Mairéad Hurley (2011), Dr Gilles Ferrand (2008), Dr Thomas Waters (2006), Dr Ronan Keegan (2005)
Past Post-Doctoral Researchers: Dr Stephen O'Sullivan (2007 – 2008), Dr Mohsen Shadmehri (2006 – 2008), Dr Sarah Tanner (2006 – 2007), Dr Fabio De Colle (2005 – 2008), Dr José Gracia (2006 – 2008), Dr Alex Rosen (2003 – 2005).

Conference/Workshop organisation
- Scientific Organising Committee for
  "Partially Ionized Astrophysical Plasmas", Tenerife, June, 2012
  "Numerical MHD and Instabilities", Sauze D'Oulx, Italy, January 2007
  "Jets from Young Stars V: High performance computing and applications", Galway, Ireland, 2008
- Organising Committee for "PRACE User Forum Meeting & Science Case Workshop", Dublin, March 2012.
- Organising Committee for "Dublin Spring School in Theoretical Physics", Dublin City University, 10 – 14 March, 2003

Relevant publications
*Jones, A.C., Downes, T.P., 2012 `The Kelvin-Helmholtz instability in weakly ionised plasmas II: multifluid effects in molecular clouds.', MNRAS, 420, 817-828.
*Jones, A.C., Downes, T.P., 2011, `The Kelvin-Helmholtz instability in weakly ionised plasmas: Ambipolar dominated and Hall dominated flows', MNRAS, 418, 390-400.
*Downes, T.P., O'Sullivan, S., 2011, `Multifluid magnetohydrodynamic turbulent decay', ApJ, 730, 12-23.
*Downes, T.P., O'Sullivan, S., 2009, `Non-ideal MHD turbulent decay in molecular clouds', ApJ, 701, 1258-1268.
*Shadmehri, M., Downes, T.P., 2008, `The role of the Kelvin-Helmholtz instability in dusty and partially ionised flows', MNRAS 387, 1318-1322.

Nikolay V. Erkaev

Prof. Doctor of Physics & Mathematics

Nationality
Russian

Fields of Research
Solar wind interaction with magnetic clouds and planets, Physics of Magnetosphere, Space Plasma Physics, Magnetohydrodynamics. The total number of international publications ~ 160.

Educational Background
1974, Diploma in Physics and Mathematics at the Novosibirsk State University, Russia. Diploma Thesis: Analytical model of variations of Bow shock position related with IMF.
1979, Scientific degree of Candidate in Physics and Mathematics at the Institute of Hydrodynamics of Russian Academy of Sciences, Novosibirsk, Russia.
Thesis: Hypersonic MHD flow around blunt bodies.
1992 A scientific degree of Doctor in Physics and Mathematics, S.-Petersburg University, Russia. Thesis: Effects of magnetic barrier and solar wind flow around magnetosphere.
1994, Diploma of Professor of the Department: "Mathematical modelling in mechanics".

Academic employment
Since 1997, Leading-Scientist at the Institute of Computational Modelling of the Russian Academy of Sciences in Krasnoyarsk, Russia.

Selected international publications
*N. V. Erkaev et al. Accelerated magnetosheath flows caused by IMF draping: Dependence on latitude. Geophys. Res. Lett., 39, L01103, doi:10.1029/2011GL050209, 2012.
*Ute V. Mostl, N. V. Erkaev et al. The Kelvin–Helmholtz instability at Venus: What is the unstable boundary? Icarus, 216, 476–484, 2011.
*C. J. Farrugia , N. V. Erkaev et al. Efects on the distant geomagnetic tail of a fivefold density drop in the inner sheath region of a magnetic cloud: A joint Wind-ACE study, Adv. Space Res., 44, 1 1288-1294, 2009.
*T. Penz, N.V. Erkaev, et al. Mass loss from ''Hot Jupiters''—Implications for CoRoT discoveries, Part II: Long time thermal atmospheric evaporation modeling, Planet. Space Sci., 56, 1260-1272, 2008.
*Erkaev N.V. et al. Aspects of solar wind interaction with Mars: comparison of fluid and hybrid simulations, Ann. Geophys., 25, 145-159, 2007.
*N. V. Erkaev et al. Roche lobe effects on the atmospheric loss from "Hot Jupiters", Astronomy&Astrophysics, 472, 329–334, DOI: 10.1051/0004-6361:20066929, 2007.
*Penz T., Erkaev N. V. et al. Plasma and magnetic field parameters in the vicinity of short-periodic giant exoplanets, The Astrophys. J., Supplement Series, 157, 396-401, 2005.

Holly R. Gilbert

Professional Preparation
B. A., Physics, 1997, University of Colorado
Ph. D., Theoretical Astrophysics, 2005, University of Oslo

Appointments
2011-present: Chief, Solar Physics Laboratory, Heliophysics Science Division, NASA's Goddard Space Flight Center
2008-2011: Heliophysics Science Division Associate Director for Science, NASA's Goddard Space Flight Center
2005-2008: Research Scientist, Rice University
1997-2005: Associate Scientist, High Altitude Observatory, National Center for Atmospheric Research

Publications Most closely related to proposed project
[1] Gilbert, H. R. T. E. Holzer, J. T. Burkepile, A. J. Hundhausen, Active and eruptive prominences and their relationship to coronal mass ejections, Ap. J., 537, 503-515, 2000.
[2] Gilbert, H. R., T. E. Holzer, B. C. Low, J. T. Burkepile, Observational interpretation of an active prominence on 1999 May 1, Ap. J., 549, 1221-1230, 2001.
[3] Gilbert, H. R., V. H. Hansteen, T. E. Holzer, Neutral atom diffusion in a partially ionized prominence plasma, Ap. J., 577, 464-474, 2002.
[4] Gilbert, H. R., T. E. Holzer, R. M. MacQueen, A new technique for deriving prominence mass from SOHO/EIT Fe XII (19.5 nm) absorption features, Ap. J., 618, 524-536, 2005.
[5] Gilbert, H. R., G. Kilper, D. Alexander, Observational evidence supporting cross-field diffusion of neutral material in solar filaments, Ap. J., 671, 978, 2007.
[6] Gilbert, H. R., D. Alexander, R. Liu, Filament kinking and its implications for eruption and reformation, Solar Phys., 245, 287, 2007.
[7] Gilbert, H. R., A. G. Daou, D. Young, D. Tripathi, D. Alexander, The filament-Moreton wave interaction of 2006 December 06, Ap. J., 685, 629, 2008.
[8] Gilbert, H. R., G. Kilper, D. Alexander, T. Kucera, Comparing Spatial Distributions of Solar Prominence Mass Derived from Coronal Absorption, Ap.J., 727, 25, 2011.

Recent grants awarded
NASA LWS TR&T (awarded in 2010)
Gilbert H., Principal Investigator, Ion-Neutral Coupling in Solar Prominence Structure and Dynamics

Maxim L. Khodachenko

Education
Mar., 1998: Ph.D. in two specialties: 1) Plasma Physics, 2) Astrophysics /Radio Astronomy by Institute of Applied Physics, Russian Academy of Sciences .
Jul., 1989: M.S. degree in Radiophysics and Electronics, Nizhny Novgorod State University, Department of Radiophysics

Employment
Since 2001: Research Scientist, Space Research Institute, Austrian Academy of Sciences, Graz, Austria, full-time
1999-2001: Max-Planck Senior Research Fellow, Max-Planck-Institut für Extraterrestrische Physik, Garching bei Muenchen, Germany; full-time
1989-1999: Research Scientist / Junior Research Scientist / Predoctoral student / Postgraduate student, Dept. of Astrophysics & Space Plasma Physics, Institute of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod, Russia; full-time

Research Interests
Solar/stellar physics; Planetary magnetospheric physics (Io-Jupiter, Exoplanets); Extra-solar planets, Stellar-planetary connections, habitability, search algorithms; Radio astronomy (radiation mechanisms, data analysis); Plasma MHD and kinetic theories in application to astrophysical and aerospace problems

Professional activities
Coordinator of EC FP7 project IMPEx (Integrated Medium for Planetary Exploration)
Coordinator of the "European Modelling and Data Analysis Facility" (JRA3-EMDAF) within EC FP7 research infrastructure project EUROPLANET-RI
Member of "Terrestrial Exoplanets / Science & Search technologies / BlueDots" international working group

Selected Publications
*Khodachenko, M.L., Alexeev, I.I., Belenkaya, E., Leitzinger, M., Odert, P., Grießmeier, J.-M., Zaqarashvili, T.V., Lammer, H., Rucker, H.O., Magnetospheres of 'Hot Jupiters': The importance of magnetodisks for shaping of magnetospheric obstacle, Astrophys. Journal, 2012, 744, 70 (doi:10.1088/0004-637X/744/1/70).

*Khodachenko, M.L., Ribas, I., Lammer, H., Grießmeier, J.-M., Leitner, M., Selsis, F., Eiroa, C., Hanslmeier, A., Biernat, H., Farrugia, C. J., Rucker, H., Coronal Mass Ejection (CME) activity of low mass M stars as an important factor for the habitability of terrestrial exoplanets, Part I: CME impact on expected magnetospheres of Earth-like exoplanets in close-in habitable zones, Astrobiology, 2007, 7, No.1, 167-184.

*Khodachenko, M.L., Lammer, H., Lichtenegger, H.I.M., Langmayr, D., Erkaev, N.V., Griessmeier, J.-M., Leitner, M., Penz, T., Biernat, H. K., Motschmann, U., Rucker, H.O., Mass loss of "Hot Jupiters" – Implications for CoRoT discoveries. Part I: The importance of magnetospheric protection of a planet against ion loss caused by coronal mass ejections, Planetary and Space Science, 2007, 55, 631-642.

Lammer, H., Güdel, M., Kulikov, Yu., Ribas, I., Zaqarashvili, T.V., **Khodachenko, M.L.**, Kislyakova, K.G., Gröller, H., Odert, P., Leitzinger, M., Fichtinger, B., Krauss, S., Hausleitner, W., Holmström, M., Sanz-Forcada, J., Lichtenegger, H.I.M., Hanslmeier, A., Shematovich, V.I., Bisikalo, D., Rauer, H., Fridlund, M., Variability of solar/stellar activity and magnetic field and its influence on planetary atmosphere evolution, Earth Planets Space, 2012, **64**, 179–199

Elena Khomenko

Tenure-track researcher at the University of La Laguna, Tenerife, Spain.

Education
09/10/2003 (approved 14/01/2004) PhD in Physics and Math, speciality: "Heliophysics and physics of solar system". Dissertation: "Five-minute oscillations in local solar structures: granules, porules, sunspots". Main Astronomical Observatory, Ukraine).
1999: Master of Sciences degree from the Kiev Taras Shevchenko University, Ukraine.

Employment
2011-present "Ramon y Cajal" tenure-track position, University of La Laguna, Tenerife, Spain
2004-2011: Post Doctoral positions at the Instituto de Astrofísica de Canarias, Spain.
1999-2004: researcher at Main Astronomical Observatory National Academy of Sciences of Ukraine.

Profesional activities
Principal Investigator of FP7 IDEAS project "Magnetic connectivity through the Solar Partially Ionized Atmosphere"; ERC Starting Grant (ERC-2011-StG 277829-SPIA).
Member of Consolider project "Supercomputing and e-Science" (PI M. Valero, BSC); member of projects "Solar atmosphere: 3D numerical simulations of the observed processes" (PI F. Moreno-Insertis, IAC) and "Solar Magnetism and Astrophysical Spectropolarimetry" (PI J. Trujillo Bueno, IAC) funded by Spanish Ministry of Science.

Selected peer-reviewed publications (out of 40 and 32 conference proceedings)

*Khomenko, E.; Collados, M. "Heating of the Magnetized Solar Chromosphere by Partial Ionization Effects", Astrophys. J. Vol. 747, p. 87 (2012)
*Khomenko, E.; Cally, P. S., "Numerical Simulations of Conversion to Alfvén Waves in Sunspots", Astrophys. J., Vol. 746, p. 68 (2012)
*Fabbian, D.; Khomenko, E.; Moreno-Insertis, F.; Nordlund, Å. "Solar Abundance Corrections Derived Through Three-dimensional Magnetoconvection Simulations", Astrophys. J., Vol. 724, p. 1536 (2010)
*Khomenko, E.; Kochukhov, O. "Simulations of magneto-acoustic pulsations in atmospheres of rapidly oscillating Ap stars", Astrophys. J. Vol. 704, p. 1218 (2009)
*Khomenko, E., Kosovichev, A., Collados, M.; Parchevsky, K., Olshevsky, V. "Theoretical Modeling of Propagation of Magnetoacoustic Waves in Magnetic Regions Below Sunspots", Astrophys. J. Vol. 694, p. 411 (2009)
*Khomenko, E., Collados, M. "Magnetohydrostatic Sunspot Models from Deep Subphotospheric to Chromospheric Layers" Astrophys. J. Vol. 689, p. 1379 (2008)

Ramón Oliver

Research Interests
Magnetohydrodynamic waves – Waves/oscillations in the solar corona and in solar prominences

Education
Ph.D., University of the Balearic Islands, Spain, April 1993
B.Sc., University of Barcelona, Spain, June 1989

Research and AcademicExperience
*Professor July 2009 – present. University of the Balearic Islands, Spain
*Lecturer October 1996 – July 2009. University of the Balearic Islands, Spain
*Research Assistant May 1993 – September 1994. University of St. Andrews, UK
*Research Assistant December 1992 – October 1996. University of the Balearic Islands, Spain
*Ph.D. Fellowship January 1990 – December 1992. University of the Balearic Islands, Spain

Professional achievements
• 107 publications in refereed journals.
• 8 invited reviews in international meetings.
• Principal investigator of 2 research grants.
• Participation in 23 research grants.
• Referee of research journals, among them Astronomy & Astrophysics, Monthly Notices of the Royal Astronomical Society, Physical Review Letters, Solar Physics, The Astrophysical Journal Letters.
• Advisor of 6 Ph.D. Thesis and 7 M.Sc. Thesis.
• Member of 8 Ph.D. Thesis committees.

Selected recent publications
• Arregui, I., Oliver, R., Ballester, J. L. (2012) "Prominence Oscillations". Living Reviews in Solar Physics, 9, 2, (109 pp)
• Soler, R., Oliver, R., Ballester, J. L. (2011) "Spatial damping of propagating kink waves in prominence threads", The Astrophysical Journal, 726, 102
• Luna, M., Terradas, J., Oliver, R., Ballester, J. L. (2010) "Transverse oscillations of a multi-stranded loop", The Astrophysical Journal, 716, 1371–1380
• Lin, Y., Soler, R., Engvold, O., Ballester, J. L., Langangen, Ø., Oliver, R., Rouppe van der Voort, L. H. M. (2009) "Swaying threads of a solar filament", The Astrophysical Journal, 704, 870–876
• Zaqarashvili, T. V., Oliver, R., Ballester, J. L. (2009) "Global shallow water magnetohydrodynamic waves in the solar tachocline", The Astrophysical Journal Letters, 691, L41–L44
• Terradas, J., Arregui, I., Oliver, R., Ballester, J. L. (2008) "Transverse oscillations of flowing prominence threads observed with Hinode", The Astrophysical Journal Letters, 678, L153–L156

Enrique Vázquez-Semadeni

PhD Diploma
Astronomy Department. The University of Texas at Austin

Current Position
Professor. Centro de Radioastronomia y Astrofísica (CRyA), UNAM.

Main Research Areas
- Compressible MHD turbulence in the interstellar medium;
- Structure and thermodynamics of the interstellar medium;
- Star formation.

Refereed Publications: 54

Citations: 3035 (on March 21, 2012)

Prizes
- **"Jorge Lomnitz Adler Prize 1997"** to young researchers (under age 45), granted by the Instituto de Física, UNAM, for research on nonlinear dynamics and collective phenomena.
- **"State of Michoacán's Prize to Scientific and Humanistic Research"**, granted by the State of Michoacán, México, 2008.

Selected Publications:
*Vázquez-Semadeni, E.; Banerjee, R.; Gomez, G.; Hennebelle, P.; Duffin, D.; Klessen, R. S., "Molecular Cloud Evolution IV: Magnetic Fields, Ambipolar Diffusion, and the Star Formation Efficiency", 2011, MNRAS, 414, 2511
*Ballesteros-Paredes, J.; Vázquez-Semadeni, E.; Gazol, A.; Hartmann, L. W.; Heitsch, F.; Colin, P., "Gravity or turbulence? II. Evolving column density PDFs in molecular clouds", 2011, MNRAS, 416, 1436
*Toalá, J. A.; Vázquez-Semadeni, E.; Gómez, G. C., "The Free-Fall time of finite Sheets and Filaments", 2012, ApJ, 744, 190
* Pon, Andy; Toalá, Jesús A.; Johnstone, Doug; Vázquez-Semadeni, Enrique; Heitsch, Fabian; Gómez, Gilberto C. "Aspect Ratio Dependence of the Free-fall Time for Non-spherical Symmetries", 2012, ApJ, 756, 145
*Naranjo-Romero, Raúl; Zapata, Luis A.; Vázquez-Semadeni, Enrique; Takahashi, Satoko; Palau, Aina; Schilke, Peter, "From Dusty Filaments to Massive Stars: The Case of NGC 7538 S", 2012, ApJ, 757, 58
*Heiner, J. S.; Vázquez-Semadeni, E., "Applying a one-dimensional PDR model to the Taurus molecular cloud and its atomic envelope", 2013, MNRAS, 429, 3584

Mark Wardle

Research Interests:
Physical, chemical, and dynamical processes in the interstellar medium; magnetohydrodynamics; star and planet formation; the Galactic Centre

Academic qualifications
PhD Astrophysics (1989), Princeton University; MSc(Hons) Physics (1984), BSc(Hons) Mathematics (1982), University of Auckland.

Employment
Macquarie University: Professor (2008–); Head, Department of Physics & Engineering (2009); Head, Department of Physics (2006–2008); Associate Professor (2005–2007); Research Director, Division of Information & Communication Sciences (2004–2006); Lecturer (2002–2004). University of Sydney: Senior Lecturer (fixed term, 2001-2002); Senior Research Fellow (2000–2002); Research Fellow (1996–1999). University of Rochester: Assistant Professor (1993–1995). Northwestern University: Visiting Assistant Professor (1992–1993); Lindheimer Fellow (1990–1992). University of Chicago: Research Associate (1988–1990).

Publication
76 refereed papers in international journals, including 2 review articles in Science; 20 conference papers; 2 theses. h-index: 28 (source: NASA ADS database 2012 Mar 21)

Selected Publications
*Pandey, B.P, & Wardle, M. 2012. Magnetorotational instability in magnetic diffusion dominated accretion discs, MNRAS, in press (accepted 2012 Feb 22)
*Braiding, C.R., & Wardle, M. 2012. The Hall effect in star formation, MNRAS, in press (accepted 2012 Jan 19)
*Wardle, M., & Salmeron, R. 2012. Hall diffusion and the magnetorotational instability in protoplanetary discs, MNRAS, in press (accepted 2011 Oct 15)
*Salmeron, R. &Wardle, M. 2008, Magnetorotational instability in protoplanetary discs: the effect of dust grains, MNRAS, 388, 1223–1238
*Pandey, B. P. &Wardle, M. 2008, Hall magnetohydrodynamics of partially ionized plasmas, MNRAS, 385, 2269–2278

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Record:

2009: Research scientist, Space Research Institute, Austria
2009: Associate Professor in Astrophysics, Ilia State University, Georgia
2008: Assistant Professor in Astrophysics, Ilia State University, Georgia
2006: Senior research associate, Abastumani Astrophysical Observatory, Georgia
2005: Research associate, University of Balearic Islands, Spain
2002: Research scientist, Abastumani Astrophysical Observatory, Georgia
2001: NATO Postdoctoral Fellow, University of St Andrews, UK
1997: Scientist, Abastumani Astrophysical Observatory, Georgia
1997: PHD Degree in Astrophysics, Abastumani Astrophysical Observatory, Georgia
1995: Junior scientist, Abastumani Astrophysical Observatory, Georgia
1991: Msc in Theoretical Physics, Tbilisi State University, Georgia

Four Most Relevant Recent Publications:

1) Zaqarashvili, T. V., Khodachenko, M. L. and Soler, R., Torsional Alfvén waves in partially ionized solar plasma: effects of neutral helium and stratification, 2013, A&A, 549, A113

2) Zaqarashvili, T. V., Carbonell, M., Ballester, J.L. and Khodachenko, M. L., Cut-off wavenumber of Alfvén waves in partially ionized plasmas of the solar atmosphere, 2012, A&A, 544, A143

3) Zaqarashvili, T. V., Khodachenko, M. L. and Rucker, H. O., Damping of Alfvén waves in solar partially ionized plasmas: effect of neutral helium in multi-fluid approach, 2011, A&A, 534, A93

4) Zaqarashvili, T. V., Khodachenko, M. L. and Rucker, H. O., Magnetohydrodynamic waves in solar partially ionized plasmas: two-fluid approach, 2011, A&A, 529, A82

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Astrophysics > Solar and Stellar Astrophysics. Title:Partially Ionized Plasmas in Astrophysics. Authors:Jose Luis Ballester, Igor Alexeev, Manuel Collados, Turlough Downes, Robert F. Pfaff, Holly Gilbert, Maxim Khodachenko, Elena Khomenko, Ildar F. Shaikhislamov, Roberto Soler, Enrique Vazquez-Semadeni, Teimuraz Zaqarashvili. (Submitted on 25 Jul 2017 (v1), last revised 26 Jul 2017 (this version, v2)). Abstract: Partially ionized plasmas are found across the Universe in many different astrophysical environments. They constitute an essential ingredient of the solar atmosphere, molecular clou Partially ionized plasmas introduce physical effects which are not considered in fully ionized plasmas, for instance, Cowlingâ€™s resistivity, isotropic thermal conduction by neutrals, heating due to ion/neutral friction, heat transfer due to collisions, charge exchange, ionization energy, etc., which are crucial to fully understand the behaviour of astrophysical plasmas in different environments.Â The non-diagonal components of p Ë† aI provide viscosity. The expressions for the components of the complete tensor for electrons and ions of a fully ionized plasma can be found in Braginskii (1965), see his equations (2.19â€“2.28), where he considered approximate expressions for the limiting cases of weak and strong magnetic field. For a PIP, Khodachenko et al.