

The Research Center for Astronomy and Applied Mathematics (RCAAM) was established in 1959 initially as “Office for Research and Calculations” and it was given its present name in 1966. Its scientific research focuses on the following fields: 1. Dynamical Astronomy, Nonlinear phenomena and Chaos Theory, 2. Galactic Dynamics and Galactic Morphology, 3. Solar and Space Physics, 4. Magnetohydrodynamics and 5. Cosmology. A recently established line of research involves the study of Extremely Low Frequency (ELF) electromagnetic waves in the Schumann (2-50 Hz) region.

The first Supervisor of the Center was Academician Prof. I. Xanthakis, who served until his passing in 1994. Between 1994 -1997 RCAAM was supervised by the Academician Prof. N. Artemiadis. Since 1997 Supervisor is Academician Prof. G. Contopoulos. As directors have served Dr. L. Mavridis (1960-1966), Dr. C. Macris (1971-1979), Dr. C. Poulakos (1981-2001), Dr. N. Voglis (2001-2007), Dr. V. Tritakis (2007, Acting Director), Dr. H.C. Dara (2008), and since 2009 Dr. P.A. Patsis (Acting Director).

RCAAM hosts the “A-EFFORT” solar-flare forecasting service of the European Space Agency (ESA) and has coordinated the “FLARECAST” Consortium of the European Union for the prediction of solar eruptions.

Six tenured researchers serve currently at RCAAM. Dr. S. Basilakos serves also as Director of the Institute for Astronomy, Astrophysics, Space Applications and Remote Sensing of the National Observatory of Athens. Research is conducted through projects supported by the Research Committee of the Academy of Athens, as well as by national and international organizations and institutions. Since 1997, competitive research funding has been amounted to about 280000€ for research on Magnetohydrodynamics, about 370000€ for research on Dynamical Astronomy and, since 2010, to more than 1.3 million € for research on Solar and Space Physics.

Research results of the Center are mainly published in high impact, peer-reviewed international journals. Secondly, they are published in conference proceedings and special volumes. Since establishment, there have been published **619** research papers in refereed journals and **263** non-refereed publications with RCAAM as affiliation. Fig.1 depicts a histogram with the number of publications in 5-years bins. The mean number of refereed papers per year over the last ten years is about **32**. There are more than **12000** third party citations to these 619 papers.

In the last 25 years RCAAM was the exclusive organizer of **4** international conferences and workshops, while its members have served as main organizers and members of the scientific organizing committees in more than **94** conferences organized jointly with, or solely by, other institutes. Since its establishment **3** volumes with conference proceedings organized by RCAAM have been published:

- Solar Physics, J.N. Xanthakis (ed.), 1967, John Wiley & Sons
- Galaxies and Chaos, G. Contopoulos and N. Voglis (eds)., 2003, LNP (Lecture Notes in Physics), vol. 626, 3, Springer-Verlag
- Chaos in Astronomy, G. Contopoulos and P.A. Patsis (eds)., 2009, Astrophysics and Space Science Proceedings, Springer-Verlag

In addition, two books have been published by Prof. G. Contopoulos:

- Order and Chaos in Dynamical Astronomy, 2002, Springer
- Adventures in Order and Chaos: A Scientific Autobiography, Astrophysics and Space Science Library, Vol. 313, 2005, Kluwer.

Finally, RCAAM researchers have served as co-editors of **29** conference proceedings volumes or as Guest Editors of special volumes.

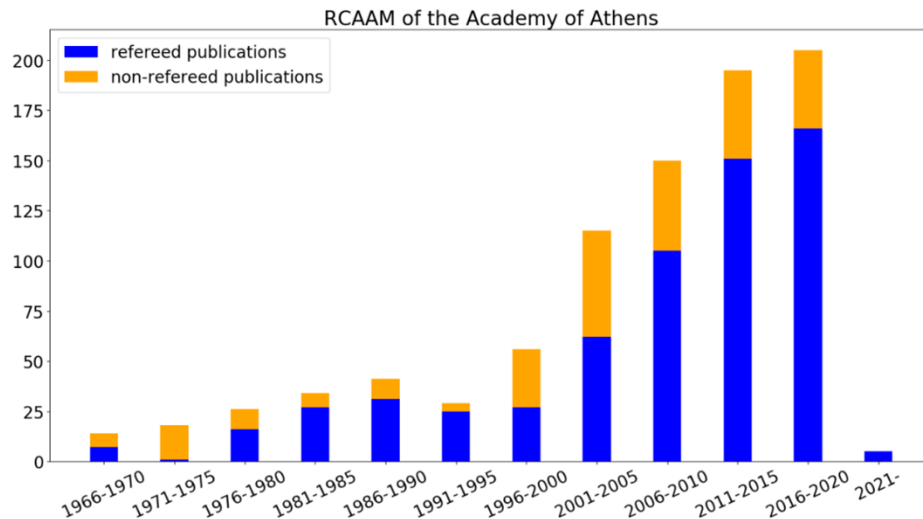


Fig. 1 RCAAM publications since its establishment. In the last 10 years RCAAM publishes about 32 refereed papers per year on average (based on NASA/ADS data)

RCAAM publishes since 2016 the annual edition “New Advances in Astronomy”. This is a Greek-language summary of recent advances in Astronomy and Applied Mathematics, associated with research conducted at RCAAM. [Our Annual Reports since 2009, including detailed publication lists, can be downloaded in PDF format from the Centers web site.](#)

RCAAM, organizes since 1997 seminars and research talks on a weekly basis. Invited speakers include, besides the researchers and students of RCAAM, Academicians, Professors and distinguished scientists from various universities and research Centers in Greece and abroad. A total of **425** talks have been organized at the seminars’ room of RCAAM, since 2009 alone.

Since 2000, RCAAM has hosted **19** postdoctoral researchers, working on inhouse scientific projects for 2-3 years on average, financed by the Research Committee of the Academy of Athens, or from external sources. During the same period, **13** PhD students have successfully defended their Doctoral Theses, working at RCAAM under the supervision of researchers of our Center (10 from the University of Athens, and one each from the Democritean University of Thrace, the National Institute of Astrophysics, Optics and Electronics, Mexico and the University of Florida, USA). Currently **2** more PhD students are hosted at RCAAM, while members of our institute participate, as main supervisors, or as members of the supervising committees, in **16** more PhDs (8 at the University of Athens, 2 at the Georgia State University, USA, 2 at the University of Ioannina and one each at the universities of Thessaloniki, Volos, Technical University of Athens and University of Leuven, Belgium). In parallel, **10** Masters students have completed their work and successfully acquired their Masters degrees working at RCAAM, under the supervision of the Center’s staff. Currently, **2** Masters-theses are supervised by RCAAM researchers. Finally, **3** undergraduate students (2 from the University of Athens and 1 from the University of Grenoble, France) have completed their Diploma Theses at RCAAM.

Since 2002, RCAAM researchers have participated in the teaching of **6** postgraduate disciplines at the University of Athens (totally for 30 semesters), as well as **2** undergraduate courses (totally for 7 semesters) at the same University and **1** undergraduate course for **1** semester at the Georgia State University, USA. In addition, they have taught, after invitation, several postgraduate courses in university departments, seminars for students and researchers, and schools organized by universities and scientific associations.

Every year RCAAM researchers accept invitations to give talks in international conferences, as well as to stay for longer terms at various institutes abroad in the frame of joint research projects (details for every year are given in our Annual Reports). Current collaborations in common research projects include: University of Helsinki (Finland); European Space Agency (ESA), Paris, Laboratoire d'Astrophysique de Marseille, University of Aix-Marseille, University of Strasbourg, Institut d'Astrophysique Spatiale, University Paris-Saclay (France); Astronomy Department, University of Munich (LMU), European Southern Observatory (ESO), Munich, Max-Planck Institute for Astrophysics, Munich, Max-Planck Institute for Radioastronomy, Bonn (Germany); National Institute of Astrophysics, Optics and Electronics (INNAOE), Puebla, Mexico; University of Padova (Italy); University of Krakow (Poland); Department of Mathematics, University of Cape Town (South Africa); Space Science Institute (ISSI), Bern, (Switzerland); Georgia State University, NASA/Goddard, NASA/Solar Radiation Analysis Group, NASA/Ames (USA).

Among the various distinctions earned by RCAAM members, we recite the election of Prof. Contopoulos as honorary Doctor of Science of the University of Athens (2009), the inclusion of the paper "Chaos in Bohmian and Quantum Mechanics" by Efthymiopoulos and Contopoulos in the list of selected papers of Journal of Physics A, the Marie Curie Fellowship and Excellent Science Award bestowed to Dr. Georgoulis (2015), the naming of the minor planet 84015 Efthymiopoulos in honor of the researcher of RCAAM Christos Efthymiopoulos (2017) and the honorable mentions by the Gravity Research Foundation to Dr. Basilakos for his research (2013, 2014, 2017 and 2019).

RCAAM researchers have participated in numerous PhD examination committees, habilitations, as well as in nominating and promotion committees in universities and research institutes. They are members of administrative councils, committees of national and international scientific organizations, among which committees of the International Astronomical Union (IAU), of the European Astronomical Society (EAS) and the Committee of Space Research (COSPAR). They serve as evaluators in research projects, observing programmes committees, as well as reviewers in all high-impact journals of Astronomy, Astrophysics and Nonlinear Dynamics. RCAAM members participate in the editorial boards of the American Astronomical Society (AAS), "Celestial Mechanics and Dynamical Astronomy", "High-Energy and Astroparticle Physics" and "The Universe". Dr. Basilakos is currently the President of the Greek National Committee for Astronomy (GNCA).

RCAAM has organized three series of full-year talks for the broad public during the whole year at the Academy of Athens. These were organized in 2009, on the occasion of the "International Year of Astronomy" (11 talks), in 2015, on the occasion of the "International Year of Light" (8 talks) and in 2019, on the occasion of the IAU Centennial (9 talks). Besides these series of talks, RCAAM researchers give many public outreach talks and publish popular articles for newspapers and journals, among appearances on television and radio programs.

Future plans: Theoretical and numerical work on Classical and Quantum nonlinear Dynamical systems in RCAAM will continue, drawing from and extending the recent successes on this field of research. Numerical and observational work on Galactic Dynamics will focus on the comparison of theoretical models with high quality observations of ground- and space-based telescopes. A main scientific endeavor will be the study of the pulsar magnetospheric structure with emphasis on understanding the mechanism of relativistic particle acceleration and emission of high energy radiation in the magnetospheric current sheet. Cutting-edge Solar Physics and Space Weather research at RCAAM will be assisted by the commissioning and future planning of relevant space missions. The RCAAM and the National Committee of the Academy of Athens, through Dr. M. Georgoulis, national representative of COSPAR, chair the

organization of the 44th COSPAR Scientific Assembly, to be held in Athens in July 2022. In addition, the theoretical and observational research in Cosmology will continue following the high standards that characterize this RCAAM line of research over the past 15 years.

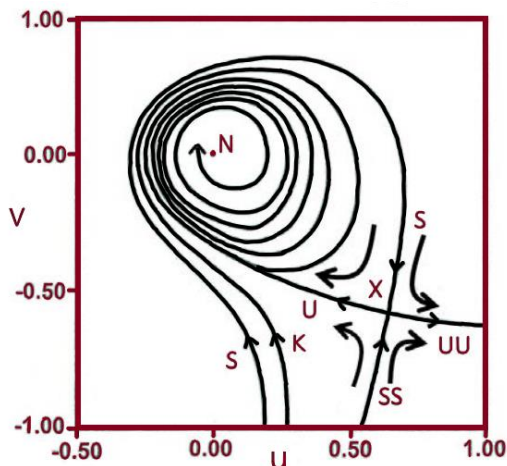
Details about all RCAAM activities can be found in the Center's website:

<http://astro.academyofathens.gr/>

Highlights of RCAAM research:

Here are some characteristic results of the research conducted in the Center and have been appreciated by the international astronomical community:

Quantum Dynamical Systems:



The RCAAM of the Academy of Athens has played a key role in developing [Chaos theory in astronomical systems and in nonlinear dynamical systems](#) in general. Special emphasis has been given in the last twenty years in the study of quantum dynamical systems in the de Broglie - Bohm interpretation of Quantum Mechanics ([Contopoulos, Tzemos 2020, Regul. Chaotic Dyn. 25, 476](#)). The main contribution of the Center is the development of the most general theoretical mechanism for the emergence of chaos in the Bohmian trajectories of two-dimensional ([Efthymiopoulos, Kalapotharakos, Contopoulos 2009, Phys. Rev. E 79, 036203](#)) and three-

dimensional quantum systems ([Tzemos, Efthymiopoulos, Contopoulos 2018, Phys. Rev. E 97, 042201](#)). This is the so called 'Nodal point-X-point mechanism', according to which whenever a Bohmian trajectory comes close to a moving node of the wave-function Ψ , it gets deflected by its accompanying hyperbolic point, the X-point, as shown in the figure. The cumulative action of many such encounters is the emergence of chaos. Based on this mechanism, the researchers of the RCAAM study the relationship between chaos, order and the entanglement of complex quantum systems ([Tzemos, Contopoulos 2020, Phys. Rev. E. 102, 042205](#)), which is very important for the theoretical understanding of the origin of Born's rule (probability density $P=|\Psi|^2$) ([Efthymiopoulos, Contopoulos, Tzemos 2017, Ann. Fond. Louis De Broglie 42, 133](#)

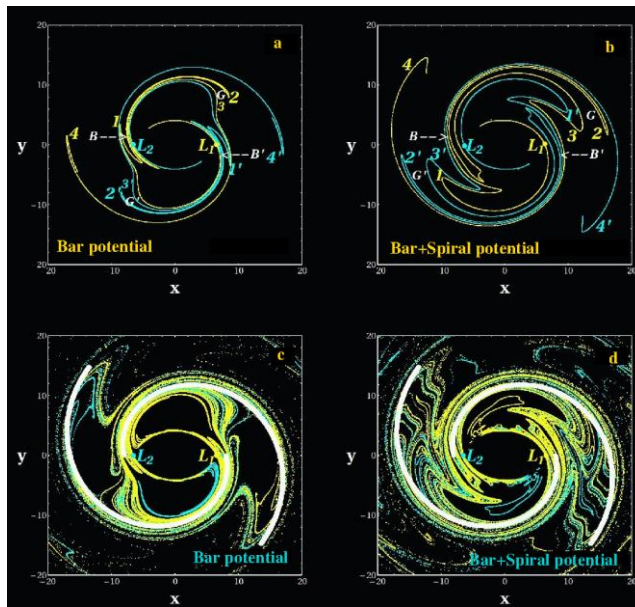
Peanut shaped galactic bulges:



The central regions of many disk galaxies, among which is also the Milky Way, have a “[peanut](#)” or X-shaped morphology, when viewed edge-on. Its presence has puzzled researchers for many years, initially considering it as a peculiar type of a galactic bulge. Research in RCAAM

contributed significantly to the clarification of this structure. In a series of 24 papers, starting in 2002 ([Patsis, Skokos, Athanassoula 2002, MNRAS 337, 578](#)), it has been shown that stars, initially on the equatorial plane of the galaxies, feeling the presence of a vertical 2:1 resonance move in such orbits, visiting the space away from the galactic plane, as to support the peanut- or X-shaped morphology. In the figure above we observe to the left a typical galaxy with this morphology (HCG 87a) and to the right a set of orbits reproducing its central structure ([Patsis & Katsanikas 2014, MNRAS 445, 3525](#)). This structure is not a distinct component, but it is the central, thick part of the galactic bars, as also N-body simulations indicate. Recent observations with the Aristarchos telescope on mount Helmos supported this idea ([Patsis et al. 2021, Astron. Astrophys. 647,20](#)).

Chaotic Spirals:



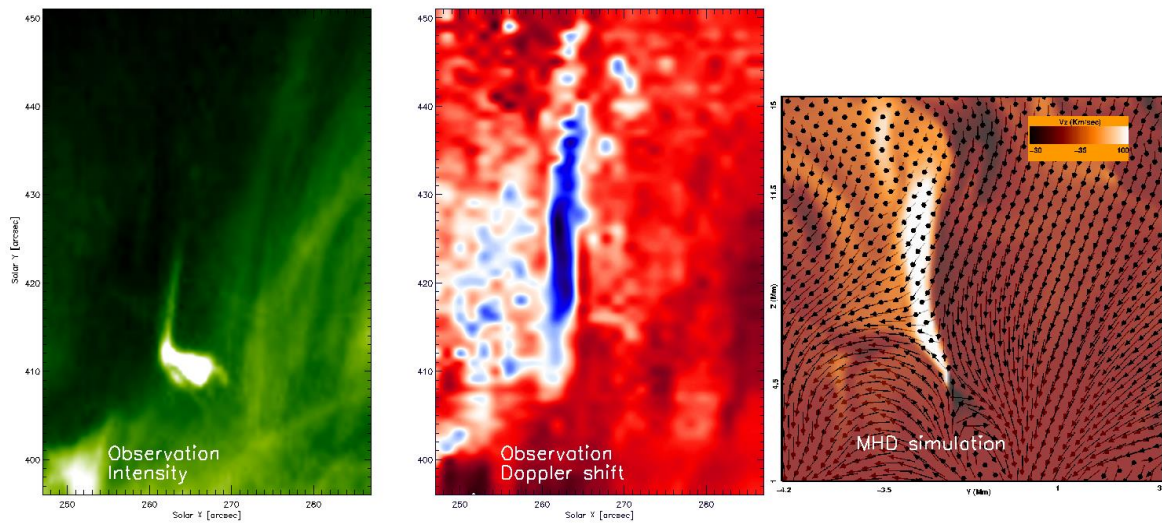
A hot topic in modern Galactic Dynamics has been the dynamical mechanism of "chaotic spiral arms" in barred-spiral galaxies. Research in the RCAAM played a key role in understanding it, starting with the papers [Voglis, Tsoutsis, Efthymiopoulos 2006, MNRAS, 373, 280](#) and [Patsis 2006, MNRAS 369, L56](#). The theory of chaotic spiral arms applies to disc galaxies with strong bars, in which the orbits of the stars in the region of corotation are, in principle, chaotic. An important issue, for the understanding of the development of a spiral structure in such systems is the study of the unstable manifolds emanating from the unstable Lagrangian points of equilibrium at the

ends of the bar. These manifolds represent chaotic orbits, in spiral arrangement, that extend to large distances away from the bar as shown in the figure ([Efthymiopoulos, Harsoula, Contopoulos, 2020, A&A 636, A44](#)). The theory of "chaotic spiral arms" through invariant manifolds can interpret also the material flow "bridges" between the bar and the spirals. Such structures have been modeled in a series of simulations by means of [an N-body code developed in our Center](#), using parallel techniques of adaptive grids. The code studies the manifold theory as well as the secular evolution of galaxies, either isolated or in an interactive environment with accompanying galaxies. Finally, during the last years, the analytical and numerical theory of manifolds has been developed in the case of multiple pattern speeds of the structures ([Efthymiopoulos, Harsoula, Contopoulos, 2020, A&A 636, 44](#)).

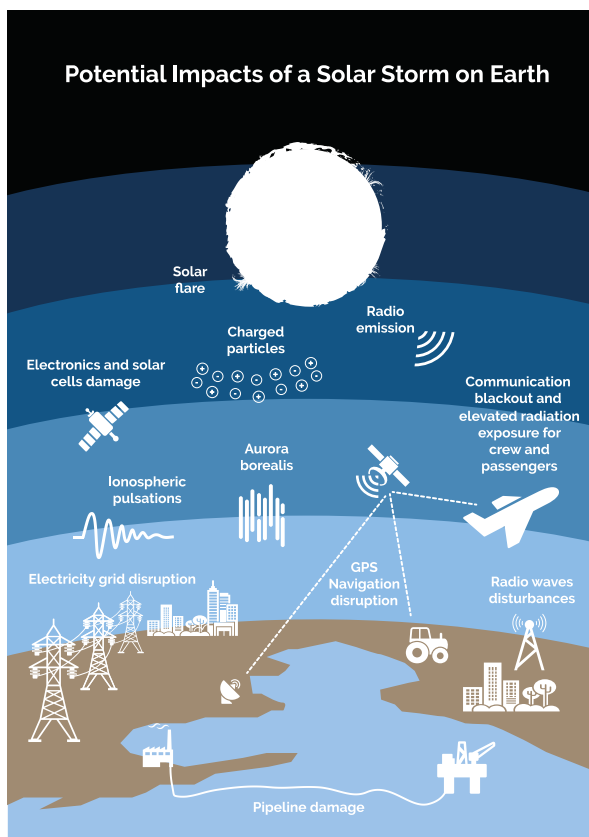
Study of solar jets using observations, MHD theory and numerical simulations:

Jets are seen very often on the solar surface in many sizes and temperatures. An important contribution of the RCAAM, which highlights the constructive combination of observations, MHD theory and simulations, was the study of a jet, observed with the SoHO/SUMER and TRACE space telescopes in 1999. The Observations were very detailed and allowed the measurement of plasma characteristics that were compared with a MHD numerical simulation of a jet. The observations indicated that photospheric magnetic flux was emerging from the photosphere during the jet. The simulation suggested that the magnetic reconnection between the emerging flux and the preexisting coronal field created the jet. In the figure above, the left and middle panels show the jet intensity and dopplergram at coronal temperatures. The blue

structure indicates ejected material at roughly 100km/s. The right panel shows the simulated velocity of the jet and the simulated magnetic lines of force (Gontikakis, Archontis, Tsinganos, 2009, A&A 506, 45).



Forecasting of the solar end of space weather:

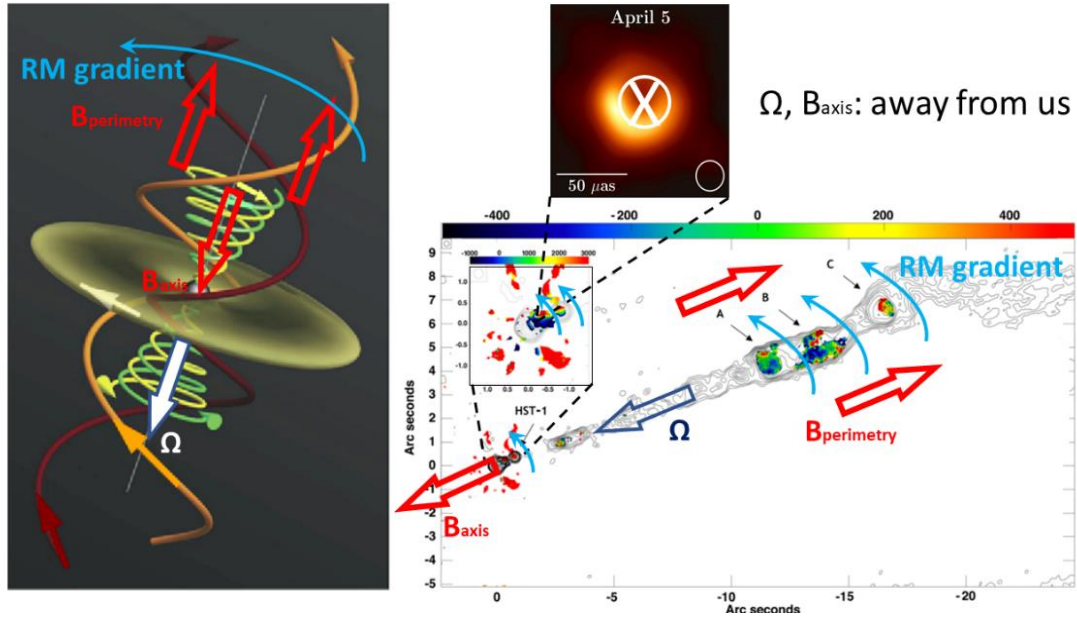


A graphical summary of extreme solar weather and its repercussions in the terrestrial atmosphere and beyond, until Earth's surface. Image courtesy of the Fachhochschule Nordwestschweiz partner of the FLARECAST Consortium, included in the FLARECAST overview paper by Georgoulis et al. (2021).

Forecasting of the solar end of space weather is an inherently interdisciplinary, worldwide endeavor encompassing fundamental solar physics, advanced statistics and performance verification analysis. A Marie Curie Fellowship of the European Commission awarded to RCAAM in 2010, entitled [Solar Magnetic Eruptions: Understanding and Forecasting](#) laid new foundations for both the understanding and forecasting tasks, via a series of about 50 refereed papers starting in 2012 ([Georgoulis, Tziotziou & Raouafi, 2012, ApJ, 759, 1](#), [Tziotziou, Georgoulis & Raouafi, 2012, ApJL, 759, L4](#), [Georgoulis, Titov & Mikic, 2012, ApJ, 761, 61](#), [Georgoulis, 2012, Solar Phys., 276, 161](#)). This groundwork ultimately resulted in attracting ESA's A-EFFort project (a-effort.academyofathens.gr), that resulted in RCAAM being named an ESA/SSA/SWE expert group, the national Thales Hellenic Network for Space Weather Research (HNSWR) and the European Union's FLARECAST (www.flarecast.eu, coordinated by RCAAM) and SWATNET (<http://swatnet.eu>) projects. Collective and collaborative work of a decade at RCAAM have culminated in an invited American Geophysical Union monograph ([Georgoulis, 2018, AGU Geophys. Monogr. Series, 235, 371](#)), an invited review in *Philosophical*

Transactions of the Royal Astronomical Society A ([Georgoulis, Nindos & Zhang, 2019, RSTA, 377, 20180094](#)) and, importantly, a state-of-the-art overview paper for the FLARECAST project in the *Journal of Space Weather and Space Climate* ([Georgoulis et al. \[incl. Gontikakis\] 2021, JSWSC, in revision](#)). An encompassing picture of this paper, summarizing the effect of solar weather in the terrestrial environment, is provided here. A parallel but related collaborative work with key role by RCAAM researchers was recently published in *Nature Scientific Data* ([Angryk et al. \[incl. Georgoulis\], 2020, NatSciData, 7, 227](#)).

Study and advancement of the Cosmic Battery:



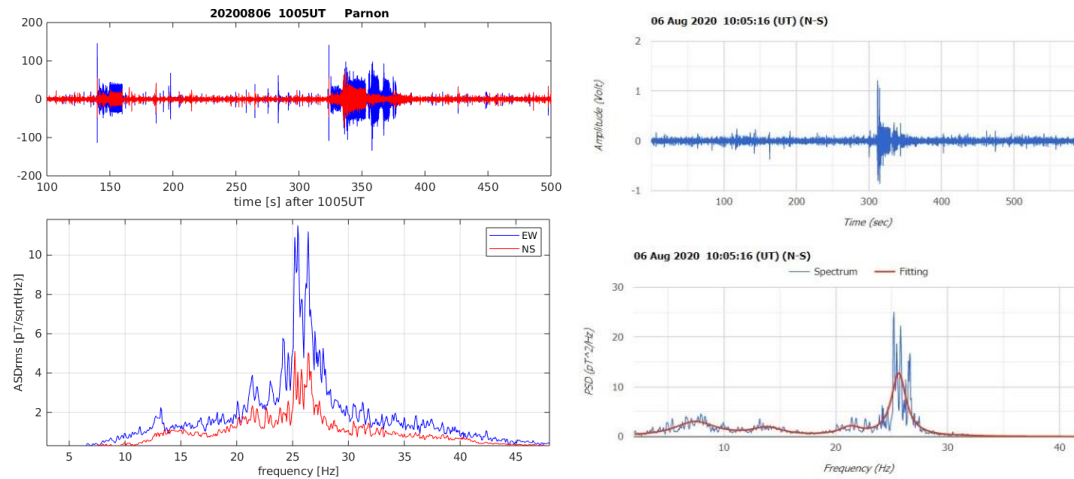
The study and advancement of the Cosmic Battery as the fundamental physical mechanism for the production of astrophysical magnetic fields around black holes, has been elaborated in the framework of the research projects of RCAAM (see volume “[The formation and disruption of black hole jets](#)”, [Contopoulos, Kylafis & Gabuzda 2015, Springer Verlag](#)). Our proposal for a Cosmic Battery is that the magnetic field that accelerates and collimates the large scale astrophysical jets observed around black holes (as is the large scale jet in galaxy M87, or the smaller scale jets from X-ray binaries in our own Galaxy) is produced in situ by the radiation of the surrounding accretion disk. The Cosmic Battery predicts that the magnetic field along the axis of the jet is parallel to the direction of the angular velocity vector Ω of the surrounding disk, whereas the magnetic field that surrounds the jet is directed opposite to Ω . Our theoretical predictions have been confirmed in both the observations of the Faraday RM gradient across the kpc-scale jet ([Christodoulou, Gabuzda, Knuettel, Contopoulos et al. 2016, 591 A61, Astronomy & Astrophysics](#)), and the direction of the axial field in the Event Horizon Telescope image of the central black hole M87* ([Contopoulos et al. 2022, in preparation](#)).

Cosmology at RCAAM

Cosmology has been one of the key research fields of our Center in the last 15 years. Research activities in the fields of Theoretical and Observational Cosmology focus on the study of the Universe as a whole, from its primordial to its late-time era, and in particular on the following topics: 1) Accelerated expansion of the Universe, 2) Dark Energy and Dark Matter, 3) Primordial Universe (Big Bang, Inflation, Reheating, Phase Transitions, Baryogenesis, Nucleosynthesis, etc), 4) Matter Clustering and Large Scale Structure, 5) Test of General Theory of Relativity at cosmological scales, 6) Modified and Extended Theories of Gravity, 7) Black Holes and Gravitational Waves, 8) Cosmological Simulations and 9) Elaboration of

Cosmological Data (from Cosmic Microwave Background Radiation (CMB), Supernovae Type Ia (SNIa), Baryonic Acoustic Oscillations (BAO), Cosmic Chronometers (CC), Growth Index, Large Scale Structure (LSS), etc) in order to check cosmological scenarios and theories. Since 2006, have been published in Cosmology 126 papers in refereed journals, 34 in conference proceedings, while the total number of citations is about 4726. The results have been presented in 45 international conferences in 14 of which RCAAM members have participated in their organization.

Recording, Analysis and filing of Schumann Resonances



Schumann Resonances (hereafter SR), are electromagnetic waves of Extra Low Frequency (ELF) in the range of 2-50 Hz. Their scientific interest emanates from their close connection with various geophysical phenomena like atmospheric electricity, ionospheric disturbances biological effects and seismic activity. Recording of SR is operated in the observational and recording site on the top of mount Parnon (1450 m) in South Greece, Laconia territory. Greece and East Mediterranean are very seismogenic areas where medium size earthquakes occur very often. For this reason, the analysis of preseismic recordings have got the priority of our research. In the figure above a characteristic preseismic SR signal is presented A possible preseismic signal recorded in Parnon is depicted. The event was recorded on the 6th of August 2020 UT 10.05, two days before a 4.2 R earthquake at the area of Kyllini and eleven days before a 5.0 R earthquake at the island of Hydra. The left panel presents the observation made by the Polish system of the University of Cracow hosted in Parnon while the right presents the observation by the Greek system. A common property of all preseismic signals is the accumulation of the spectrum power around the 25Hz frequency. Both earthquakes mentioned above occurred within a distance of 300 km from the observation site. This is a distance within the empirical limits of an area, in which preseismic signals can be recorded.