FORTH
INSTITUTE OF ASTROPHYSICS

Institute of Astrophysics
FORTH
2022 Annual Report

www.ia.forth.gr

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1. Executive Summary

The present document presents the activities of the members of the Institute of Astrophysics (IA) at the Foundation for Research and Technology – Hellas (FORTH), during the 2022 calendar year.

IA was founded on March 2, 2018 and commenced its independent operations in the summer of 2019. The Institute was established in order to facilitate and further enhance the very successful research activities of the Crete Astrophysics Group, which has been operating for nearly 30 years, within the Institute of Electronic Structure and Laser (IESL) of FORTH and the Department of Physics of the University of Crete.

During the past year, members of the IA published **75** papers in refereed journals, that is **4** papers per PhD researcher per year, in the fields of Theoretical and Observational Astrophysics. The research of IA was supported by national and international research grants, as well as private donations and the total funding awarded in 2022 was ~**3,5 MEuros.**

A major highlight of the year was a new strategic collaboration with the Instutute of Computer Science (ICS-FORTH) in the area of Astroinformatics. This was established thanks to a 2.5MEuro ERA Chair, which starting January 2023 will enable Dr. Jean-Luc Starck (CEA-Saclay, France) to build at FORTH a group in this promising reseach field over the next five years. In addition, two new major competitive grants, an ERC Starting grant entitled "SMILE: Search for Milli-lenses to discriminate between dark matter models" and a HORIZON-INFRA-DEV concept design study entitled "ARGOS: Designing a next-generation radio facility for multi-messenger astronomy" will create new opportunities for IA-FORTH.

Regarding Skinakas Observatory, our major reseach infrastructure, the bulding of the new 5.3m dome was completed in May 2022 and the 0.6m robotic telescope became again operational. Moreover, thanks to a generous donation by the Committee "Greece 2021", which was complemented with additional funds from the Univ. of Crete, an order for a new 1.0m robotic telescope was placed.

The affiliated faculty of the Department of Physics at the University of Crete (including one emeritus professor and the Director) also taught undergraduate and graduate courses.

This document was prepared in February 2023, based on contributions from all members.

2. Structure

As of March 6, 2019, Director of the Institute is Prof. Vassilis Charmandaris. Since June 18, 2021, the Deputy Director is Prof. Vasiliki Pavlidou.

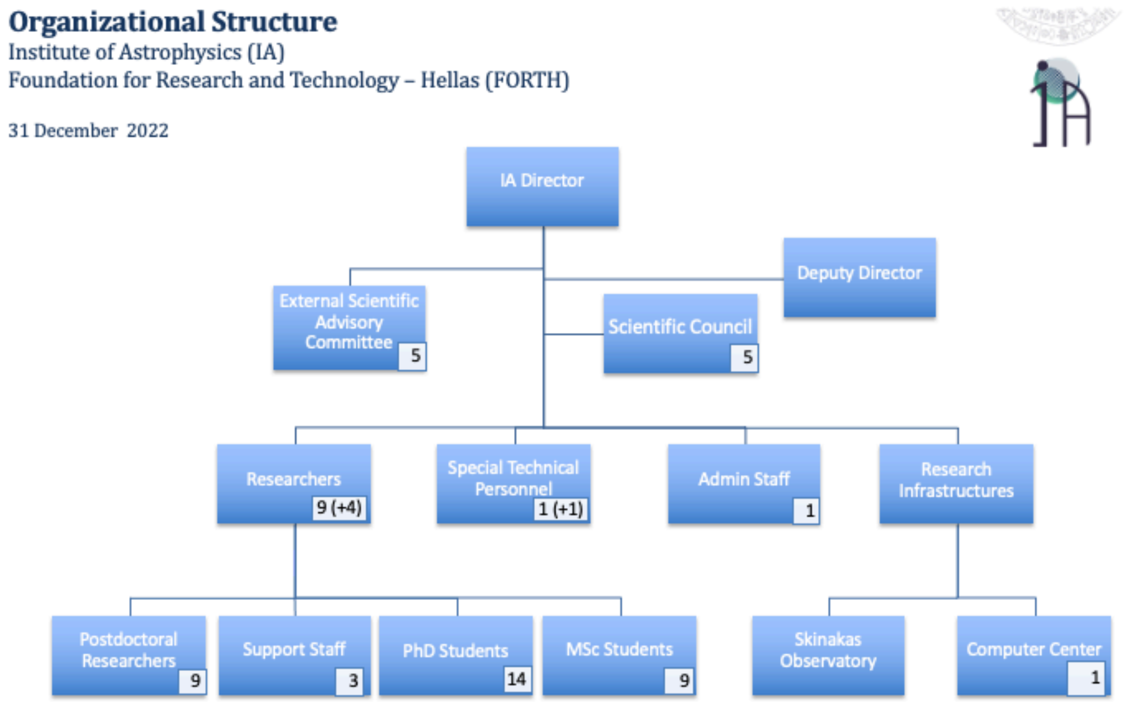
The current Scientific Council of the Institute (SCI) was formed on April 21, 2021 and it consists of:

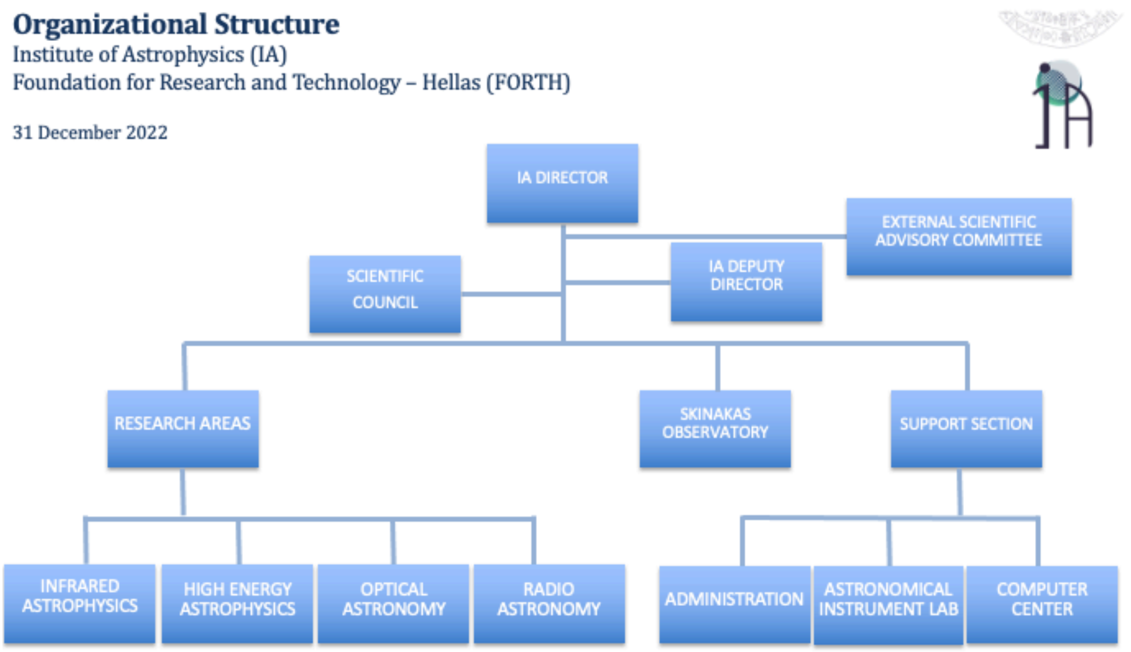
- Ioannis (John) Antoniadis
- Tanio Diaz Santos
- Iossif Papadakis
- Pablo Reig, Chair
- Andreas Zezas

The External Scientific Advisory Committee (ESAC) of IA plays a crucial role in the strategic development of the Institute. Its current members were proposed by the SCI and approved by the Governing Council of FORTH on June 22, 2019:

- Roger Blandford, Professor of Physics, Stanford University (USA)
- Paola Caselli, Director Max-Planck Institute for Extraterrestrial Physics (Germany)
- George Helou, Executive Director IPAC/Caltech (USA)
- Jason Spyromilio, Senior Astronomer, ESO (Germany)
- Michiel van der Klis, Professor of Astrophysics, Amsterdam University (The Netherlands)

The organizational structure of IA-FORTH is presented in the two flowcharts below:





3. Personnel

3.1. Personnel of the Institute of Astrophysics

At the end of the period of this report, December 31, 2022, the core personnel of IA consisted of the Director, 4 permanent researchers, 2 technicians as well as 4 affiliated faculty and one technician from the Department of Physics of the University of Crete. The personnel also include 2 professors emeriti and 9 post-doctoral researchers, as well as 4 support staff. In addition, 14 PhD students, 9 MSc students, and 10 undergraduate students were trained by members of IA. To the above local members, we should add 4 Affiliated Research Fellows and two Honorary Fellows from institutes outside Greece, who often visit IA and interact with the local personnel.

In detail, these individuals were:

Director of the IA:
- Vassilis Charmandaris (Professor)

Four (4) Permanent Researchers
- Ioannis (John) Antoniadis (Associate Researcher / Researcher C)
- Carolina Casadio (Associate Researcher / Researcher C)
- Tanio Diaz Santos (Associate Researcher / Researcher C)
- Pablo Reig (Research Director / Researcher A)

Two (2) Permanent Support Staff:
- Mr. Giannis Kapetanakis – IT/Network support
- Mr. Anastasios Kougentakis - Special Technical Personnel

Seven (7) Affiliated Univ. of Crete Faculty members:
- Vassilis Charmandaris (Professor, Director of IA)
- Nikolaos D. Kylafis (Emeritus Professor)
- Iossif E. Papadakis (Professor)
- Ioannis Papamastorakis (Emeritus Professor)
- Vasiliki Pavlidou (Associate Professor)
- Kostas Tassis (Associate Professor)
- Andreas Zezas (Professor)

Four (4) IA Affiliated Research Fellows:
- Manos Chatzopoulos (Louisiana State Univ., USA) - since Oct. 2021
- Anamparambu Ramaprakash (IUCAA, India) - since Sep. 2019
- Paul Kallas (U. of California Berkeley, USA) - since Sep. 2019
- Dimitra Rigopoulou (Oxford University, UK) - since Oct. 2019

One (1) IA Honorary Fellow:
- Anthony Readhead (California Institute of Technology, USA) - since Jul. 2021

One (1) FORTH (ICS & IA) Honorary Fellow:
- Jean-Luc Starc (CEA-Saclay, France) - since Oct. 2022

Nine (9) postdoctoral researchers in non-tenure track positions:
- Dr. David Aguilera Dena – until Oct. 2022
- Dr. Dmitry Blinov
- Dr. Sebastian Kiehlmann
- Dr. Konstantinos Kouroumpatzakis – until May 2022
- Dr. Ioanna Leonidaki
- Dr. Siddharth Maharana - since Oct. 2022
- Dr. Grigoris Maravelias
- Dr. Eva Ntormousi – until Dec. 2022

- Dr. Georgios Pavlou
- Dr. Vincent Pelgrims
- Dr. Felix Poetzl - since Oct. 2022
- Dr. Maria Sánchez-García - since Oct. 2022

Four (4) Support Staff on soft money:
- Mr. Panagiotis Evangelopoulos – Public Outreach Officer
- Mr. Vangelis Pantoulas - Engineering support
- Mr. Stylianos Roumpakis - Pipeline software support - until Jun. 2022
- Ms. Anna Steiakaki - Engineering support
- Ms. Eleftheria Tsentelierou - Executive Secretary

One (1) Support Staff of the Univ. of Crete for Skinakas Observatory:
- Mr. George Paterakis - (Telescope technical support)

Fourteen (14) PhD students:
- Mr. Diego Alvarez Ortega (with C. Casadio) - since Dec. 2022
- Mr. Savvas Chanlaridis (with I. Antoniadis) - since Jan. 2021
- Mr. Charalampos Daoutis (with A. Zezas) - since Nov. 2022
- Mr. Román Fernández Aranda (with T. Diaz Santos) - since Jan. 2021
- Ms. Anna Konstantinou (with K. Tassis & E. Ntormousi) - since 2021
- Ms. Maria Kopsacheili (with A. Zezas) – until Aug. 2022
- Mr. Georgios Korkidis (with V. Pavlidou) - since Feb. 2020
- Mr. Ioannis Kypriotakis (with K. Tassis) - since 2017
- Mr. Elias Kyritsis (with A. Zezas) - since 2020
- Ms. Cristina Maria Lofaro (with T. Diaz-Santos) – since Nov. 2022
- Mr. Nikolaos Mandarakas (with K. Tassis) - since 2019
- Ms. Katerina Papadaki (with G. Tzagkarakis & K. Tassis) - since Nov. 2021
- Mr. Charalampos Politakis (with A. Zezas) - since 2016
- Mr. Stylianos Romanopoulos (with V. Pavlidou) - since Dec. 2019
- Mr. Raphael Skalidis (with K. Tassis) – until Oct. 2022
- Mr. Alexandros Tsouros (with V. Pavlidou) - since Sep. 2020

Nine (9) MSc students:
- Mr. Charalampos Daoutis (with A. Zezas) - until Nov. 2022
- Mr. Konstantinos Droudakis (with A. Zezas) - until Nov. 2022
- Ms. Katia Gkimisi (with K. Tassis) - until Mar. 2022
- Ms. Anna Kyvernitaki-Synani (with V. Pavlidou) - since Sep. 2022
- Mr. Nikos Loudas (with V. Pavlidou and N. Kylafis) - since Sep. 2022
- Ms. Lydia Makropoulioti (with T. Diaz Santos) - until Mar. 2022
- Mr. Michalis Mastorakis (with I. Antoniadis) - since Sep. 2022
- Mr. Marios Papoutsis (with I. Papadakis) - since Sep. 2022
- Mr. Charalampos Psarakis (with A. Zezas) - since Sep. 2021
- Mr. George Stravogiannis (with I. Antoniadis) - since Sep. 2022
- Mr. Andreas Tersenov (with V. Pavlidou) - since Sep. 2022
- Mr. Nikolaos Triantafyllou (with V. Pavlidou) - since Sep. 2022
- Ms. Theodora Zacharopoulou (with I. Antoniadis) - since Sep. 2022
- Ms. Christiana Vasilaki (with K. Petraki & V. Pavlidou) - until Nov. 2022

Ten (10) Undergraduate students:
- Mr. Nikolas Aspradakis (with I. Antoniadis)
- Mr. Vasileios Binas-Valavanis (with I. Papadakis)
- Ms. Falalaki Myrto (with V. Pavlidou, K. Tassis)
- Mr. George Kalaitzidakis (with C. Casadio)
- Mr. Panagiotis Kotoulas (with A. Zezas)
- Mr. Thomas Koutsikos (with A. Zezas)
- Ms. Maria Papadaki (with I. Antoniadis)
- Ms. Anastasia Tzouvanou (with P. Reig) - graduated Nov. 2022
- Ms. Anna Vervelaki (with I. Antoniadis)
- Mr. Athanasios Zoumis (with K. Tassis)

3.2. Personnel Changes and Notable Events

During 2022, the following personnel changes took place:

Dr. Carolina Casadio, who was a postdoctoral researcher with the group of Prof. Tassis, was awarded an ERC starting grant and obtained a tenure researcher position at IA-FORTH, which commenced in July 2022.

Mr. Giannis Kapetanakis, who was on soft-money for many years, was hired in a permanent position as IT/Network support engineer in December 2022.

Dr. Eva Ntormousi, who was an HFRI postdoctoral fellow obtained a tenure track researcher position at the Scuola Normale Superiore di Pisa (Italy) in December 2022. Moreover, Dr. David Aguilera Dena complete his postdoctoral appointment and moved to a private company in the Munich area (Germany) and Dr. Konstantinos Kouroumpatzakis moved to a postdoctoral position to the Czech Academy of Sciences in Prague (Czech Republic).

Three new postdoctoral researchers joined IA: in October 2022, Dr. Siddharth Maharana joined the group of Prof. Tassis, Dr. Felix Poetzl, joined the group of Dr. Casadio in November 2022, and Dr. Maria Sánchez-García joined the group of Dr. Diaz-Santos in October 2022.

Three new PhD students and eight new MSc also joined the Institute and their details are presented in Section 3.1, while the following 7 graduated:

Two (2) PhD students defended their thesis:

- Raphael Skalidis - thesis title: " Estimating the magnetic field strength in the interstellar medium " - supervisor K. Tassis. In November 2022 Dr. Skalidis moved as a postdoctoral researcher to the California Insitute of Technology, Pasadena, CA (USA)
- Maria Kopsacheili - thesis title "A multi-wavelength study of extragalactic supernova remnants" - supervisor A. Zezas. In August 2022 Dr. Kopsacheili moved as a postdoctoral researcher to the Institute of Space Sciences - CSIC, Barcelona (Spain)

Five (5) MSc students defended their thesis:

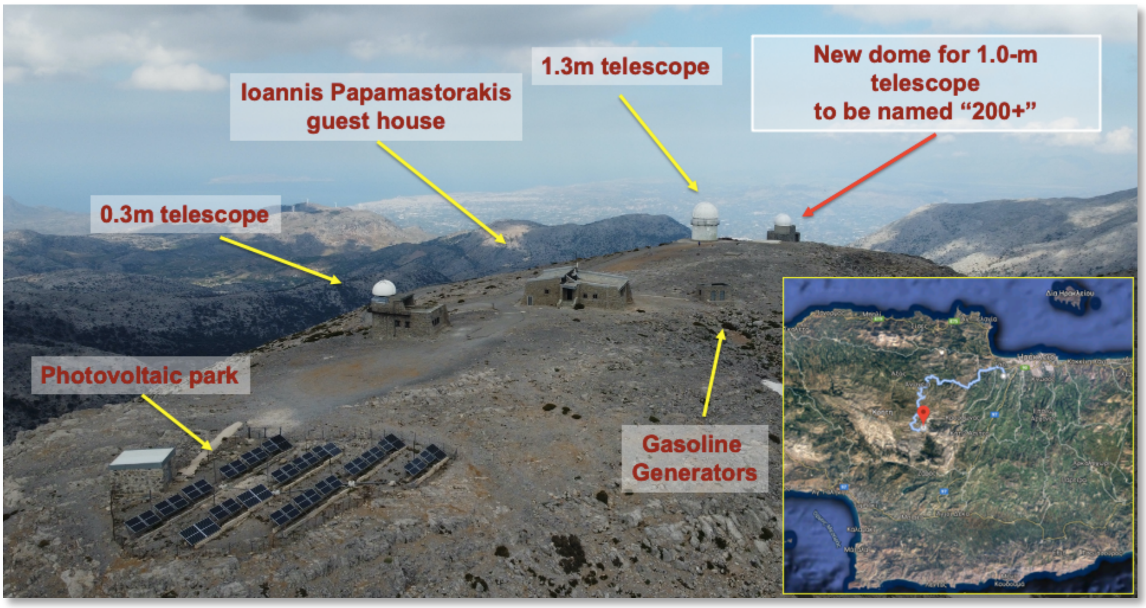
- Charalampos Daoutis - thesis title: "Galaxy activity classification and dominant photo-ionization mechanism characterization using optical spectra and machine learning method" - supervisor A. Zezas.
- Konstantinos Droudakis - thesis title: "Spectral and timing analysis of transient X-ray pulsars" - supervisor A. Zezas.
- Christiana Vasilaki - thesis title: "Dark matter bound state formation and thermal decoupling in the early universe" - supervisors K. Petraki & V. Pavlidou
- Katia Gkimisi - thesis title: "Measurement of the magnetic field in the polaris flare region using data from the RoboPol instrument" - supervisor K. Tassis.
- Lydia Markopoulioti - thesis title: "Studying the Spectra of Luminous Infrared Galaxies (LIRGs)" - supervisor T. Diaz-Santos.

A complete record of all past members of IA, as well as those of the Crete Astrophysics Group of IESL/FORTH & Dept. of Physics, Univ. of Crete, with many relevant information, including their last position, if known, is kept at: https://www.ia.forth.gr/past_members

4. Facilities

4.1. Skinakas Observatory

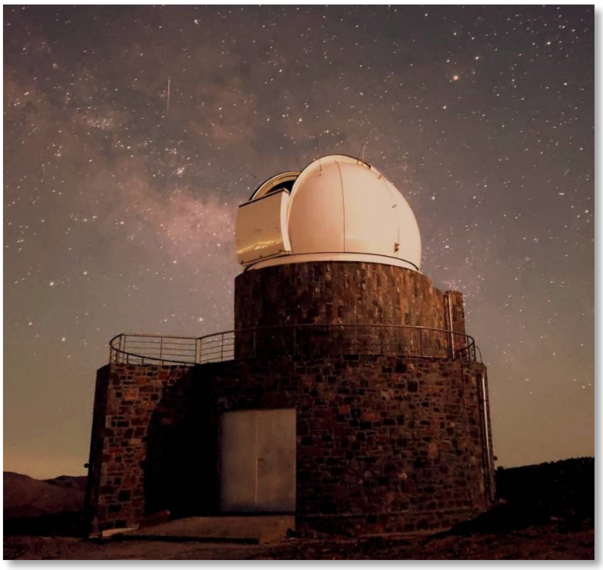
Skinakas Observatory is a common research infrastructure of IA-FORTH and the University of Crete.



An aerial view of Skinakas Observatory.

An MoU, signed between FORTH and the University of Crete in 2018, formally assigns the management of Skinakas Observatory[1] to the Director of IA-FORTH, who also acts as the Director of the Observatory.

The 1.3 m telescope was operating full-time at Skinakas Observatory in 2022. This telescope is a modified Ritchey-Chrétien with 1.3 m aperture (focal ratio of f/7.6), which was built by DFM Engineering and Zeiss and became operational in 1995.



The new 5.3m dome at Skinakas, currently housing the 60cm telescope.

The 60 cm telescope (focal ratio f/8 and f/3) was installed in its new dome, shown to the right, and commenced its nominal operations in June 2022 (see Appendix).

The 30 cm telescope (f/3.2) was also operating, but for a limited time period on select long term projects on galactic SN remnants.

The RoboPol[2] polarimeter, which saw first light in 2013, continued its nominal operations as the main instrument of the 1.3 m telescope.

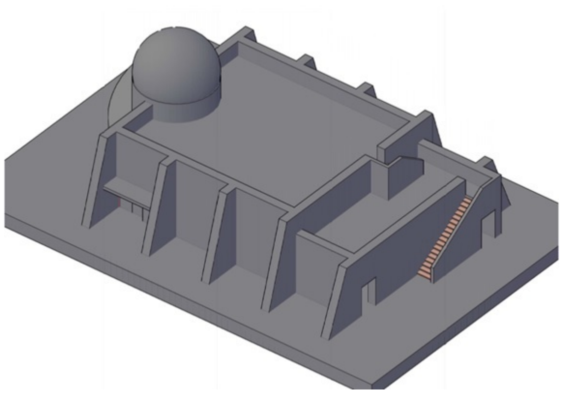
[1] For more information on Skinakas Observatory visit: https://skinakas.physics.uoc.gr/en/
[2] For more information on RoboPol visit: http://robopol.org/

The development of the WALOP polarimeter at IUCAA, funded by the Stavros Niarchos Foundation, was affected by the influence of the COVID-19 pandemic to the industry and experienced delays in construction and delivering of its optics. However, rapid progress is taking place and the commissioning at Skinakas is scheduled for the summer of 2023.

The major infrastructure activity at the Observatory was the completion, in May 2022, of a new building with a 5.3m dome in which the 60cm robotic telescope was placed.

Moreover, progress was made in six major projects, which are expected to transform the operational capabilities of the facility by the end of 2024.

One is related to the construction of a new visitor center, the so called "Astroschool", which includes an 85-seat lecture room, as well as an additional 5.3 m dome. The selection of the contractor for the project, which will cost nearly 1 MEuros, was formally finalized in October 2022. The works will commence in spring of 2023 and the town of Anogeia will have the oversight of the construction, which is expected to be completed in 2024.



3D design of the new "Astroschool" bldg.

The second was the donation of 410,000 Euros by the Committee "Greece 2021" towards the purchase of a new 1.0m robotic telescope. Using additional funds of 325,000 Euros by the Univ. of Crete the order for new telescope was placed to ASA Astrosysteme GmbH in September 2022. The new telescope, which will be placed in the new 5.3m dome, is expected to begin operations in the spring of 2024.

The 1.0m "200+" telescope ordered

The third project is the construction of the "Total-Coverage Ultra-Fast Response to Binary Mergers Observatory (TURBO)". This project, which commenced in mid 2022, is funded by NSF (Award: 2117236) and led by Prof. Patrick Kelly (Univ. of Minnesota, USA). It will develop two state-of-the-art robotic telescope facilities, one at Magdalena Ridge Observatory, New Mexico (USA) and one at Skinakas Observatory. At each site, TURBO will consist of large-format CMOS detectors mounted on sixteen 0.25-meter diameter optical tube assemblies. Within two seconds of a trigger alert,

A prototype of a TURBO telescope at the Univ. of Minnesota campus.

TURBO will start to obtain continuous, multi-band imaging of over ~120 square degrees. The investment at Skinakas Observatory will be nearly $350,000. By searching more quickly than existing facilities, the telescopes of TURBO will identify new, brightening sources, such as Supernovae or sources of Gravitational Waves, on the sky and obtain early data. The project will also monitor nearby galaxies for very young supernovae. Students from the University of Minnesota, New Mexico, and Crete, as well as the citizen scientists will participate.

The fourth was securing 1MEuros towards the connection of Skinakas Observatory with FORTH with an optical fiber via the Hellas Quantum Communication Initiative entitled "Deploying advanced national QCI systems and networks in Greece". The 2.5 year project started in January 2023. Moreover, in December 2022 the Prefecture of Crete confirmed that it will provide the 210,000 Euros necessary in order to connect in 2023 the Skinakas peak with the electric grid of the island.

An artist's conception of ARGOS.

The fifth project is ARGOS, a concept (TRL2) for a leading-edge, low-cost, sustainable "small-D, big-N" radio interferometer, which will directly address multiple fundamental scientific questions, from the nature of dark matter and dark energy to the origin of fast radio bursts. The project, which is funded by the European Commission, is led by Dr. John Antoniadis and is a collaborative effort of IA-FORTH, ICS-FORTH and the Univ. of Piraeus in Greece, CEA Saclay in France and the Max-Planck-Institute for Radio Astronomy in Bonn, Germany. The study will culminate with the installation of a prototype radio telescope consisting of 16 parabolic antennas at the Skinakas Observatory in Crete. The prototype will be used to develop and test the innovative technologies required for ARGOS and will also significantly enhance the research and educational work of the Institute.

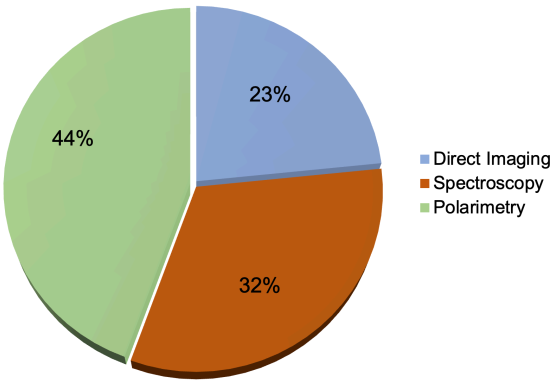
Finally, the sixth major development follows the validation, in May 2021, of Skinakas Observatory by the European Union Space Surveillance and Tracking (EU-SST) Campaign #4, as an optical ground station, which can be used in the future to monitor satellites in orbit around the Earth in projects related to space traffic managment. To that extend an MOU between FORTH and the National Observatory of Athens, which is the national central point for the SST activities of Greece, was signed in 2022. In parallel, ESA selected Skinakas Observatory and has scheduled its upgrade in order to be able to participate in projects related to space to ground optical communication with lasers, which will increase the data transfer by 5 orders of magnitude, as well as enable quantum cryptography. One of the two ESA contracts associated with this activity, which is coordinated by Dr. Pablo Reig, was signed in December 2022.

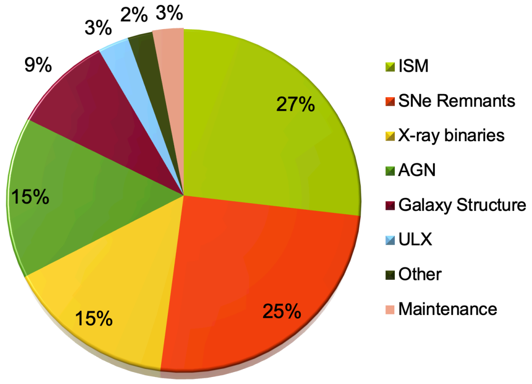
We anticipate that both these new aspects in the usage of the observatory - space traffic management and space telecom with lasers - will provide new opportunities and greatly facilitate both the sustainability of science operations and the future overall growth of the site.

The main science projects during the 2022 observing period were:

- Optical polarization of galaxies
- Target of Opportunity opto-polarimetric follow-up of GRBs and TDEs
- Polarimetry, Photometry, and Spectroscopy of Binaries with a compact star companion
- Narrow-band imaging and spectroscopy of Galactic Supernova Remnants
- ISM magnetic fields
- Follow-up spectroscopy of galaxies detected in the eROSITA survey

The time distribution of the **171** nights that Skinakas was operating during 2022 is presented in the following pie charts.





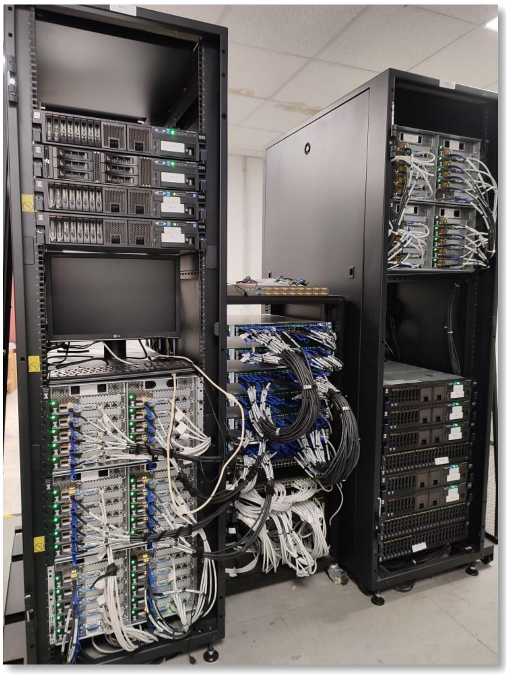
A total of **12 refereed papers** using data from Skinakas Observatory, **including one in Nature and one in Science**, were published in 2022.

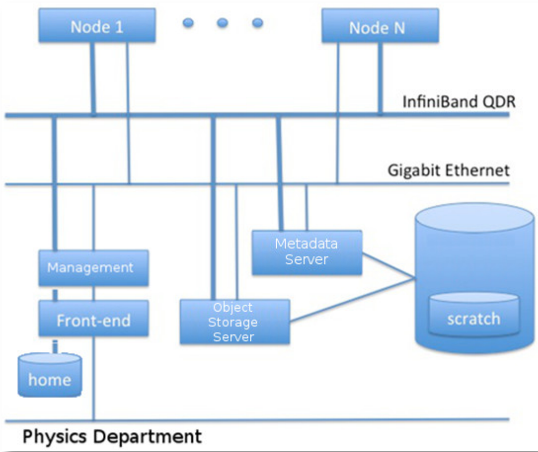
The tradition of open nights resumed in 2022, since the restrictions due to the COVID-19 pandemic were relaxed, and six open night events took place at the Observatory, attracting over 2500 visitors.

More details on Skinakas Observatory, the quality of the site, the telescopes, and the available instrumentation can be found in its recently updated web page at: http://skinakas.physics.uoc.gr/en/

4.2. METROPOLIS HPC CLUSTER

The IA provides the IT/engineering support for the operation of the "Metropolis" HPC cluster of the Dept. of Physics of the Univ. of Crete since 2015. The cluster has a performance of ~25 Tflops and a storage capacity of 30 TB. It consists of 50 nodes, each with a Dual CPU with 10 cores (1000 cores total) and 96 GB RAM (4.7 TB total RAM) connected with Infiniband 4X QDR running Linux OS.





The Metropolis Cluster

The Metropolis Architechure

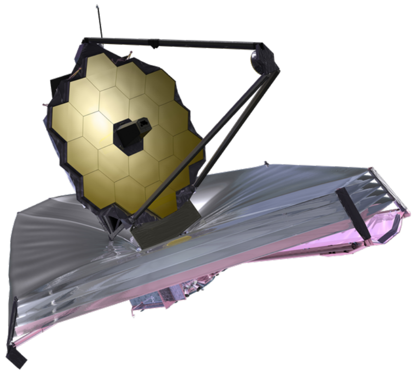
Members of the IA have privileged access to "Metropolis" using it extensively mostly for magnetohydrodynamics and ISM chemistry calculations. More information on the technical specifications is available at:

https://qcn.physics.uoc.gr/content/infrastructure/computing-facilities

5. Science Highlights

5.1 Revealing the hidden nuclei of galaxies with JWST

The James Webb Space Telescope (JWST) is the largest infrared telescope facility ever sent to space, and is poised to provide a tremendous leap forward in our quest to understand how the first galaxies in the Universe formed and assembled over cosmic time. To realize JWST's full science potential and help the science community early on, the Director's office created the Early Release Science (ERS) program.



Artist's model of JWST.

Dr. Tanio Diaz Santos and Prof. Vassilis Charmandaris of IA-FORTH actively participate in this initiative as members of the ERS program "A JWST Study of the Starburst-AGN Connection in Merging LIRGs", led by Dr. Lee Armus (Caltech) and Prof. A. Evans (Univ. of Virginia). The goal of this project is to transform our understanding of galactic evolution, providing a detailed look at the physics of star formation and black hole growth in nearby merging galaxies. Photometric (NIRCam and MIRI/Imager) and spectroscopic (NIRSpec and MIRI/MRS 3D) observations are currently being obtained, to unveil the dynamics and energetics of the interstellar medium on scales of 50-100pc in the nuclei of a few local Luminous Infrared Galaxies (LIRGs) selected from the Great Observatories All-sky LIRG survey (GOALS). Recently, spectacular JWST results on two galaxies of the sample, VV 114 and IIZw 096, have been published as Letters to the Editor of the Astrophysical Journal.

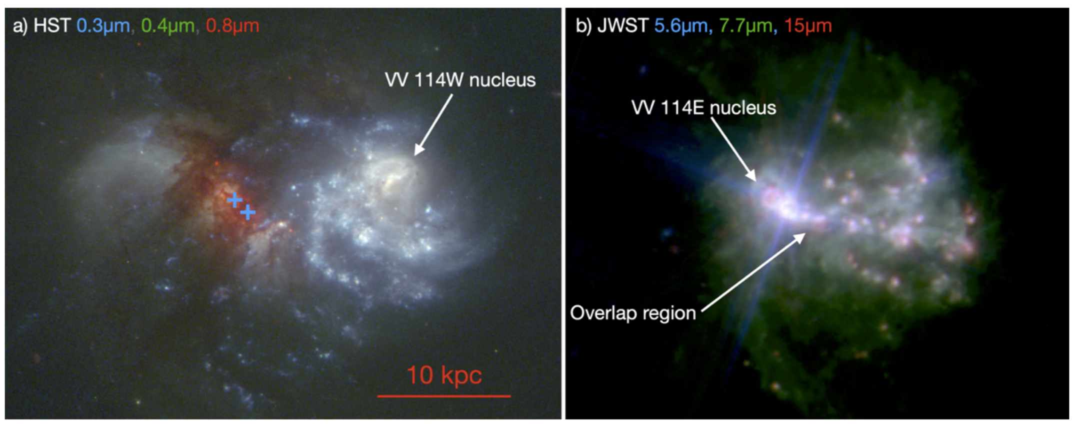


Fig. 1: (left) False-color optical image of VV114 constructed with HST WFC3/UVIS F330W (0.3μm) and the ACS/WFC F435W (0.4μm) and F814W (0.9μm) data. The blue "+" symbols mark the location of the VV 114E NE and SW cores detected with MIRI. (right) False color mid-IR image constructed with F560W, F770W and F1500W MIRI data. The images show the optical star formation (white knots) and dust lanes (red), the reddened nucleus and star-forming regions (pink), and the extended, filamentary 7.7μm PAH emission (green).

VV 114 is an interacting system with a western component (VV 114W) rich in optical star clusters and an eastern component (VV 114E) hosting a luminous mid-IR nucleus hidden at UV and optical wavelengths by dust lanes. Thanks to JWST/MIRI, the VV 114E nucleus is now resolved primarily into bright NE and SW cores separated by 630 pc, or ~ 2000 light years (see Fig 1). Moreover, this nucleus comprises 45% of the 15μm light of VV 114, with the NE and SW cores having IR luminosity surface densities as large as those in the Orion star-forming core, the most active star-forming region in our Galaxy, and the nuclei of Arp 220, the archetype of the infrared-luminous galaxy merger population. The NE core, previously speculated to have an Active Galactic Nucleus (AGN), has starburst-like mid-IR colors. In contrast, the VV 114E SW has AGN-like colors, suggesting that a buried super-massive black hole is lurking at its center. Diffuse emission accounts for 40-60% of the mid-IR emission, and mostly notably, filamentary Polycyclic Aromatic Hydrocarbon (PAH) emission stochastically excited by UV and optical photons accounts for half of the 7.7μm light of VV 114.

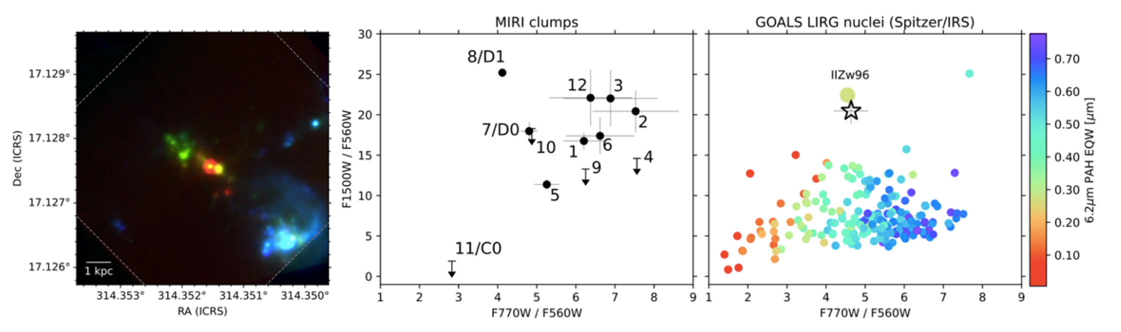


Fig. 2: (left) False color image of the IIZw096 obscured region, made with JWST/MIRI F560W (5.6μm, red), HST/NICMOS F160W (1.6μm, green), and HST/ACS F435W (0.4μm, blue); (center) F1500W/F560W−F770W/F560W color-color diagram for all clumps detected in the MIRI images; (right) The same diagram but showing the colors of local LIRG nuclei derived from synthetic photometry on the Spitzer/IRS low-resolution spectra. The data points are color-coded by the 6.2μm PAH EQW measured from the spectra. The color derived from the totalflux of the MIRI clumps in the left panel is shown as a star.

IIZw 096 is an interacting LIRG system in which previous observations with the Spitzer Space Telescope suggested that the vast majority of the total IR luminosity of the system originated from a small region outside of the two merging nuclei. The new JWST/MIRI observations (Fig. 2) now allow for an accurate measurement of the location and luminosity density of the source that is responsible for the bulk of the IR emission. The study estimates that 40-70% of the infrared luminosity of the galaxy, which shines with the power of around 500 billion Suns, arises from a source no larger than 570 light-years in radius, suggesting a luminosity density close to the maximum limit allowed by the predictions of some theoretical models. In addition, the study detects 11 other star forming sources, five of which were previously unknown and undetected by the Hubble Space Telescope (HST). The MIRI mid-IR colors of most of these sources (see Fig. 2), including the source responsible for the bulk of the far-IR emission, are much redder than the nuclei of local LIRGs, suggesting they are extremely obscured by dust.

More results JWST of the GOALS galaxies are available here.

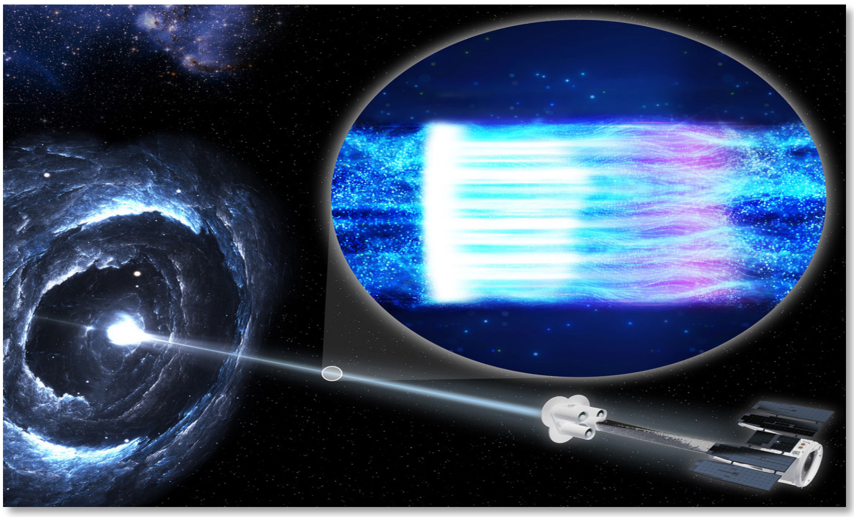
Articles:

- "GOALS-JWST: Hidden Star Formation and Extended PAH Emission in the Luminous Infrared Galaxy VV 114", A.S. Evans, et al. (including V. Charmandaris & T. Diaz Santos), 2022, ApJ Letters, 940, 8
- "GOALS-JWST: Unveiling the Heavily Dust Obscured Compact Sources in the Merging Galaxy IIZw096", H. Inami, et al. (including V. Charmandaris & T. Diaz Santos), 2022, ApJ Letters, 940, 6

5.2 BLACK HOLE JET REVEALS ITS SECRETS!

Blazars are some of the brightest objects in the sky. They consist of a supermassive black hole feeding off material swirling around it in a disk, which can create two powerful jets perpendicular to the disk on each side. A blazar is especially bright because one of its powerful jets of high-speed particles points straight at Earth. For decades, scientists have wondered: "How do particles in these jets get accelerated to such high energies?"

NASA's Imaging X-Ray Polarimetry Explorer, or IXPE, has helped astronomers get closer to an answer. A new study in the journal Nature, authored by a large international collaboration, including a very significant contribution from current and past members of the Institute of Astrophysics -FORTH and the University of Crete, as well as data from the Skinakas Observatory, finds that the best explanation for the particle acceleration is a shock wave within the jet.



This illustration shows the IXPE spacecraft, at right, observing blazar Markarian 501, at left. A blazar is a black hole surrounded by a disk of gas and dust with a bright jet of high-energy particles pointed toward Earth. The inset illustration shows high-energy particles in the jet (blue). When the particles hit the shock wave, depicted as a white bar, the particles become energized and emit X-rays as they accelerate. Moving away from the shock, they emit lower-energy light: first visible, then infrared, and radio waves. Farther from the shock, the magnetic field lines are more chaotic, causing more turbulence in the particle stream

"This is a 40-year-old mystery that we've solved," said Yannis Liodakis, lead author of the study and astronomer at FINCA, the Finnish Centre for Astronomy with ESO. "We finally had all of the pieces of the puzzle, and the picture they made was clear." Liodakis, a native of Crete, graduated with a PhD from the University of Crete in 2017, and he has received both national and international awards for his work at the Skinakas Observatory and abroad, including the Young Researcher Award by the University of Crete, The Hellenic Astronomical Society Best PhD thesis award, a Gruber fellowship from the International Astronomical Union, and, most recently, the Best Young Cretan Researcher Award by the Region of Crete for his involvement with IXPE.

Launched Dec. 9, 2021, the Earth-orbiting IXPE satellite, a collaboration between NASA and the Italian Space Agency, provides a special kind of data that has never been accessible from space before. This new data includes the measurement of X-ray light's polarization, meaning IXPE detects the average direction and intensity of the electric field of light waves that make up X-rays. Information about the electric field orientation in X-ray light, and the extent of polarization, is not accessible to telescopes on Earth because the atmosphere absorbs X-rays from space.

The new study used IXPE to point at Markarian 501, a blazar in the constellation Hercules. This active black hole system sits at the center of a large elliptical galaxy. IXPE watched Markarian 501 for three days in early March of 2022, and then again two weeks later. During these observations, astronomers used other telescopes in space and on the ground to gather information about the blazar in a wide range of wavelengths of light including radio, optical, and X-ray. While other studies have looked at the polarization of lower-energy light from blazars in the past, this was the first time scientists could get this perspective on a blazar's X-rays, which are emitted closer to the source of particle acceleration.

"This exciting project was expertly coordinated by Yannis Liodakis, who kept us observers at the various facilities around the world up-to-date to manage near real-time follow-up of the Xray data collection. From the Caltech side, the WIRC+pol polarimeter at Palomar provided NIR data on the source" said co-author Gina Panopoulou, who was a postdoctoral fellow at Caltech at the time of the observations, and is now a Professor at Chalmers University in Sweden. Panopoulou is and another celebrated University of Crete and Skinakas Observatory PhD graduate – with awards including the Young Researcher Award of the University of Crete, the International Astronomical Union Best Thesis Award, and a Hubble Fellowship from NASA. Scientists found that X-ray light is more polarized than optical, which is more polarized than radio. But the direction of the polarized light was the same for all the wavelengths of light observed and was also aligned with the jet's direction.

The radio observations of Mrk 501 were led by Carolina Casadio, Staff Researcher at the Institute of Astrophysics – FORTH, and holder of a prestigious ERC starting grant. "It took a lot of effort to coordinate these many telescopes across Earth and Space, but the results were really rewarding! At radio frequencies, data were taken from the POLAMI project, the only systematic project for 3 & 1mm full-Stokes polarimetry of blazars" Casadio said. Archival optopolarimetric data from the RoboPol instrument, operating since 2013 at the Skinakas Observatory, was used to understand how the current polarization of Mrk 501 relates to its historical behavior.

After comparing their information with theoretical models, the international team of astronomers realized that the data most closely matched a scenario in which a shock wave accelerates the jet particles. A shock wave is generated when something moves faster than the speed of sound of the surrounding material, such as when a supersonic jet flies by in our Earth's atmosphere. As particles travel outward, they emit X-rays first because they are extremely energetic. Moving farther outward, through the turbulent region farther from the location of the shock, they start to lose energy, which causes them to emit less-energetic light like optical and then radio waves. This is analogous to how the flow of water becomes more turbulent after it encounters a waterfall – but here, magnetic fields create this turbulence.

Scientists will continue observing the Markarian 501 blazar to see if the polarization changes over time. IXPE will also investigate a broader collection of blazars during its two-year prime mission, exploring more longstanding mysteries about the universe.

Article: "Polarized Blazar X-rays imply particle acceleration in shocks", Liodakis, Y., et al. (including Casadio, C.) Nature, 23 Nov. 2022

5.3 PULSATION VS ROTATION IN BE/X-RAY BINARIES

We think of stars as stable systems and indeed they take millions of years to evolve significantly. However, stable does not mean static. Many stars, from all masses and sizes display pulsations on timescales between minutes and years, as for instance the Be stars. The most obvious pulsation mode is the radial one, where the star becomes bigger and smaller periodically, and like any expanding/compressing gas also gets cooler and hotter.

Many early-type stars are known to be pulsating in modes other than radial. The non-radial pulsations divide the stellar surface in regions with different velocity fields, which, in the presence of rotation, redistribute the flux over the absorption line profile to create moving patterns of peaks and troughs. Likewise, the non-radial pulsations divide the stellar surface in regions with different temperatures. If the amplitude of the pulsations is large enough, the temperature variations across the surface of the star can be detected photometrically as differences in brightness.

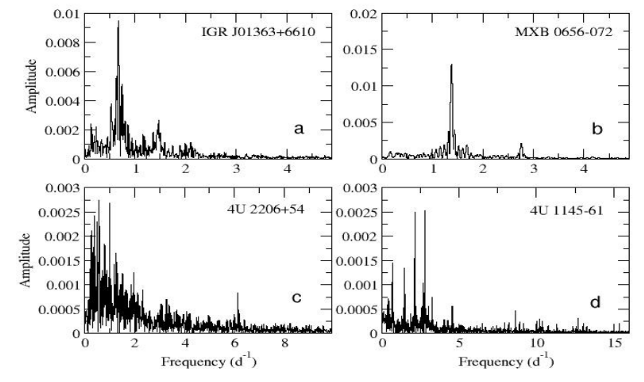


Fig. 1: Representative examples of the different types of periodograms in BeXBs

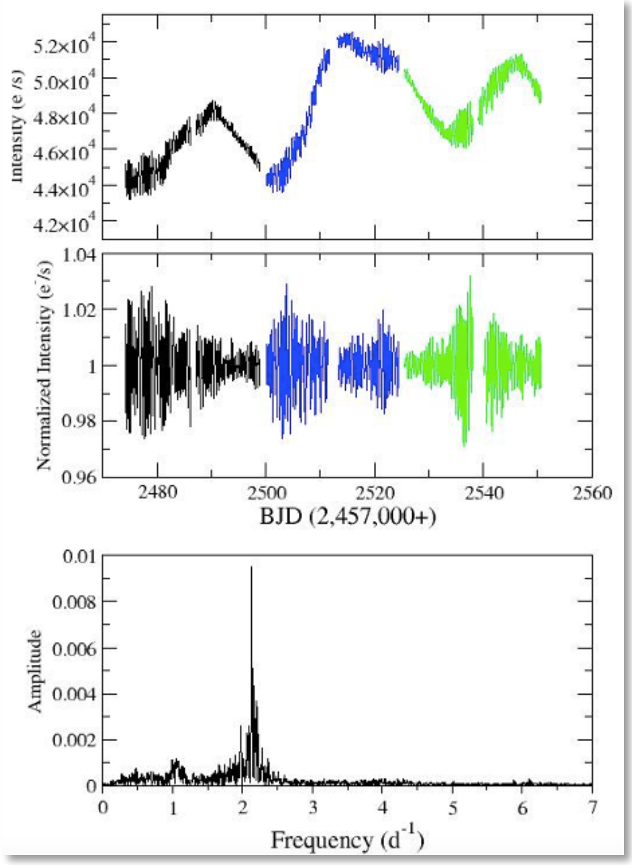


Fig. 2: Raw TESS light curve of 1A 0535+26 and its periodogram

The Be phenomenon refers to the presence of a circumstellar disk around the equator of OB-type stars. This disks forms, grows and dissipates on time scales of years. The source of matter that feeds the disk is the photosphere of the Be star. The ultimate mechanism that expels matter with enough angular momentum is unknown. The most favoured model combines the fast rotational velocity of the Be stars with non-radial pulsations. When two or more pulsation modes are in phase, the resulting amplitude of the oscillations can grow significantly and trigger the ejection of matter.

BeXB occupy a very narrow range in spectral type O9-B2 and by definition they are III-V stars. In the HR diagram they occupy the upper left part. In this part there a number of pulsator systems. The Be in a BeXB have the same mass, luminosity, temperature ranges as the group known as B Cepheids. So, we expect the Be in BeXB to pulsate. Is that the case?

Dr. Pablo Reig, Research Director at the Institute of Astrophysics, and his collaborator have analysed space-based data from the TESS mission and ground-based photometry from the Skinakas observatory to investigate the pulsational properties of the optical counterparts to Be/X-ray binaries. Figure 1 shows some representative examples of periodograms in BeXBs. Figure 2 (top panel) shows a characteristic TESS light curve of the BeXB 1A0535+26, the same light curve normalised where the amplitude of the pulsation can be observed clearly, and the peridogram displaying a group of frequencies.

Their study reveals that short-term optical photometric variability is a very common, if not ubiquitous, feature intrinsic to the Be optical companions in Be/X-ray binaries. The fact that all sources display multi-frequency oscillations and that some of the detected frequencies of the modulations are higher than the maximum allowed for rotation favors the interpretation that non-radial pulsations is the main driver of the fast time optical variability in BeXBs.

Article: "Fast time optical variability in Be/X-ray binaries. Pulsation and rotation" Reig, P. & Fabregat J., 2022, A&A, 667, 18

5.4 A NEW PATHWAY TO SNE-IA EXPLOSIONS

It is known that low-mass stars end their lives as white dwarfs, while high-mass stars become neutron stars or black holes. But what bridges the divide?

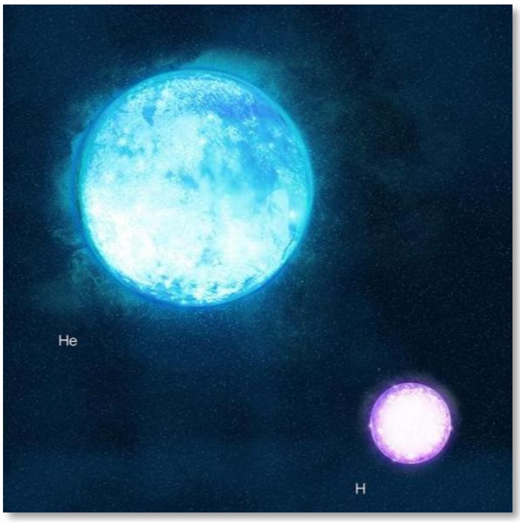


Fig. 1: An artist's conception of a binary progenitor system of the supernova iPTF13bvn. Larger diameter but smaller mass (4 times mass of the Sun) helium star shown on the left is to explode. The companion star shown on the right is a hydrogen-rich star and 30 times mass of the Sun. Source: Kavli Foundation.

The evolution of so-called "intermediate-mass" stars – with masses between 8 and 12 solar masses – is extremely complex and puzzling. As they approach their final evolutionary stages, such stars develop dense oxygen-neon (ONe) cores and emit most of their radiation in neutrinos. At the same time, their outer layers expand and evaporate via powerful stellar winds owing to weak surface gravity.

It is the competition between the loss of pressure due to electron captures, and the release of thermonuclear energy, that determines the final outcome: if electrons are absorbed fast enough, the core collapses in what is known as an "electron-capture supernova", and a low-mass neutron star is formed. If energy release prevails then the star can be partly, or even completely, destroyed in a thermonuclear explosion.

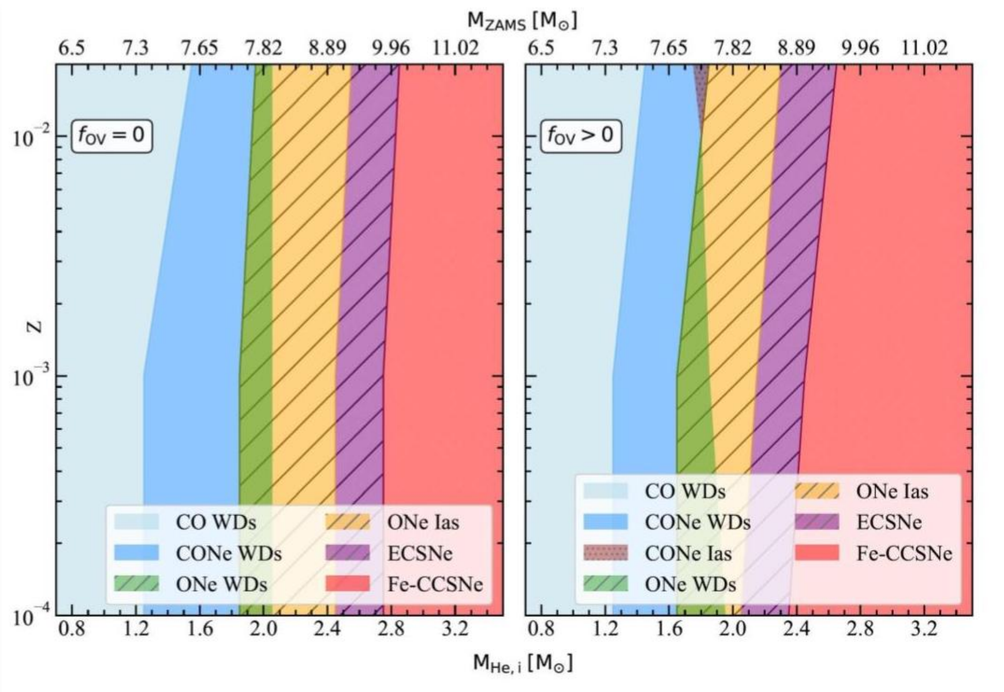


Fig. 2: Mass boundaries for final fates of stripped stars as a function of initial mass and metallicity.

Once their degenerate cores reach a critical density, atomic nuclei begin to absorb the surrounding electrons reducing the pressure that stabilises the star against gravity. At the same time, this exothermic process releases nuclear energy that can trigger a so-called "thermonuclear" explosion.

In a recent study, Savvas Chanlaridis, a PhD candidate at the Department of Physics and the Institute of Astrophysics - FORTH, and his supervisor Dr. John Antoniadis suggested a new mechanism for "Type-Ia" thermonuclear supernovae (SNe-Ia). They have found that when intermediate-mass stars lose their hydrogen envelopes, for example due to interactions with a binary companion, their evolution accelerates significantly. As a result, a thermonuclear explosion is triggered when the stellar core is still not dense enough to allow for electron captures.

The result is a hydrogen- and helium-free thermonuclear explosion that destroys the entire star making these systems atypical progenitor candidates of SNe-Ia. This novel explosion channel, which the research group members call (C)ONe SNe-Ia, is a benchmark that may help explain some peculiar "Type-Ia" supernovae discovered in numerous recent photometric surveys. Additionally, these results carry broader implications for the formation of neutron stars in binary systems affecting the observed pulsar populations.

Articles:

- "Type Ia supernovae from non-accreting progenitors", J. Antoniadis, S. Chanlaridis, G. Gräfener, and N. Langer, 2020, A&A, 635, 72A
- "Thermonuclear and electron-capture supernovae from stripped-envelope stars", S. Chanlaridis, J. Antoniadis et al., 2022, A&A, 668, 106C

5.5 Understanding Supernova Remnants as populations

Supernova remnants are the final act in the life of a massive star which ends with a violent explosion. They consist of the material released during the stellar explosion, which is traveling with supersonic speeds in the interstellar space. Supernova remnants play a major role in the galactic ecosystem by transferring the heavy elements that are formed in the cores of their progenitor stars into the interstellar space. In addition, their shock waves interact with the surrounding interstellar material and they heat it. Therefore, the study of the populations of supernova remnants in our Galaxy, and in other nearby galaxies gives us crucial information on the effect of dying stars in the interstellar medium. A tool that is used to describe the populations of supernova remnants is the distribution of their luminosity in different spectral lines or bands of the electromagnetic spectrum. Owing to sensitive instruments and large-scale surveys such data are becoming available for increasingly more galaxies.

Fig. 1: The supernova remnant IC435 which has an age of ~25-30x10^3 years. The image has been obtained at Skinakas observatory.

However, what is missing is a theoretical framework that would allow us to calculate these distributions for different assumptions of the evolution of supernova remnants and interstellar medium parameters.

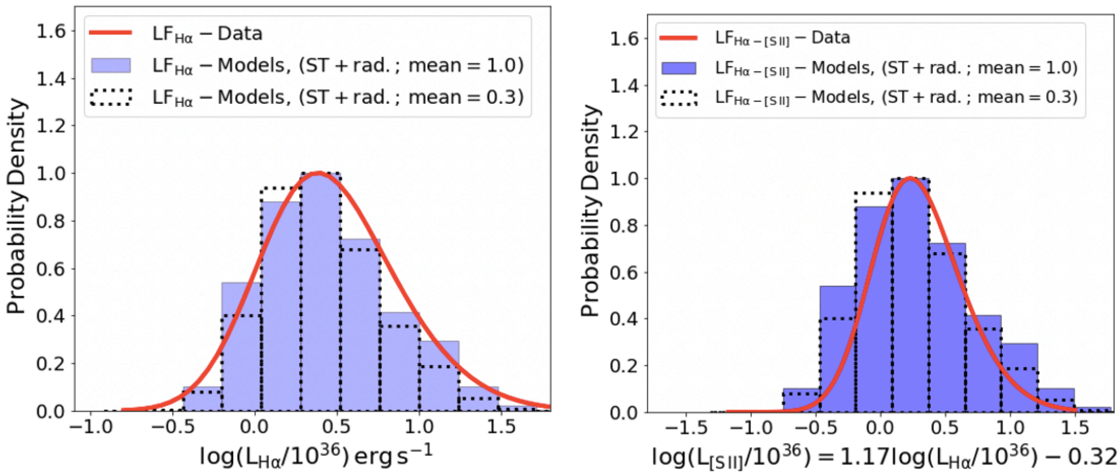


Fig. 2: Comparison of the Hα (left) and the joint Hα-[SII]λλ6716,6735 A (right) luminosity functions of SNRs based on the theoretical models (blue histogram) with the measured luminosity function of SNRs observed in nearby galaxies (red line, Kopsacheili et al. 2021). The two histograms correspond to models calculated for insterstellar medium with mean density of 10 cm-3 and 2 cm-3 respectively.

A work published in the Monthly Notices of the Royal Astronomical Society, led by Dr. Maria Kopsacheili, member of the Institute of Astrophysics, presented the first such model. Other authors of this work are Dr. Ioanna Leonidaki, postdoctoral fellow at the Institute, and Prof. Andreas Zezas, affiliated faculty member. This work presents a framework for calculating theoretical luminosity distributions of the Hα emission of supernova remnants, but also joint distributions of the Hα and the [SII]λλ6716,6735 A lines.

The modeled distributions show remarkable agreement with those observed in nearby galaxies. This methodology provides a powerful tool for modeling the populations of supernova remnants, understanding their complex evolution in the context of their surrounding material, and calculating the total kinetic energy that is injected into the interstellar medium, a key element for models of galaxy evolution.

Articles:

- "Optical emission-line luminosity function models for populations of supernova remnants", Kopsacheili M., Zezas A., & Leonidaki I., 2022, MNRAS, 514, 3260
- "The supernova remnant populations of the galaxies NGC 45, NGC 55, NGC 1313, NGC 7793: luminosity and excitation functions", Kopsacheili M., Zezas A., & Leonidaki I., 2021, MNRAS, 507, 6020

5.6 The accretion disc size "problem" in Active Galaxies

Active Galactic Nuclei (AGN) are the most powerful, persistent objects in the Universe. They emit enormous amount of light (equivalent to the light emitted by all the stars in the galaxy) from regions which are not much larger than our Solar system.

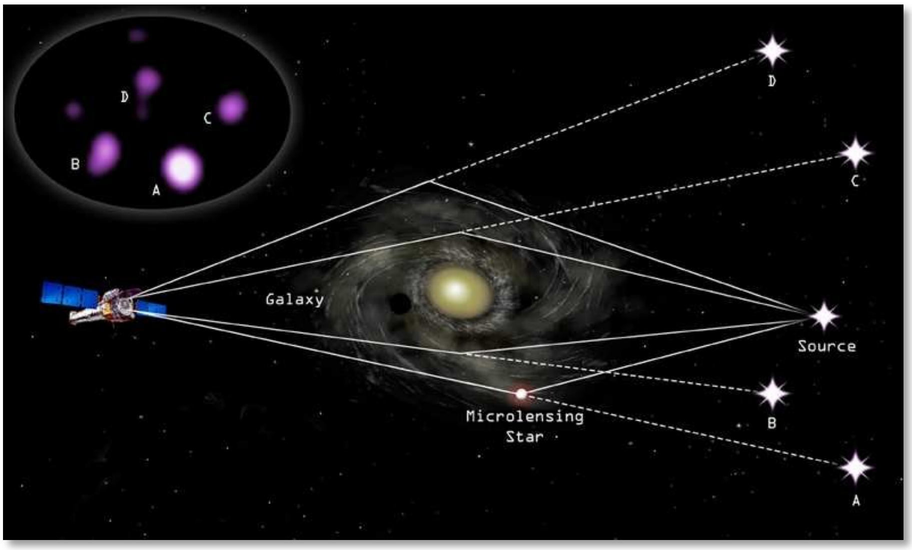


Fig. 1: Representation of quasar gravitational lensing from a massive, foreground galaxy. Lensing is this case creates four individual images of the same object (as shown in the upper, left panel). (Credit: X-ray: NASA/CXC/Penn State/G.Chartas et al; Illustration: NASA/CXC/M.Weiss).

We currently believe that all galaxies host supermassive black holes at their center. Their mass is up to billion times larger than the mass of our own Sun. In approximately 10 per cent of the nearby galaxies, gas is accreted to the central black hole. Through this process, gravitational power is released and heats the gas, which then emits the vast amount of light that we observe at almost all wavelengths from these objects. The gas forms a disc, which is very small in size and cannot be resolved by any telescope on Earth. We are therefore forced to test our theories of AGN via other means. One of the most imaginative, and powerful, way to study the size of the accretion discs in these objects is through variability observations of gravitationally lensed quasars.

Being so luminous, AGN can be detected at very large distances from Earth (in fact, the most distant objects detected by the most powerful telescopes are all AGN, or quasars, as we often call the most luminous of them). In some cases, the distant quasar's light can be altered by a massive foreground galaxy along the light path. The foreground galaxy's powerful gravity can warp and magnify the quasar's light, producing multiple quasar images. It is possible that light from the individual lensed images of the background quasar can be re-magnified by a star in the foreground galaxy, as it moves over the quasar's accretion disc. As a result, study of the "microlensing" variations in these systems can be used to (literally) measure the size of the accretion disc in these distant quasars.

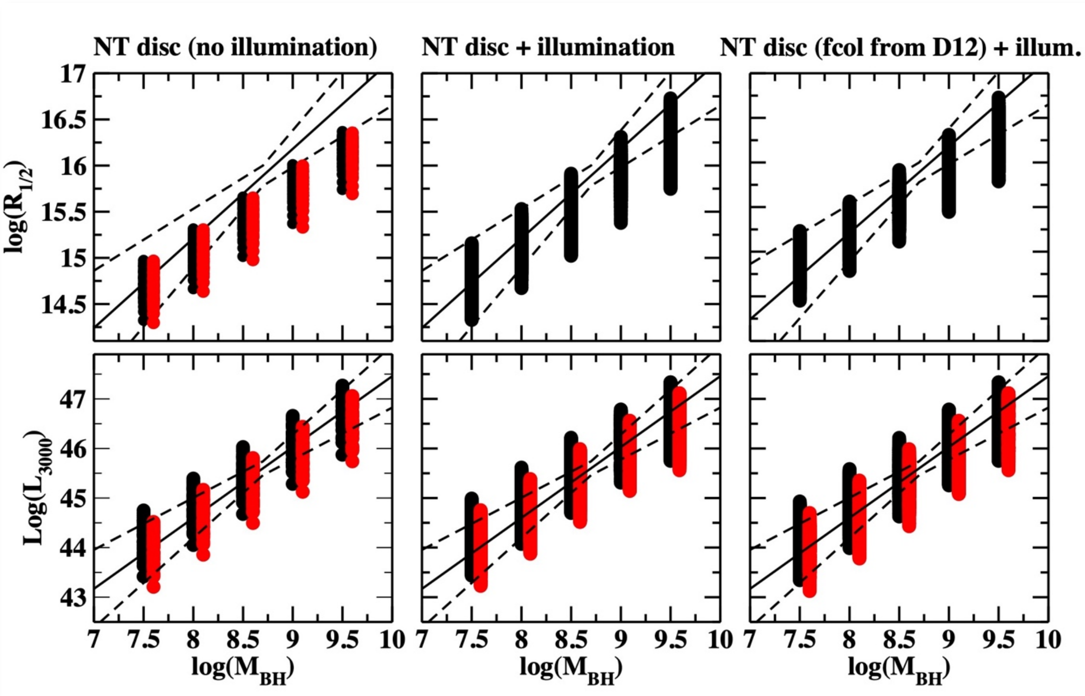


Fig. 2: Plot of the model accretion disc size and luminosity (top and bottom panels, respectively) versus the black hole mass (black and red points), in the case of a standard disc (right panels) and discs which are illuminated by X-rays (middle and right panels). The solid and dashed lines show the best-fit to the observed data, and its 1-sigma uncertainty, respectively. The middle and right panels how that the model predictions are in excellent agreement with the observations when X-rays illuminate the disc.

However, microlensing variability studies over the last 10 years have shown that the accretion disc in quasars appeared to be significantly larger than the theoretical predictions. This discrepancy is one of the most serious problems regarding our understanding of the power mechanism in AGN.

Recently, Prof. Iossif Papadakis and his collaborators studied the theoretical disc size in the case when the accretion disc is illuminated by an X-ray source using a theoretical model that they developed the last few years. They considered general relativistic effects, correct treatment of the X-ray absorption/reflection from the accretion disc, and various inclinations, and they computed the model accretion disc size in thousand systems. They found that the disc size can be up to ~ 3.5 times greater than the radius of a standard disc, even for a non-spinning black hole, based on a wide range of model parameters – as long as a significant part (at east 40-50 per cent) of the total accretion power is transferred to the corona and the height of the X-ray source above the black hole is greater than ~ 20 Schwarzschild radii.

The idea of the X-ray disc illumination was proposed many years ago to explain various features that are commonly observed in the X-ray spectra of AGN. Recently, Prof. Papadakis and his collaborators, showed that X-ray illumination of the accretion disc can also explain the observed UV/optical time-lags in AGN. The fact that the same model can also account for the quasar micro-lensing disc size "problem" strongly supports the hypothesis of the disc X-ray illumination in AGN.

Article: "X-ray illuminated accretion discs and quasar microlensing disc sizes", Papadakis, I. E., Dovčiak, M. & Kammoun, E. S., 2022, A&A , 666, 11

5.7 The first glimpse of galaxies in the eROSITA Final Equatorial-Depth Survey

The X-ray emission of galaxies is a powerful tool for studying the populations of stellar remnants such as neutron stars and black holes. This is because many of these remnants are members of binary stellar systems in which they may accrete material from a companion star, resulting in the emission of X-ray radiation. The connection between X-ray binary systems, populations of stellar remnants, and the stellar populations in their host galaxy has been the subject of systematic theoretical and observational studies using the Chandra and XMM-Newton X-ray observatories. These studies showed that there is a strong correlation between the integrated X-ray emission from X-ray binaries in galaxies, and the star-formation rate and stellar mass of the galaxies. Furthermore, there is strong evidence that low-metallicity galaxies tend to have higher X-ray luminosities.

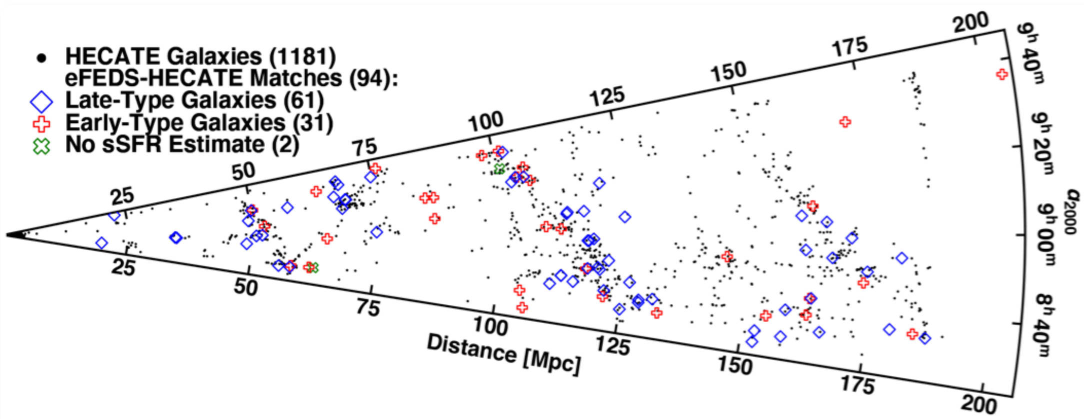


Fig. 1: The distribution of normal galaxies in the eFEDs field as a function of their distance (black points). Blue diamonds show star-forming galaxies with X-ray emission in the eFEDs survey, while red crosses show galaxies with X-ray emission and low-intensity or absent star-formation. (Figure adopted from Vulic et al. 2022).

The eROSITA instrument on board the “Spectrum-Roentgen-Gamma” mission performs the most sensitive all-sky survey in the X-ray band. A pathfinder survey of a small (140 deg^2) part of the sky reaching the full depth of the final all-sky survey (which is expected to be completed in 4 years) gives us a first glimpse of the potential of this rich dataset for studies of the X-ray emission from galaxies. This is the eROSITA Final Equatorial-depth Survey (eFEDS).

Two members of the Institute of Astrophysics (Elias Kyritsis, PhD student, and Andreas Zezas, affiliated faculty) participate in the eROSITA nearby galaxies group led by Dr. Frank Haberl at the Max-Planck Institute for Extraterrestrial

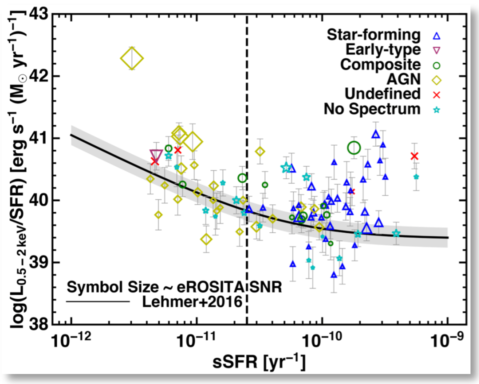


Fig. 2 Left: The relation between X-ray luminosity and star-forming activity as a function of the specific star-formation rate of the eFEDS galaxies. Blue points indicate confirmed star-forming galaxies. Several of these galaxies lie well above the scaling relation for normal galaxies (Lehmer et al. 2016, ApJ, 825, 7) shown by the black solid line and the shaded area.

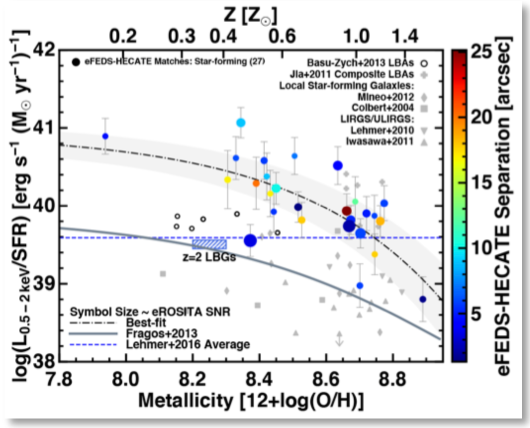


Fig. 2 Right: The relation between X-ray luminosity and star-formation rate as a function of the gas-phase galaxy metallicity. The coloured points indicate the star-forming galaxies detected in the eFEDs survey (the colour indicates the offset of the X-ray source from the center of the galaxy it is associated with). The gray points indicate galaxies detected in other surveys. The blue dashed line and the black solid line indicate the scaling relation from observations of local galaxies, and a theoretical relation from X-ray binary populations synthesis models respectively. The black dashed line shows the best-fit relation based on the galaxies detected the eFEDS field. The eROSITA observations reveal a population of galaxies with systematically higher X-ray output in comparison to results from previous studies, even when accounting for the effect of metallicity.

Physics. A recently published study by this group (Vulic et al. 2022, Astronomy & Astrophysics, 661, A16) presented the first detailed study of the star-forming galaxies in this survey.

This work explored the X-ray emission of the galaxies in the Heraklion Extagalactic Catalogue (HECATE), that are covered by the eFEDs survey. This is a catalogue of all known galaxies within 200 Mpc and it contains extensive information regarding distance, star-forming activity, metallicity, presence of AGN. It is developed at the Institute of Astrophysics, and it is the result of a wide collaboration involving researchers at the Institute of Space Sciences (ICE-CSIC, Barcelona), the Czech Academy of Sciences, and NASA's Goddard Space Flight Center της NASA (Greenbelt, USA).

Despite the relatively small area of the eFEDs field, this study revealed a population of dwarf star-forming galaxies with very low metallicity, which however, have much higher X-ray emission than expected based on previous studies of low-metallicity star-forming galaxies with other X-ray observatories. This excess can be as much as a factor of 10 above the expected luminosity given the star-forming activity of the studied galaxies.

An extensive search for active galactic nuclei in these galaxies did not show any such signs, leaving X-ray emission related to stellar remnants or multi-million degree hot gas as the main interpretation of the intense X-ray emission. This intriguing result has important implications for understanding the X-ray emission of star-forming galaxies in higher redshifts, and especially in the early Universe where low-metallicity dwarf star-forming galaxies were more common.

Articles:

- "The eROSITA Final Equatorial-Depth Survey (eFEDS). Presenting the demographics of X-ray emission from normal galaxies", Vulic N. et al., 2022, A&A, 661, A16
- "A census of ultraluminous X-ray sources in the local Universe", Kovlakas K. et al., 2020, MNRAS, 498, 4790

6. RESEARCH AREAS

In the following, we present the research areas in which members of the IA contributed in 2022. The section is organized and sorted by cosmic scales, from largest to smallest; and each scale is structured in research topics. The IA members actively investigating each topic are indicated in parentheses.

A description of the research areas is also presented in the web page of IA, specifically at: https://www.ia.forth.gr/all-research-areas

6.1. COSMOLOGY, LARGE-SCALE STRUCTURE & THE HIGH-Z UNIVERSE

General Background:
The formation of large-scale structure in the Universe is a cosmic battle between expansion inertia, gravity, and the accelerating influence of dark energy. The properties of the largest structures in the Universe (galaxy clusters and superclusters) respond to the contents of the Universe - dark matter and dark energy. On smaller scales, the evolution of galaxies within those clusters is also subject to radiative processes associated with baryonic matter; processes that give rise to one of the most energetic phenomena in the Universe: quasar activity. Quasars are the most powerful manifestation of accretion of material onto the supermassive black-holes (SMBHs; from several millions to several billion times the mass of the Sun) found at the centers of massive galaxies, a phenomenon producing the so-called active galactic nuclei (AGN). The result of this accretion is the production of intense radiation over the whole electromagnetic spectrum and often the ejection of material in the form of collimated relativist radio jets or larger scale gas outflows.

COSMOLOGY

(Researchers involved: V. Pavlidou, K. Tassis, E. Ntormousi)

Specific Background:
The properties of these largest structures on the largest possible non-expanding scale (the so-called turnaround scale, which is the boundary between a structure and the expanding universe) can be used to obtain information about the contents of the Universe and the relative proportions of its dark constituents. In contrast to other probes of cosmology, such as the cosmic microwave background of the expansion history of the Universe, the turnaround scale of structures probes dark energy locally - here and today - and it maps its result on specific objects (say a galaxy cluster, or a supercluster) rather than on the Universe as a whole.

Current efforts:

<u>The growth of structure and its link to cosmological models</u>: Our group uses analytical and semi-analytical calculations, numerical simulations of cosmological volumes, and observations, to map the turnaround scale and obtain the information it encodes about cosmology. Using analytic and semi-analytic calculations we follow the formation and growth of structure under different cosmologies. In universes with dark energy, the ultimate fate of structure formation is the halting of structure growth – a state which can leave observable imprints in the mass-radius relations of local-universe structures such as groups and clusters of galaxies.

Quasar Activity and Early Galaxy Assembly

(Researchers involved: T. Diaz Santos)

Specific Background:

By studying broad-band images and spectra of quasars from radio to X- and Gamma-rays, we can learn about the physical state of the material surrounding them and which are experiencing extreme physical and dynamical conditions. In addition, quasars are among the most distant sources of radiation in the Universe, and have been found up to redshifts larger than 7, when the Universe was less than 1 billion-year-old. Therefore, by deeply surveying large portions of the sky and collecting multi-wavelength data from large sample of quasars at different epochs, we can study the growth of the supermassive black-holes over cosmic time and investigate how the most massive galaxies are assembled at the center of cosmic over-densities.

Current efforts:

High-redshift dust-obscured quasars: Hot dust-obscured galaxies (Hot DOGs) are a previously unknown population of obscured quasars at $z > 1$ recently discovered by the NASA's WISE mission, which mapped the entire sky at near/mid-IR wavelengths. The bolometric luminosities of Hot DOGs exceed 10^{13} $L_{\odot}$. This outstanding energy output is thought to be powered by accretion onto supermassive black holes (SMBHs) buried under enormous amounts of gas and dust. Their host galaxies are detected in the near-infrared by Spitzer, but are less massive than expected from such hyper-luminous active galactic nuclei, which implies that either the SMBH has a much larger mass than expected given the stellar mass of its host, or it is radiating well above the limit dictated by the isotropic balance between gravity and radiation pressure. Such luminous nuclei harbored by otherwise normal galaxies are likely at a key stage of their evolution, where feedback from the active nucleus may be quenching star-formation – a "quasar" phase that some theoretical models require in order to explain the star-formation and interstellar medium (ISM) properties of red, compact, and mostly quiescent galaxies already identified at cosmic noon, $z \sim 2$. Our group uses the Atacama Large Millimeter/submillimeter Array (ALMA), the largest radio telescope in the world, to characterize the impact the central SMBH has on the ISM of its host galaxy. In addition, the 3D (2D spatial sky-projection + frequency) nature of ALMA's interferometric observations allows us to study the environment of these obscured quasars and search for companion galaxies and signatures of mergers, as Hot DOGs live in over-dense regions likely located at the nodes of the filamentary cosmic web. Moreover, we have been awarded a GO1 proposal with the James Webb Space Telescope (JWST), the largest mid-IR space telescope ever built, to target the most luminous and distant Hot DOG. With these data, we will study the ISM properties and energy sources in a multiple-merger system only 1.3 Gyr after the Big Bang.

Pulsar Timing Arrays: Pulsars as direct gravitational wave detectors

(Researchers involved: J. Antoniadis)

Specific Background:

Pulsar Timing Array (PTA) experiments rely on the precise measurement of the time-of-arrivals (TOAs) of the pulses for a network ("array") of millisecond pulsars spread over the sky. Changes in the local spacetime metric induced by gravitational waves result in TOA variations that correlate among different pulsars. PTA experiments are mostly sensitive to nanoHz gravitational waves (periods of ~1-50 years). The main signal in this regime is believed to be a stochastic GW background induced by merging supermassive black holes. The overall effect of the GW signal on the TOAs is expected to be well below 100ns. The measurement accuracy of pulse arrival times is *determined by the signal-to-noise of the pulse profile, but also depends on other effects, especially those caused by free electrons in the interstellar medium such as dispersion and scattering. In particular, their low-level variations can induce significant low-frequency power in the timing residuals that must be removed before the putative GW signals can be detected.*

Our PTA activities focus on contributions to the European Pulsar Timing Array (EPTA), a consortium of institutions and universities using European telescopes and resources to directly detect low-frequency GWs. The EPTA utilizes the MPIfR's Effelsberg 100-m Telescope, the Nançay Decimetric Radio Telescope (NRT), the Lovell Telescope at Jodrell Bank, the Westerbork Synthesis RadioTelescope (WSRT), and the Sardinia Radio Telescope (SRT). This range of telescopes give the EPTA a significant advantage over other PTA projects as it provides a larger total number of TOAs, high-cadence time coverage, immediate cross-checks on instrumental effects such as polarization calibration and clock offsets.

Current Efforts:

<u>The EPTA second data release (DR2):</u> Since 2020, the EPTA has been working on producing its second data release. This will include pulsar timing data from a new generation of data acquisition systems that provide a significant increase in bandwidth and sensitivity compared to our legacy systems. Current efforts focus on data combination, noise modeling, stochastic GW searches, single-source searches, ISM studies, and pulsar astrophysics. The produced dataset will allow for the most sensitive search of low-frequency GWs to date. In addition, it will be combined with datasets from other PTA collaborations to produce the next International Pulsar Timing Array (IPTA) data release. Publication of these results will be coordinated among PTA collaborations, following the approval of an independent "Detection Committee".

<u>Detection of a candidate GW signa</u>l: Using a small set of the preliminary results from DR2, we have performed a search for the stochastic gravitational-wave background (GWB) (Chen et al. 2021). As explained above, a GWB manifests itself as a long-term low-frequency stochastic signal common to all pulsars, i.e., a common red signal (CRS). The signals from different pulsars are correlated based on their angular separation in the sky, which is the so-called characteristic Hellings-Downs (HD) spatial correlation. Our search detected a CRS among the pulsars being analyzed, and the detection significance was largely increased in comparison with the evidence that was seen with the EPTA DR1 data. The spectral properties of the signal are also compatible with theoretical GWB predictions. However, our search did not find significant evidence of the HD correlation, which is the requirement for a claim of GWB detection. During the year of this report these results were confirmed by an independent analysis of the IPTA DR2 (Antoniadis et al., 2022), a combination of legacy data from the PTAs (EPTA, Parkes PTA and NanoGrav). The findings of a more sensitive GWB search using the full DR2 dataset will be released in 2023.

<u>Large European Array for Pulsars (LEAP):</u> The Large European Array for Pulsars (LEAP) is a key science project within the EPTA collaboration, which coherently combines the five EPTA radio telescopes to deliver an L-band sensitivity equivalent to a 200-m single dish. LEAP conducts monthly observations of over twenty EPTA pulsars including all high-priority EPTA sources. Current LEAP activities focus on observations, data reduction and analysis (using a dedicated HPC cluster at the University of Manchester), contributions to the EPTA DR2, searches for Fast Radio Bursts (FRBs), and studies of the ISM and Solar Wind.

6.2. Galaxies and Their Evolution

General background:
Galaxies are the places where stars form and spend their lives. They exhibit a wide variety of morphologies and colors, which in general terms reflect their past history. Hence studies of galaxies provide information on the formation of stars over the history of the Universe and the growth of the SMBHs residing in their nuclei. Galaxies are very dynamic systems, which often collide and merge to form new structures. These interactions depend on the local environment of each galaxy and therefore studies of galaxies can provide information on the evolution of the Universe as a whole.

Our group has a deep interest in understanding the properties of galaxies and their evolution. In particular we focus on the following topics:

Ultra-luminous X-ray Sources

(Researchers involved: P. Reig, A. Zezas)

Specific background:
Ultra-luminous X-ray sources are an intriguing class of objects with luminosities above 10^{39} erg/s and often reaching extreme luminosities of 10^{40} or even 10^{41} erg/s, well above the Eddington limit for a stellar-mass black-hole. The nature and formation pathways of these sources is an open question, and their understanding is particularly important given their significant contribution in the X-ray output of galaxies, which they often dominate. Detailed studies of their X-ray spectra also provide information on the accretion physics at extremely high accretion rates.

Current efforts:

At the IA, researchers are performing systematic studies of ULX populations in individual nearby galaxies, as well as their demographics in large samples of galaxies. Our goal is to constrain the dependence of their populations on the age and metallicity of their parent stellar populations. In addition to studies of ULX populations in individual galaxies, in 2022 we continued our efforts in studying the populations of ULxs in large samples of galaxies by combining Chandra and XMM-Newton catalogues.

Active Galactic Nuclei

(Researchers involved: D. Blinov, C. Casadio, V. Charmandaris, S. Kiehlmann, I. Papadakis, V. Pavlidou, V. Pelgrims, A. Ramaprakash, A. Readhead)

Specific background:
Active Galactic Nuclei (AGNs) are the most luminous, persistent objects in the Universe. They emit an enormous amount of luminosity, from a tiny volume, at the center of their host galaxies. It is quite common that the bolometric luminosity emitted by the active nucleus will surpass that of the host galaxy. Today we believe that AGN are powered by accretion of matter, in the form of a disc, around the super-massive black hole that resides at the center of galaxies.

The mass of the BHs at the center of galaxies ranges from one hundred thousand to several billion solar masses. As matter accretes on them, it releases gravitational energy with an efficiency far greater than the efficiency of the nuclear reactions at the center of stars. As a result, an AGN emits intense radiation at all wave bands, from radio to gamma-rays. Approximately 10 per cent of AGN are particularly luminous in radio waves, and they show evidence of collimated relativist jets. The

AGN radiation is highly variable, at all wavelengths, with the amplitude and variability rate increasing with increasing frequency.

By studying the broad-band (from radio to optical to X- and Gamma-rays) spectra and the extreme variability of an AGN we can learn about the physical properties that operate in the vicinity of the super-massive black-holes and in the relativistic outflows. In addition, AGNs are among the most distant sources of radiation in the Universe, and have been found up to "redshift" larger than 7, when the Universe was less than one tenth of its current age. Therefore, by deeply surveying large portions of the sky and collecting multi-wavelength data from large samples of AGN at different "redshift" we can study the growth of the supermassive black-holes over cosmic time and their connection to galaxy formation.

AGNs are also ideal tools to investigate the matter content in the Universe, through the gravitational lens effect. Most of the known cases of strong gravitational lensing involve multiple images of nucleus of active galaxies. Studies of gravitationally lensed AGNs have a two-fold function: revealing more and finer details about AGNs, and tell us something about the lens, like for example its mass distribution.

Current efforts:

AGN variability: Our group has long worked on the study of the AGN variability, mainly in the optical/UV and X-rays. We have used optical data from the Skinakas observatory to study the optical variability of both radio quiet and radio-loud AGN, and data from space observatories (like Swift and XMM-Newton) to study the fast, X-ray variability in these objects. The group studies the variations of both high-z and nearby AGN, using sophisticated methods in the frequency domain (like power-spectrum, and time-lags analysis) as well as the use of simple statistics like variance-frequency plots, as well as simple spectral shape variations as a function of time. Recently, a theoretical effort has been initiated to construct a theoretical model for the broad-band emission (from optical to UV and X-rays) and use it to fit the broad-band spectral energy distribution from unobscured AGN, and the correlated optical/UV/X-rays variability that is observed in them.

ROBOPOL blazars: Blazars belong to the fraction of AGN whose supermassive black holes host a relativistic jet which is closely aligned with our line of sight. As a result, their emission is enhanced by relativistic effects, appearing shifted to higher frequencies and significantly boosted to very high observed brightnesses. Blazar jets emit across the electromagnetic spectrum. In optical wavelengths, they radiate optically thin Synchrotron, sampling various emission sites along the jet. This emission is highly polarized, with its polarization variability revealing important information about the location of the emission sites, the strength and degree of disorder of the jet magnetic field, and the relation of synchrotron with high-energy gamma-ray inverse Compton emission. Our group has been monitoring blazar optopolarimetric variability using the RoboPol polarimeter since 2013, conducting some of the most detailed, statistically robust studies to-date of the coherent rotations of the polarization angle observed occasionally in certain blazars.

Search for Milli-lenses (SMILE): Gravitational lensed images with angular separation on milliarcsecond scales probe gravitational lens systems where the lens is a compact object with mass in the range 10^6 -10^6 $M_{\odot}$. This mass range is particularly critical for the widely accepted cosmological model, which predicts many more DM sub-galactic halos (masses below ~ 10^{11} $M_{\odot}$), than currently observed. The most direct way to explore these small angular scales is through the high-resolution of radio Very Long Baseline Interferometry (VLBI). In the SMILE project, we propose to use VLBI data on a complete and large sample of radio loud active galaxies (~ 5000 sources) to search for gravitational lens systems on milliarcsecond scales. Given that no gravitational lenses on milliarcsecond scales have yet been found, if any of the gravitational lens candidates that this search will produce is indeed confirmed as a true gravitational lens system, this would be a first and a major discovery. A null result instead will allow us to infer a new constraint on the abundance of compact objects in the mass range of interest, with over an order of magnitude better precision than in previous studies. Since the number of DM sub-galactic halos that can be detected through milli-lenses depends both on the mass function and the density profiles of DM halos, with the SMILE project we will be able to discriminate between many currently viable DM models.

Star Formation and Galaxy Mergers in the Local Universe

(Researchers involved: V. Charmandaris, T. Diaz-Santos, K. Kouroumpazakis, M. Sanchez-Garcia, A. Zezas)

Specific background:

Stars are the building blocks of galaxies. The process of star formation, starting from the collapse of rarefied gas and leading up to the ignition of thermonuclear reactions at the center of gravitationally bound molecular clouds is an extremely complex process. Moreover, the feedback from stellar winds and the eventual "death" of the most massive stars in super-novae (SN) explosions inject large amounts of energy and momentum in their surrounding interstellar medium (ISM), setting the stage for the formation of the next generation of stars. This "life cycle" of baryons within galaxies, together with the environmental conditions they are subject to (such as galaxy-galaxy mergers and the accretion of inter-galactic matter), are probably the most important pillars over which current theories of galaxy evolution stand, and therefore they are central to modern astrophysics.

Current efforts:

<u>The most energetic galaxies in the nearby Universe</u>: Luminous and ultra-luminous infrared galaxies ((U)LIRGs) are dust-obscured galaxies powered by star formation and/or AGN activity, with luminosities ten to hundred times larger than our own Galaxy. While they are not very common in the nearby Universe and only represent a modest fraction of the total infrared (IR) emission observed, their importance at earlier cosmic times becomes evident from the fact that they dominate the star formation rate density in the Universe during cosmic noon, from z ~ 1 to up to z ~ 3. A large fraction of (U)LIRGs are interacting systems. Researchers at the IA are active participants in large, international collaborations that focus on the study of nearby IR galaxies, such as the Great Observatories All-sky LIRG Survey (GOALS) and the Star-formation Reference Survey (SFRS). Multi-wavelength observations across the electromagnetic spectrum, from the radio through the X-rays, obtained with a wide suite of first-class observatories, are used in combination with state-of-the-art stellar evolution synthesis models to fit their spectral energy distributions and characterize their physical properties. In addition, we investigate the connection between galactic activity (star formation and AGN) and galactic parameters such as stellar mass, dust content, and morphology. We have produced a census of AGN activity in local IR galaxies and study of the relation between star-formation and stellar mass and other galaxy-wide scaling relations not only globally but also at sub-galactic scales. On-going projects include Hα and NIR imaging which will be used for the comparison of Hα and other SFR indicators in a variety of star-forming environments. Our group is heavely involved in several recent discoveries made with the James Webb Space Telescope as part of an Early Release Science program. Using mid-IR MIRI/MRS 3D observations of three nearby LIRG nuclei, we have shown the critical interplay between the ionized and molecular ISM phases as well as the impact of AGN feedback in their circum-nuclear regions. Further, on-going studies will deepen our undertstaning on the physics of these extraordinary objects.

Galaxy interactions and mergers: Galaxy mergers trigger vigorous star-formation and are responsible for activating their central SMBHs. Energetic feedback from these sources can generate high-velocity gas outflows heating up and carrying away a large fraction of the gas mass within the host galaxy, thereby rapidly truncating future star formation. We study galaxy mergers in the IR via spatially resolved mapping and integral field unit observations obtained with the Spitzer Space Telescope, the Herschel Space Observatory and the James Webb Space Telescope, which commenced operations in 2022. The IR radiation can penetrate through the dust which is ubiquitous in those galaxies and hence these data can give us a clear picture of the star-forming activity, the activity due to their SMBHs and their connection to the interaction process. Studying these galaxies helps us understand the origin of these outflows and more generally understand galaxy evolution during its most rapid and violent stages. In this effort we also use multi-wavelength data from the Skinakas Observatory. In addition, the NuSTAR observatory gives us an unprecedented view of the hard X-ray emission from nearby galaxies. We are leading the development of diagnostic tools for the characterization of X-ray observations of nearby galaxies with the NuSTAR and other X-ray telescopes.

Star-formation and AGN activity in normal, Milky-way type, nearby galaxies: Our group is leading studies of the star-forming activity in a representative sample of galaxies in the local Universe. The goals of this project are to: (a) compare different methods for measuring the star-formation rate and address the factors that influence these measurements; (b) measure the connection between recent and past star-forming activity in galaxy-wide as well as sub-galactic scales; (c) study the connection between star-forming activity and AGN activity. During 2022 we have published a paper comparing the SFR inferred from Hα measurements with SFR based on other indicators for a representative sample of galaxies. In addition, we are developing a new calibration for the determination of SFR using WISE photometric data accounting for the contribution of old stellar populations in the dust emission, and a new diagnostic for the characterization of star-forming, passive and AGN-hosting galaxies based on infrared (WISE) photometry. We also continued the development of the Heraklion Extragalactic Catalogue (HECATE). This is the most complete, value-added catalogue of galaxies in the local Universe, including information on their stellar content (star-formation rate, stellar mass), metallicity, AGN activity. Such a catalogue is extremely useful for statistical investigations of nearby galaxies, but also for the fast identification and characterization of the hosts of transient events (e.g., gravitational-wave sources, gamma-ray bursts, tidal disruption events, supernovae etc).

Star-formation and X-ray binary populations in nearby galaxies: X-ray binaries are a key tool for understanding the evolution of binary stellar systems and the formation of their end-points such as sources of gravitational waves and short gamma-ray bursts. Studies of the discrete X-ray source populations (in particular accreting sources) in nearby galaxies allow us to: (a) probe areas of the parameter space that are not present in our neighborhood (e.g., different metallicity or star-formation history), and (b) obtain large statistical samples and explore rare types of systems. We have embarked in a systematic study of the X-ray binary populations and their integrated X-ray emission in nearby galaxies and their connection with their parent stellar populations (star-formation history, metallicity, etc) and star-cluster parameters. In addition, as members of the eROSITA Nearby Galaxies collaboration we are exploring the correlation between the integrated X-ray emission of galaxies and their stellar populations. The first results from this work are very intriguing since they suggest a population of galaxies with X-ray luminosities much larger than expected from the existing correlations between X-ray emission, SFR and stellar mass.

Dynamical signatures of past mergers in early type galaxies: According to the current scheme describing galaxy evolution, elliptical galaxies are the end-points in galaxy evolution, forming when the galaxies have converted most of their gas into stars, often during intense interactions. Recent deep observations of elliptical galaxies show that they exhibit ubiquitous structures that are tell-tale signatures of interactions that took place several billion years ago. The IA is very active in developing methods for the identification of these structures and studying their connection with past merger activity of the galaxy. In particular, we are interested in the determination of the mass function of disks and bulges in the local Universe. In addition, our group has pioneered the use of the spatial distribution of globular clusters as indicators of past merger activity, and more recently it is heavily involved in systematic studies of the identification of non-uniformities in the globular cluster distribution in elliptical galaxies in the Virgo and Fornax clusters. We have also extended this study to an investigation between the fine structure in elliptical galaxies and the stellar-mass deficit in their cores.

6.3. The Contents of Our Galaxy

General background:
Accretion is the dominant physical process of generating high energy radiation in many astrophysical contexts. Accretion of matter onto super massive black holes, located at the centers of nearly all galaxies, produces some of the most violent and energetic electro-magnetic and gravitational processes in extragalactic astrophysics: from giant radio lobes extending over tens of kiloparsec into the intergalactic medium, to relativistic jets of ionized, highly collimated matter (blazars), to X-rays from the interaction of BH binaries, to AGN-powered high-velocity galactic gas outflows.

Whether in isolation or in binary systems, white dwarfs, neutron stars, and black holes —collectively referred to as compact objects— allow the study of a variety of open questions in fundamental physics as they represent excellent laboratories to study matter under extreme conditions of gravity and magnetic field. In our work we use data from all major X-ray and radio telescopes as well as, supporting multiwavelength data from Hubble as well as ground-based telescopes.

Members of our group study individual sources that exhibit interesting or unique characteristics, populations of X-ray binaries, as well as their integrated X-ray emission and their connection to the stellar populations they are associated with.

X-ray Binaries

(Researchers involved: K. Kouroumpatzakis, N. Kylafis, I. Papadakis, P. Reig, A. Zezas)

Specific background:
X-ray binaries are stellar systems consisting of a star and a stellar remnant such as black-hole, neutron star or a white dwarf. When material from the star (or donor) is falling onto the stellar remnant (or compact object), it is heated to temperatures of several million degrees and produces copious X-ray emission. In this process we may also observe jet-like collimated outflows or wide-angle winds of highly ionized plasma. The properties of this emission depend on the conditions close to the compact object and therefore can be used to study the behavior of matter under the influence of strong gravitational fields. In addition, the properties of a binary stellar system (e.g. parameters of the two objects and their orbit, long-term evolution) depend on the past of the two objects. Therefore, X-ray binaries are very useful laboratories for studies of the properties of compact objects and stellar evolution.

The vast majority of X-ray binaries with massive companions harbor X-ray pulsars. The detection of pulsations from an accreting X-ray source provides one of the strongest pieces of evidence that the compact object is a neutron star. X-ray pulsations result from the misalignment of the neutron star spin and magnetic axis. Gas is accreted from the stellar companion and is channeled by the magnetic field onto the magnetic poles producing two or more localized X-ray hot spots. As the neutron star rotates, pulses of X-rays are observed as the hotspots move in and out of view. The change in the neutron star, rotation velocity (spin-up or spin-down) allows measurements of accretion torques, which can provide a measure of the accretion rate and the magnetic field. In addition, we use multi-band (photometry, spectroscopy, and polarimetry) observations of X-ray binaries to study the nature of their donor stars, their orbital parameters and address their long-term variability. We combine these observational data with theoretical models of the emission from the accretion flow and jet outflows in order to obtain a better understanding of the physical processes which take place in those extreme environments.

Current efforts:

Black hole X-ray binaries: At present, the origin of the hard X-rays emitted by black hole binaries is controversial. There is general consensus that the hard X-rays result from inverse Compton of low-energy photons, presumably coming from the accretion disk, by high-energy electrons. However, the physical nature and the geometry of the Comptonization medium is still under debate. Black hole binaries exhibit relativistic jets at low/medium X-ray luminosity. We propose that the Comptonization medium is the entire jet. Our jet model has been able to explain many timing and spectral properties of black hole binaries. Currently, we work to improve the model to explain even more challenging results resulting from X-ray observations. Hard X-ray observations provide a valuable probe of the emission region near the compact object. Another goal of this project is to study the correlation between spectral parameters (X-ray continuum and discrete lines) and timing parameters (power-spectra, time lags) and of those with other observables (mass accretion rate, hardness of the spectrum). These correlations represent the tightest constraints for models.

Accreting pulsars: Members of the IA are working on providing unified characterization of accretion-powered pulsar spectral states during giant outbursts. In the last twenty-five years, the discovery of different “states'' in the X-ray emission of black-hole binaries (BHB) and neutron-star Low-Mass X-ray Binaries (LMXBs) constituted a large step forward in the understanding of the physics of accretion onto compact objects. While there are numerous studies on the timing and spectral variability of BHB and LMXBs, very little work has been done on High-mass X-ray Binaries (HMXBs). The goal of this project is to investigate the current observational evidence and find new one for the existence and identification of the various accretion regimes the pulsars go during a major X-ray outburst. We have also embarked in a systematic study of the hard X-ray emission of outbursting accreting pulsars in the Small Magellanic Cloud. The goal of this project is to measure their magnetic field strength from the detection of Cyclotron lines, and the study of their phase resolved spectra at these high luminosities in order to constrain the dominant emission mechanisms and the geometry of the emitting region at different energies.

Variability time scales in Be/X-ray binaries (BeX): BeX consist of a neutron star orbiting a O9e-B2e main-sequence star. The letter "e" stands for emission, as instead of the normal photospheric absorption lines the optical spectra of Be stars display emission lines. Strong infrared emission is another defining characteristic of Be stars. A third observational property is that the light from a Be star is polarized. The origin of these three observational properties (emission lines, infrared excess, and polarization) lies in a gaseous, equatorially concentrated circumstellar disc around the OB star. This disc constitutes the main source of variability in BeX and the fuel that powers the X-ray emission through accretion. The main objective of this project is to characterize the optical/IR variability time scales of Be/X-ray binaries in correlation with their X-ray activity.

X-ray binary characterization and spectral synthesis: The characterization of the compact objects in X-ray binaries is a critical component for understanding their nature and testing binary populations synthesis models. In 2022 we continued our efforts to develop methods for the characterization of the compact objects in X-ray binaries based on hard X-ray observations with NuSTAR. We also embarked in an effort to calculate integrated X-ray spectra from X-ray binary populations associated with stellar populations of different ages. In addition, using a spectral library of Galactic X-ray binaries, we initiated a project for the calculation of bolometric corrections and band-to-band conversion factors for X-ray binaries in different accretion states. These results are presented in a refereed publication.

MASSIVE BINARIES AND THEIR COMPACT REMNANTS

(Researchers involved: J. Antoniadis, D. Aguilera-Dena)

Specific background

Massive stars are among the most influential components of galaxies. They regulate star formation and inject vast amounts of energy and chemically-enriched material into the interstellar medium. Upon death, they often produce extremely energetic transients such as supernovae and gamma ray bursts. Their remnants (black holes and neutron stars) are often strong gravitational-wave emitters, important sources of heavy elements and exquisite tools for probing the properties of fundamental physical laws under extreme conditions. Most massive stars are thought to be members of binary or multiple systems that ultimately interact via mass transfer. Such binary interaction is expected to at least partially remove the hydrogen-rich envelope, creating stripped-envelope helium stars. These objects are thought to be responsible for approximately half of all observed supernovae, as well as for the majority of compact-object binaries. Despite their importance, their properties remain poorly constrained. Understanding their formation and evolution is a fundamental open question in astrophysics, motivating multi-billion-euro facilities such as the LIGO/Virgo/Kagra network, the Vera Rubin Observatory, SKA and the James Webb Space Telescope.

Current Efforts

Electron Capture Supernovae: An electron-capture supernova (ECSN) is thought to occur when a degenerate ONeMg stellar core reaches the Chandrasekhar mass limit. As the density increases, Ne nuclei start capturing electrons, resulting in a sudden loss of outward pressure. The outcome of an ECSN depends on the competition between gravitational collapse, and the release of energy from explosive burning, and can range from the formation of a low-mass neutron star (NS), to the complete disruption of the star in a thermonuclear explosion. ECSNe are thought to be a crucial source of low-velocity NSs, which are required to explain the population of binary pulsars in the Galaxy, as well as the mergers seen by LIGO/Virgo.
Current Efforts at IA focus on modeling the complex evolution of ECSN progenitors in binary systems and understanding the impact of yet uncertain factors (such as nuclear reaction rates, stellar winds, initial composition, convection, etc.) on determining the final outcome. Recently we were able to demonstrate that a considerable fraction of ECSN progenitors is likely to avoid core collapse. This happens because they initiate explosive oxygen burning when their central densities are below $\log\rho_c$ (g/cm^3) < 9.6, long before they reach the threshold for e-captures on Ne. The result is a thermonuclear runaway that looks similar to a Type Ia SN

(CONe SN Ia). Our models imply that the amount of residual carbon retained after core carbon burning plays a critical role in determining the final outcome: Chandrasekhar-mass cores with residual carbon mass fractions of $X_{min}(^{12}C) > 0.004$ result in (C)ONe SNe Ia, while those with lower carbon mass fractions become ECSNe. (C)ONe SNe Ia are more likely to occur at high metallicities, whereas at low metallicities ECSNe dominate.

Neutron star birth masses and islands of explodability: Despite their importance, the relation between the initial properties of helium stars (e.g., mass, composition, rotation) and the remnants they create remains equivocal. The main reason is related to the complexity and computational cost of detailed core-collapse SN simulations. We have recently developed a toolbox that combines stellar evolution models with rapid semi-analytic neutrino-driven supernova models, to make predictions for the explosions (type, kinetic energy, ejecta mass, nickel mass) and remnants (type, mass, kick velocity). This approach enables parametric studies of thousands of progenitor models, at very small computational cost. Some highlights from the application of this approach to helium star models include: a) Detailed predictions for the mass spectrum of neutron stars and black holes across Cosmic Time (i.e., at different metallicities); b) the identification of low-energy explosions that result from a weak sound pulse that is launched when the initial SN ejecta become subsonic. The latter quickly become spherical, resulting in symmetric core-collapse explosions with *negligible natal kicks.* Such explosions may produce both low- (1.4 Msol) and high-mass (2.0 Msol) neutron stars, as well as stellar-mass black holes in the so-called lower mass gap (2.5 Msol); c) A large number of very massive stars with pre-collapse carbon-oxygen core masses above 10 solar masses, and extending up to at least 30 solar masses, may produce NSs or mass-gap objects, instead of BHs. This explosion landscape would naturally cause a fraction of massive binaries to produce compact object binaries with highly asymmetric masses, instead of symmetric-mass binary BHs. A population of such binaries, i.e. GW190814 and GW200210, has been identified during the third LIGO/Virgo run, in line with the predictions of this model.

Observations of slow transients: We have also been involved in a number of observational studies of stellar explosions, both at radio and optical wavelengths with facilities such as Effelsberg, MeerKAT and the Korean Microlensing Telescope Network (KMTNet). A recent highlight includes the earliest detection of a Type Ia supernova, only ~1 hour after the explosion (Ni et al. 2022). The infant phase of this transient provides strong evidence for radioactive material being present near the surface of the exploding white dwarf, as well as for interaction between the ejecta and a low-mass compact companion. This provides support for the so-called double degenerate scenarios in which a high-mass WD accretes material from a lower-mass WD. This discovery was made possible by the unique capabilities offered by KMNTNet. The latter consists of three, 1.5 m telescopes located in Australia, South Africa, and Chile, equipped with large 3x3 deg CMOS detectors and RVB optical filters.

Pulsar Population studies: The advent of multi-wavelength all-sky surveys in the past decade has created unique opportunities to probe various aspects of the Galactic pulsar population that were previously inaccessible. One important such survey is performed by the GAIA mission, that is delivering precise positions, distances and velocities for several billions of Milky-Way stars. In recent studies led by IA-FORTH members, the second (DR2) and early third (EDR3) GAIA data releases were used to perform a systematic search for optical counterparts to 1534 rotation-powered pulsars with positions known to better than 0.5 arcsec. This search returned 22 matches to known pulsars – thereby providing distance and velocity constraints – as well as 8 new candidate companions to young pulsars. This result was used to place a stringent constraint on the multiplicity fraction of young pulsars ($f_{young} < 5.3\%$ at 95% C.L) and the properties of SN kicks.

Targeted Pulsar Searches: Similarly, the information provided by GAIA can also be used to identify objects that are likely to be orbited by millisecond pulsars. Such objects may include low-mass white dwarfs with high peculiar velocities, ablated stars that are coincident with gamma-ray counterparts, and nearby binary white dwarfs. We performed a pilot radio survey of 10 such white dwarfs with the 100-m Effelsberg and LOFAR telescopes, placing constraints on the fraction of NSs orbiting white dwarfs.

THE ISM AND STAR FORMATION

(Researchers involved: D. Blinov, S. Kiehlmann, V. Pavlidou, V. Pelgrims, K. Tassis)

Specific background:

Investigating the physics of the interstellar clouds enables us to understand the initial conditions of star formation. In particular, the role of magnetic fields is critical, as it affects the formation of dense molecular clouds from the diffuse atomic clouds (by directing the accumulation of gas), it affects the dynamics of the clouds (by resisting the gravitational collapse as it provides an effective pressure) and together with turbulence regulates star formation. We observe the magnetic field in the optical through the polarization of starlight, induced by dichroic absorption of aspherical interstellar dust grains aligned with the local magnetic field that permeates the clouds. We also use magnetohydrodynamic simulations (both ideal and non-ideal) to explore the dynamical effect of the magnetic field both locally in the clouds and globally in galactic scales.

Current efforts:

The IA hosts a world-class center for polarimetric studies of point sources in the optical, featuring cutting-edge, innovative instruments, international collaborations with world-leading groups in instrumentation, observations, and theory, and a wide variety of applications, including studies of extragalactic jets, the interstellar medium, binaries, transient-follow ups, and study and control of foregrounds in the study of the polarization of the cosmic microwave background. Current opto-polarimetric programs running at Skinakas include PASIPHAE, RoboPol, and CIRCE/PHAESTOS. Our group uses observational data in the Infrared part of the electromagnetic spectrum from space-based (Planck, Herschel) and airborne-based (SOFIA) observatories; in the radio from single dish telescopes (ARO, FCRAO, Arecibo, Effelsberg) and in the optical at Skinakas Observatory (RoboPol).

Magnetic Fields in the Interstellar Medium: After suffering absorption by interstellar cloud dust, starlight may become polarised if the dust grains have a preferential alignment induced by the interstellar magnetic field. Studies of this polarisation with the RoboPol instrument can reveal the magnetic field structure in interstellar clouds.

Origins of molecular clouds: Our group has studied the transition from neutral atomic to molecular hydrogen in a cloud towards Ursa Major using a diverse dataset including HI, CO, C+ and optopolarimetric observations as well as theoretical interpretation efforts. We showed that the magnetic field is dynamically important, and plays an important role in determining where in the cloud the transition takes place.

Tomographic mapping of the interstellar magnetic field: We have developed a novel technique, to be used with PASIPHAE data, for the Bayesian tomographic decomposition of optopolarimetric observations along specific lines of sight. The technique determines the number and locations of different interstellar clouds in the line of sight, with simultaneous determination of the average polarization direction in each cloud, and the dispersion of polarization directions. This is achieved based on optopolarimetry of stars and stellar parallaxes alone, without input from other observables.

Interpretation of extreme turbulence in the Galactic center: We have provided an explanation for the abnormally high levels of turbulence observed in clouds within the central molecular zone of the Milky way, in terms of kinetic output from winds of massive stars. The model reproduces both the levels of turbulence, the scaling of turbulence line widths with cloud size, and the observed cutoff of excess turnulence with Galactocentric distance.

Astrophysics of ultra-high-energy cosmic rays and gamma rays: With energies higher than 10^{18} eV, ultra-high-energy cosmic rays are the most energetic particles known. They pack the energy of an aggressively served tennis ball in a single subatomic particle. Their flux at the highest energies is as low as one particle per square kilometer per century! Their origin remains, to this day, unknown, but they are certain to encode important information about the most extreme processes in the Universe. Our group develops novel approaches to their study, including assessing the possibility of back-tracing of their paths through the Galactic magnetic field to uncover their true arrival directions and thus better constrain their origin; develop tests of a multiple-source-population origin; and use gamma rays resulting from intergalactic cascades to identify the location of their sources. Our group also demonstrated that optopolarimetric observations can be used for development and demonstration of techniques to identify previously unknown members of this class.

SUPERNOVAE AND THEIR REMNANTS

(Researchers involved: I. Leonidaki, I. Papamastorakis, A. Zezas)

Specific background:
Massive stars end their lives with spectacular explosions (supernovae). These explosions enrich the interstellar material with the heavy elements produced in the stars during their lifetime. In addition, the strong shock waves of the explosion heat the surrounding interstellar medium to temperatures ranging from ~10^3 to 10^7 degrees. Therefore, study of these supernova remnants can reveal information about the latest stages of stellar evolution, nucleosynthesis, physics of shock-waves and the properties of the interstellar medium.

Current efforts:
Constraining the distribution of supernova kick velocities. Supernova kicks are a critical parameter in the evolution of binary stellar systems with compact objects. They determine the survival of a system, its orbital parameters and its subsequent evolution. We are performing a multi-faceted study aiming at: (a) constraining the kick velocities of X-ray binaries based on modelling their evolution given their observed parameters, and (b) directly measuring their center-of-mass velocities based on their displacement from their birthplaces.

Narrow-band imaging of Galactic Supernova Remnants: Supernova Remnants (SNRs) are an important tool for understanding the physical processes that take place in the interaction between the shock wave from a supernova explosion and the stellar ejecta and/or the surrounding interstellar material. Narrow band images of SNRs in our Galaxy allow us to study their morphology and map their excitation, important parameters for understanding how the mechanical energy of the shock wave is transferred in the surrounding material.

Supernova Remnants in Nearby Galaxies: Studies of Supernova remnants in nearby galaxies provide a more complete picture of their populations by proving a wider range of supernova progenitors and ISM structures. We have embarked in a systematic study of the supernova remnant populations in nearby galaxies using narrow-band imaging observations from the CTIO and Skinakas Observatory. These observations are supplemented by IFU observations of individual regions of the galaxies. During 2022 we published a paper presenting a new methodology for the derivation of the multi-variate luminosity functions of SNRs and also introducing their excitation function. As part of this effort, we published a paper presenting a population synthesis model for the calculation of the Hα and the joint Hα-[SII] luminosity function of SNRs in a galaxy.

Extrasolar Planetary Systems

(Researchers involved: P. Kalas)

Specific background:
Over the past 25 years, several thousand planetary systems around other stars have been discovered and characterized around pre-main-sequence and main-sequence stars, encompassing many sub-disciplines such as planet formation, circumstellar disks, dynamics, atmospheric chemistry, demographics, astrobiology, and even the search for techosignatures. Our focus is on observational studies of dusty debris disks, wide-separation gas giant planets, and circumplanetary rings using a variety of resources, such as the Hubble Space Telescope, the Gemini Planet Imager, VLT/SPHERE, ALMA, Gaia, and eventually JWST and WFIRST. Data from these observatories provide unique and fundamental information, such as:

Physical Properties of Exoplanets: Relying mostly on direct imaging techniques we estimate the masses of exoplanets, by analyzing how bright they appear and the properties of their orbits. Their composition is estimated, by analyzing the color of thermal emission from the planet, or by obtaining a spectrum. Finally, the origin of exoplanets is derived, by comparing their current observed properties with simulations of how planets form in a circumstellar disk and subsequently evolve.
Ultimately, this research provides an empirical notion of how common or rare our own planetary system must be in our own galaxy and throughout the universe.

6.4. Statistical Methods and Simulations

(Researchers involved: K. Kouroumpatzakis, N. Kylafis, E. Ntormousi, I. Papadakis, V. Pavlidou, P. Reig, K. Tassis, A. Zezas)

General background:
Modeling of complex astrophysical phenomena is an important tool for constraining as well as understanding the physical processes at play and for constraining the underlying physical parameters based on comparisons with observational data. In addition, the increasing volume and complexity of the astronomical data requires the development of more efficient techniques for their analysis and interpretations, often involving state-of-the-art statistics and machine learning methods.

Specific background:
Our group is active is the development of models for complex astrophysical phenomena with the goal of comparing their predictions with observational results in order to understand the underlying physical processes. These efforts are focused in the fields of radiation transfer, chemistry, and fluid dynamics in the ISM, magnetic fields in the ISM, and X-ray binaries. In addition, we are interested in the development of methods for the analysis and characterization of astrophysical data using a broad range of information based on a wide array of space and ground-based observatories.

Current efforts:
Astrochemistry: Non-equilibrium chemodynamical multi-fluid non-ideal MHD simulations of star-forming molecular cloud cores. Our group developed and made

public the non-LTE line radiative transfer code PyRATE.

Monte Carlo simulations of Compton up scattering in accreting neutron-star X-ray binaries: A major issue in High-Energy Astrophysics is where the high-energy, power-law emission occurs in black-hole and neutron-star X-ray binaries. One possibility is the hot, inner, accretion flow and the other is the jet. In a series of papers, we have advocated for the jet and have explained a number of observational constraints using a simple jet model. In a recent paper, we have been able to explain the neutron-star X-ray spectra, using the same simple jet model.

Classification of astrophysical sources: The reliable characterization of sources detected in large astronomical surveys is a major challenge given the growing volume of the available samples and the complexity of the available data. We are working on the development of efficient methods for the classification and characterization of sources employing state-of-the-art statistical and machine learning tools. The project underway includes: the distinction of supernova remnants from HII regions, the characterization of X-ray binaries on the basis of their compact object or accretion state, the characterization of stars according to their spectral types, and the activity classification of galaxies into star-forming, passive galaxies or AGN. In 2022 we published a paper presenting a method for the classification of early-type stars according to their spectral-type, while a paper presenting a mid-IR galactic activity diagnostic is ready to be submitted.

Astrostatistics: In addition to the source classification methods, we have also embarked in an effort to develop methods for the principled analysis of imaging and spectroscopic data affected by source confusion. These methods are particularly relevant for the X-ray and gamma-ray regime. In addition, we are working on methods for the analysis of LogN-LogS distributions at the Poisson limit accounting for source confusion. In this context we published a paper presenting a graph-based method for the identification of extended sources in event lists.

Modelling of X-ray binary populations: Standard methods of modeling the formation and evolution of X-ray binaries rely on a brute force approach and are relatively inefficient. We have introduced a methodology that uses a Markov Chain Monte Carlo technique as a wrapper to an already built and maintained binary evolution code. This way we are able to focus computational power on the region of the parameter space of interest. This approach allows efficient fitting of observed binary populations, while taking into account their spatial distribution and the spatially resolved star-formation history of their parent stellar populations. This method is now applied on the formation of the GW150914 progenitor.

Numerical studies of the Galactic Magnetic Field: Magnetic fields lie at the heart of all the outstanding problems in galactic evolution. We are developing the first simulations to include all the core processes of galactic evolution, such as a multi-phase interstellar medium, time-dependent star formation and stellar feedback, and the realistic non-ideal MHD terms necessary for modeling a realistic magnetic field evolution. The simulations are performed with the RAMSES and FLASH codes.

7. RESEARCH FUNDING

The following projects, funded by national and international agencies, enabled the research activities of the IA during the period of the report.

- Stavros Niarchos Foundation Grant in support of the project "PASIPHAE" (P.I.: K. Tassis, budget: $1,457,000, duration: 2016 – present)

- <u>ERC Consolidator Grant</u> "PASIPHAE", entitled "Overcoming the Dominant Foreground of Inflationary B-modes: Tomography of Galactic Magnetic Dust via Measurements of Starlight Polarization", (P.I.: K. Tassis, budget: €1,887,500, duration: 2018 – 2023)
- <u>H2020 RISE</u>, entitled "ASTROSTAT-II: Development of novel statistical tools for the analysis of astronomical data", (P.I.: A. Zezas, budget: €556,800, duration: 2019 – 2025)
- <u>Interreg</u> Greece-Cyprus GEOSTARS, (P.I.: A. Zezas, budget: €410,000, duration: 2019 – 2023)
- <u>HFRI</u> "Cosmic rays at the highest energies", (P.I.: V. Pavlidou, budget: €199,500, duration: 2020 – 2023)
- <u>HFRI</u> "European Pulsar Interior Composition Survey", (P.I.: I. Antoniadis, budget: €194,400, duration: 2020 – 2023)
- FORTH Synergy Grant "Reconstructing the Magnetic field of the Milky way via Astrophysical Techniques and Numerical Simulations", (P.I.: V. Pavlidou, budget: €80,000, duration: 2020 – 2023)
- <u>H2020 INFRAIA</u>, entitled "Opticon-Radionet Pilot", (Local contact: V. Charmandaris, budget: €40,000, duration: 2021 – 2025)
- <u>ERASMUS+</u>, entitled "Large Scientific Infrastructures enriching online and digital Learning", (Local contact: V. Charmandaris, budget: €53,300, duration: 2021 – 2023)
- <u>HFRI</u> "Magnetized galaxies through cosmic time: Simulating the galactic magnetic field across scales and epochs", (P.I.: E. Ntormousi, budget: €194,400, duration: 2021 – 2023)
- <u>HFRI</u> "Discovery Space - Creating an innovative network for teaching astronomy to K-12 via remote access of the telescopes at Skinakas Observatory", (P.I.: V. Charmandaris, budget: €94,500, duration: 2021 – 2023)
- <u>HFRI</u> PhD fellowship "Reconstructing the Magnetic Field of the Milky Way via Astrophysical Techniques and Numerical Simulations", (Fellow.: A. Tsouros, budget: €29,700, duration: 2021 – 2024)
- FORTH Synergy Grant "Computational Intelligence for Multimodal Astrophysical Tomography", (P.I.: K. Tassis, budget: €73,600, duration: 2021 – 2023)
- <u>ERC Starting Grant</u> "SMILE", entitled "Search for Milli-lenses to discriminate between dark matter models", (P.I.: C. Casadio, budget: €1,486,000, duration: 2022 – 2027)
- <u>HFRI</u> "The Extended Interstellar Medium of Extreme Galaxies (XTREME)", (P.I.: T. Diaz Santos, budget: €199,840, duration: 2022 – 2026)
- <u>Committee "Greece 2021"</u>, in support of the project "A new 1.0m optical telescope at Skinakas Observatory" (P.I.: V. Charmandaris, budget: $410,000, duration: 2022 – 2024)

Moreover, the following grants were awarded in 2022 but they will commence in 2023:

- <u>HORIZON-INFRA-DEV</u> "ARGOS", entitled Designing a next-generation radio facility for multi-messenger astronomy", (P.I.: J. Antoniadis, budget: €3,000,000, duration: 2023 – 2025)
- DIGITAL-SIMPLE, "HellasQCI", entitled "Deploying advanced national QCI systems and networks in Greece", (P.I.: V. Charmandaris, budget: €39,600, duration: 2023 – 2025)
- ESA/EUC-PECS2021-01, entitled "CYprus models for Galaxies and their NUclear Spectra (CYGNUS+)", (P.I.: T. Diaz Santos, budget: €40,500, duration: 2023 – 2024)
- ESA/AO 1-11157/22, entitled "Skinakas Observatory upgrade as an Optical Ground Station", (P.I.: P. Reig, budget: €177,200, duration: 2023 – 2024)

8. INSTITUTIONAL COLLABORATIONS

Members of IA have established active long term scientific collaborations, funded by common research proposals and/or supported by institutional MoUs, with the following universities and research institutes:

- GREECE
  - National Observatory of Athens, Athens
  - University of Athens, Dept. of Physics, Athens
  - University of Piraeus

- INTERNATIONAL
  - California Institute of Technology, Pasadena, CA, USA
  - Cambridge University, Institute of Astronomy, Cambridge, UK
  - CEA/Saclay, Service d'Astrophysique, Paris, France
  - Astronomical Institute of the Czech Academy of Sciences, Czech Republic
  - European Southern Observatory, Garching, Germany
  - Geneva Observatory, Geneva, Switzerland
  - Harvard-Smithsonian Center for Astrophysics, Cambridge, MA, USA
  - Imperial College, London, UK
  - Max-Planck-Institut für Extraterrestrische Physik, Garching, Germany
  - Max-Planck-Institut für Radioastronomie, Bonn, Germany
  - NASA/Jet Propulsion Laboratory, Pasadena, CA USA
  - Nicolaus Copernicus Astronomical Center, Warsaw & Torun, Poland
  - Northwestern University, Evanston, IL, USA
  - South African Astronomical Observatories, Sutherland, South Africa
  - Universidad Diego Portales, Santiago, Chile
  - University of California, Davis, Davis, CA, USA
  - University of Valencia, Valencia, Spain

Our polarimetric projects with colleagues at the Institute of Astronomy at Cambridge University are partially supported by The Gianna Angelopoulos Programme for Science Technology and Innovation (GAPSTI) and in particular its "Impact for Greece" initiatives

9. Committees and Service

During the 2022 calendar year period covered by this report, members of the IA served in a number of national and international committees. Specifically:

Dr. J. Antoniadis is a member of the FORTH Gender Equality and Diversity Committee (since 2021), member of the Consortium Board of the Einstein Telescope, coordinator of the Greek Node and Council Board Member of the European Consortium for Astro-pArticle Theory and member of the ORP Sky Protection Working Group management Team and PI of the ARGOS Consortium.

Dr. C. Casadio is a member of the European VLBI Network (EVN) Program Committee since the beginning of 2022.

Prof. V. Charmandaris is a member of the Scientific Council of INSU/CNRS since 2019. He is the representative of Greece to the Board of Directors of the scientific journal "Astronomy & Astrophysics" since 2013, becoming a member of the Executive Committee in 2017 and Vice Chair of the Board in 2021. Since 2020 he has been the elected President of the Hellenic Astronomical Society as well as appointed member of the Section "Natural Sciences & Mathematics" of the National Council for Research & Innovation by the minister of research.

Professor N. Kylafis is a member of the Council of the European Astronomical Society since 2018 and is a Treasurer of the Society since 2019.

Professor I. Papadakis is a member of the Greek National Committee for Astronomy since 2018.

Professor I. Papamastorakis is the Scientific Director of the Onassis Foundation Science Lecture Series, that take place every July at FORTH, since 2001.

Professor V. Pavlidou is serving as the Management Panel Chair of the RoboPol Collaboration, as a National Education Coordinator of the International Astronomical Union for Greece, as the Chair of the "Eureka" creative teaching prize committee, and as a member of the Greek National Committee for Astronomy (since 2022).

Dr. P. Reig is the Scientific Operations Manager of Skinakas Observatory.

Professor K. Tassis is serving as the Management Panel Chair of the PASIPHAE Collaboration, as a National Education Coordinator of the International Astronomical Union for Greece, and is a member of the governing council of the Hellenic Astronomical Society.

Professor A. Zezas is serving as a member of the NuSTAR Users Committee as well as a member of the Athena WFI Instrument and Science Ground Segment team. He is also Deputy Chair of the Dept. of Physics of the Univ. of Crete.

10. Conference & Workshop Organization

The following conferences were organized by members of iA in Crete during the period of this report

- "Astronomy Summer School for K to 12 teachers", 3-8 July 2022
- "SynCRETism 2022: Particle physicists dining with Astrophysicists", 20-24 June 2022

- "The Interstellar Medium of Infrared Galaxies, from the Present to Cosmic Noon", Special Session 7, EAS2022 Annual Meeting. Valencia, Spain, 27th June to 1st July 2022.
- "2022 Summer School for Astrostatistics in Crete", 11-15 July 2022
- "The 2022 Onassis Lectures in Physics: Gravitational Waves", 25-29 July 2022
- "Alvio@80: Conference in honor of Alvio Renzini", 5-20 September 2022
- "Lensing Odyssey 2022", 18-23 September 2022
- "European Pulsar Timing Array Annual Meeting", 19-23 September 2022
- IAU Symposium: The multimessenger chakra of blazar jets, Kathmandu, Nepal, 5-9 December 2022

In 2019 IA established the "Nick Kylafis Lectureship" in order to honor Nick Kylafis, Professor Emeritus at the Dept. of Physics of the Univ. of Crete, on the occasion of his 70th birthday, for his 35 years of scientific contributions and leadership towards the founding and continuous improvement of the astrophysics group at the University of Crete and FORTH. This lifelong commitment has been instrumental in the international recognition of the research activities of the Crete astrophysics group, which eventually led to the creation of the Institute of Astrophysics at FORTH. Under the auspices of the Lectureship, one distinguished theoretical astrophysicist is invited annually at FORTH for a brief visit.

The 2022 "Nick Kylafis Lectureship" was awarded to Prof. Françoise Combes, Chair of Galaxies and Cosmology at College de France and Astronomer, Classe Exceptionnelle, at Observatoire de Paris, France "for her seminal contributions in the field of theoretical astrophysics and cosmology". Prof. Combes visited the Institute of Astrophysics from October 5 to 7, 2022. Her lecture entitled "When black holes impact galaxies".

The formal seminars of IA organized on nearly weekly basis took place on Wednesday, with Dr. J. Antoniadis being the host. The complete program with recorded videos of most talks is available at: https://www.ia.forth.gr/seminars

Moreover, informal journal club talks organized by graduate students take place every Friday, and their schedule is available at: https://www.ia.forth.gr/journal-club

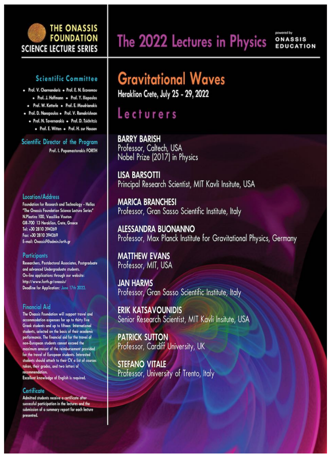
11. Education And Training

The affiliated faculty members of IA also offer undergraduate and graduate astronomy courses as part of their teaching responsibilities in the Dept. of Physics, of the Univ. of Crete. These are in addition to other physics courses they teach. For the 2022 calendar year these were:

- Spring Semester
  - "Astrophysics II" (Galactic and extragalactic astrophysics) (A. Zezas)

- Fall Semester
  - "Astrophysics I" (stellar structure and evolution) - V. Charmandaris
  - "Astrophysics III" (Advanced radiative processes and radiative transfer) - V. Pavlidou

IA-FORTH in collaboration with the Dept. of Physics of the Univ. of Crete and the Society of Physicists of Crete organized the **2nd online School of Astrophysics of Crete**. The school took place during the months of March to May 2022 and it was addressed to high school students from Crete who were interested in obtaining a broad overview of modern astrophysics, as well as understanding the basic principles of physics that determine how our Universe works. A total of 155 students from 40 high schools of Crete attended the 8 online lectures.



Over the past 22 years FORTH also organizes on a yearly basis the "Onassis Foundation Science Lecture Series". The main speakers of these lectures are recipients of the Nobel Prize or of equivalent scientific stature. Support for the lectures is provided by the Onassis Foundation and Scientific Director of the Lectures is Prof. Ioannis Papamastorakis.

The 2022 lectures, which took place in July 25-29, 2022 were on "Gravitational waves". The main Lecturer was Prof. Barry Barish the Linde Professor of Physics Emeritus at Caltech (USA) and 2017 Physics Nobel Prize winner. The lectures of all 9 speakers are available online in the Youtube channel of the Institute

https://www.youtube.com/watch?v=XYw_i9T-Ro0&list=PLtVadXKiv58Ok4L2NbrbTAzBJVjYOjblo

The institute also organized two summer schools under the auspices of LaScil, an Erasmus+ project, and the HFRI D-Space project. The schools aimed towards teachers in the K-12 level who wish to use astronomy as tool to introduce science education to their classrooms. A total of 35 teachers attended the schools which included lecture presentations followed by practical sessions and workshops.

12. Public Outreach

With the suppression of the restrictions related to the COVID-19 pandemic the PO activities of IA-FORTH commenced once again. A total of five open nights at Skinakas Observatory were offered to the public in 2022 with great success as more than 2500 visitors had the opportunity to visit the observatory.

IA-FORTH in collaboration with the Center for Open Online Courses Mathesis of the Crete University Press, continued for a second year its support of the "Eureka Prize" which is addressed to the anxious Secondary Education teachers who experiment with more creative forms of teaching and learning, either in the main body of the curriculum program or outside school hours. More specifically, the prize recognizes educational activities that are inspired by the most attractive and at the same time the most dynamic part of fundamental physics today: Astronomy.

On September 2, 2022 the Institute, in collaboration with the French Institute of Greece and Crete University Press organized a cultural event entitled "The sky in science, music and literature. A tribute to the connection of art and science". Particular emphasis was given on the work of the prolific composer Mikis Theodorakis and internationally known writer Nikos Kazantzakis, who were educated and had spent a large fraction of their life in France.

The main speakers were Dr. David Elbaz (CEA/Saclay, France) and Prof. Anastasia Georgaki (Univ. of Athens, Greece) and Prof. Theodosis Tasios (National Technical Univ. of Athens, Greece). The event included a musical part with Dr. Fiori Anastasia Metallinou (voice) and Christos Ntaoulas (piano).

In the framework of the World Space Week 2022, IA-FORTH in collaboration with the Department of Physics of the University of Crete organized a public outreach event on Friday 7 October 2022.

The event which was also supported by students from the Astronomical Student Group of the University of Crete and astronomy PhD students, offered educational activities hands on experiments on topics related to space sciences to nearly 80 students of all ages.

13. Visitors

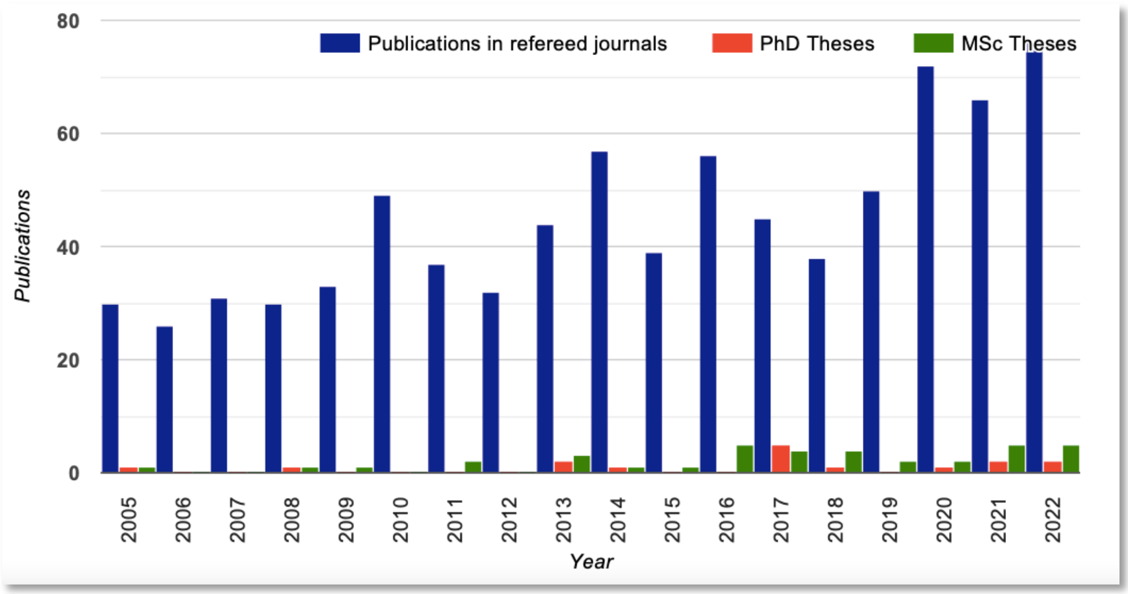
In addition to the IA fellows, Prof. M. Chatzopoulos, Prof. P. Kalas and Prof. A. Readhead, a total of 26 scientists visited IA in 2022 in order to collaborate with our staff and/or give seminars. These researchers were: Dr. Gerd Baumgarten (Univ. of Rostock, Germany) Dr. Tomaso Belloni (INAF - Osservatorio Astronomico di Brera, Italy), Prof. Roger Blanford (Stanford Univ., USA), Prof. Françoise Combes (Obs. de Paris & College de France, France), Prof. Roger Davies (Oxford Univ., UK), Dr. Roberto Decarli (INAF OAS Bologna, Italy), Dr. David Elbaz (CEA/Saclay, France), Prof. Gerhard Haerendel (MPE, Germany), Dr. Michael Janssen (Max Planck Institute for Radioastronomy, Germany), Dr. Maria Kopsacheili (IEEC-CSIC, Spain), Dr. Ioannis Liodakis (Univ. of Turku, Finland), Prof. Apostolos Mastichiadis (Univ. of Athens, Greece), Dr. Valentina Missaglia (Univ. of Torino, Italy), Dr. Fabrizio Nicastro (INAF - Rome Observatory, Italy), Prof. Kallia Petraki (Sorbonne Univ., France), Dr. Divya Rawat (IUCAA, India), Dr. Christoph Schürmann (Univ. of Bonn, Germany), Dr. Sagiv Shiber (Louisiana State Univ., USA), Prof. Joseph Silk (Institut d'Astrophysique de Paris, France), Dr. Jean-Luc Stark (CEA/Saclay, France), Dr. Anton Strigachev (Bulgarian Academy of Sciences, Bulgaria), Prof. Joachim Truemper (MPE, Germany), Dr. Gururaj Wagle (Louisiana State Univ., USA), Prof. Amanda Weinstein (Iowa State Univ., USA), Prof. Peter N. Wilkinson (Univ. of Manchester, UK), Dr. Manos Zapartas (National Obs. of Athens, IAASARS, Greece).

Morover, a total of 7 students (all but one in a PhD or MSc) visited IA-FORTH to collaborate with our scientists. These were: Mr. Vincenzo Petrecca (Univ. of Naples "Federico II", Italy), Mr. Diego Álvarez Ortega (Univ. de Cantabria, Spain), Mr. Yorgos Chatziantoniou (École Polytechnique, France), Mr. Maharana Siddharth (IUCAA, India), Ms. Melissa Fuentealba (Univ. of Chile, Chile), Ms. Danae Maria Droutsa (German School of Athens), Mr. Lee R. Martin (Univ. of Leicester, UK)

Finally, on June 19-21 2022, an extrernal committee appointed by the Gereral Secretariat of Research and Innovation visited IA-FORTH and its facilities and evaluated its performance. The committee consisted of Prof. Chryssa Kouveliotou (George Washington Univ., USA) as Chair, Prof. Ralph Wijers (Univ. of Amsterdam, The Netherlands), Prof. Johan P.U. Fynbo (Copenhagen Univ., Denmark), Prof. Peter Gallagher (Trinity College Dublin, Ireland), and Prof. Karl Reichard (Penn State Univ., USA) as members.

14. Publication Statistics

During 2022 the members of IA in Crete produced **75** publications that appeared in print in refereed journals (according to NASA/ADS). This corresponds to **4** publications per PhD researcher. An additional **5** refereed papers published by IA-FORTH research fellows, who spend only a fraction of their research time visiting Crete. The full publication list is available in the Appendix.



The histogram above shows the number of papers published in refereed journals by members of IA-FORTH since 2019. We also include the publications, from 2005 until 2018, of the Crete Astrophysics Group of FORTH and Univ. of Crete, which preceded the creation of IA-FORTH.

15. Contact

All members of the Institute of Astrophysics - FORTH are housed in a dedicated area of ~600 m^2 on the second floor of the Physics Bldg, on the campus of the University of Crete located 8 km south-west of Heraklion, the largest city on the island of Crete, Greece. The postal address of the IA is:

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More details on how to reach an individual member by phone or e-mail are available in the web page of the IA at: http://www.ia.forth.gr

16. APPENDIX

16.1. SKINAKAS OBSERVATORY

Skinakas Observatory operates as part of a scientific research collaboration between the University of Crete and the Foundation for Research and Technology-Hellas (FORTH). A new MoU, signed between FORTH and the University of Crete in 2018, formally assigns the management of the Observatory to the Director of IA-FORTH, who also acts as the Director of the Observatory. The location of the observatory was chosen in the early 1980's after an intensive search for a site with clear and dark skies. The site of the Observatory is the Skinakas summit of Mount Ida (Psiloritis) at an altitude of 1750 m and a distance of 60 km from Heraklion (on the island of Crete, Greece). Its geographic coordinates are: Longitude 24º 53' 57'' East and Latitude 35º 12' 43'' North.

Facilities on site

The Observatory hosts three telescopes: a Modified Ritchey-Chrétien telescope with a 1.3 m aperture (f/7.6), which became operational in 1995, a 60 cm Cassegrain robotic telescope (f/8) installed in 2006, and the first 30cm Schmidt telescope (f/3.2) of the Observatory which had its first light in 1986.

In 2001, a photovoltaic plant was built, making the Observatory independent of external fossil energy sources. Two emergency generators, rated at 45 and 33 kVA, are capable of supporting all Skinakas observatory operations in the event of power failure. A Guest House, formally named "Ioannis Papamastorakis" in 2019, to honor the founding Director of the Observatory, completes the infrastructure of the observatory. The ground floor of the Guest House accommodates three bed-rooms, two bath-rooms, one storage-room, fully-equipped kitchen and a living-room. The basement is used for storage purposes.

In 2012 the dome hosting the 60 cm telescope had serious damage due to extreme weather which made it inoperable. Funding from an Interreg program between Greece and Cyprus as well as additional support from the University of Crete made it possible to construct a new building and an associated 5.3m dome, built by Baader Planetarium GmbH, in its place. The works commenced in the fall of 2020 and were completed in May 2022. As of summer 2022 the dome hosts again the 60 cm robotic telescope. A new 1.0m robotic optical telescope, which was ordered from ASA Astrosysteme GmbH in September 2022, is expected to be placed in this dome in the spring of 2024.

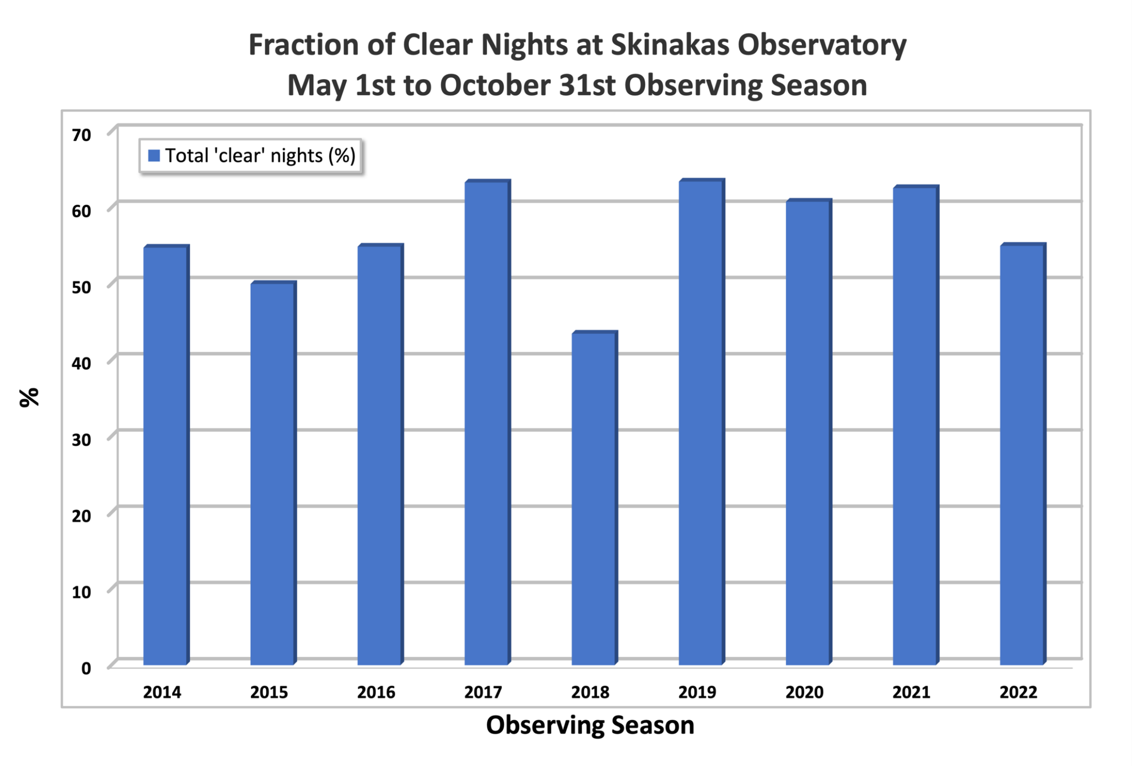
Facilities at sea level

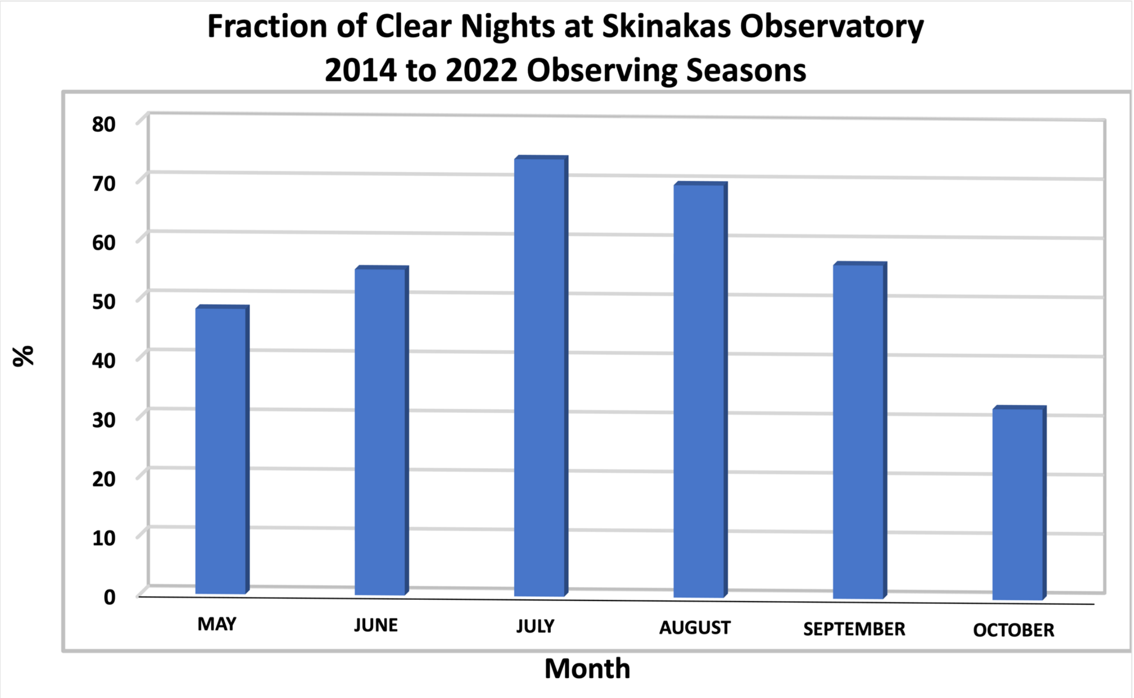
Office space for the staff is located on the premises of the Department of Physics of the University of Crete. An instrumentation lab with an optical table and a computing room are also part of the sea-level facilities. The observatory owns two vehicles used for the transportation of material and personnel. These are a SKODA Rapid (2014) and a TOYOTA HILLUX (2008).

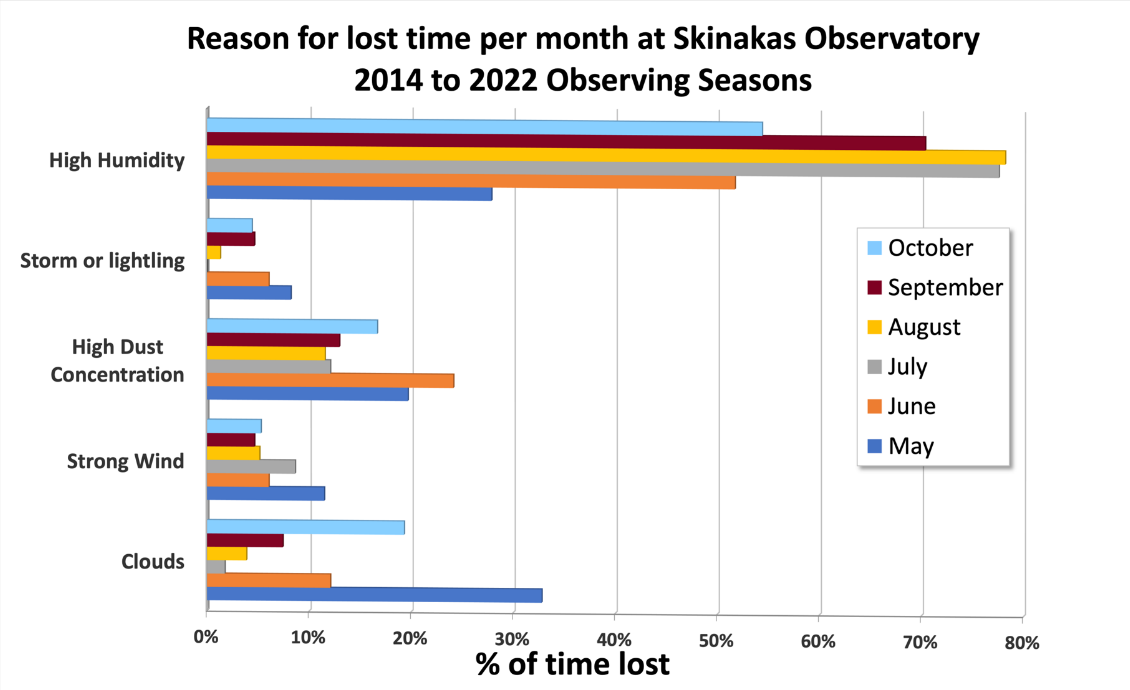
Scientific Operations

Typically, the Observatory operates from late April until early December. The Observatory remains closed for the winter months, mainly because of the cost to keep the road open from snow. However, the founding of IA in 2018 and emerging possibilities to also perform service operations using the telescopes of Skinakas for satellite tracking and/or support ground to space laser telecommunications, will likely increase the operational window of the facility in the coming years.

In the following we present some statistics on the operations of the facility based on the observers logs over the past nine years (2014 to 2022). The average number of nights the Observatory operates per season is 176 with the average full clear nights to be over 60% the past three years. The best months are July and August, with over 70% of the nights being clear. High humidity is the major reason for not observing (~50% of the cases) with clouds and then dust, due to southern winds, being the other two reasons.







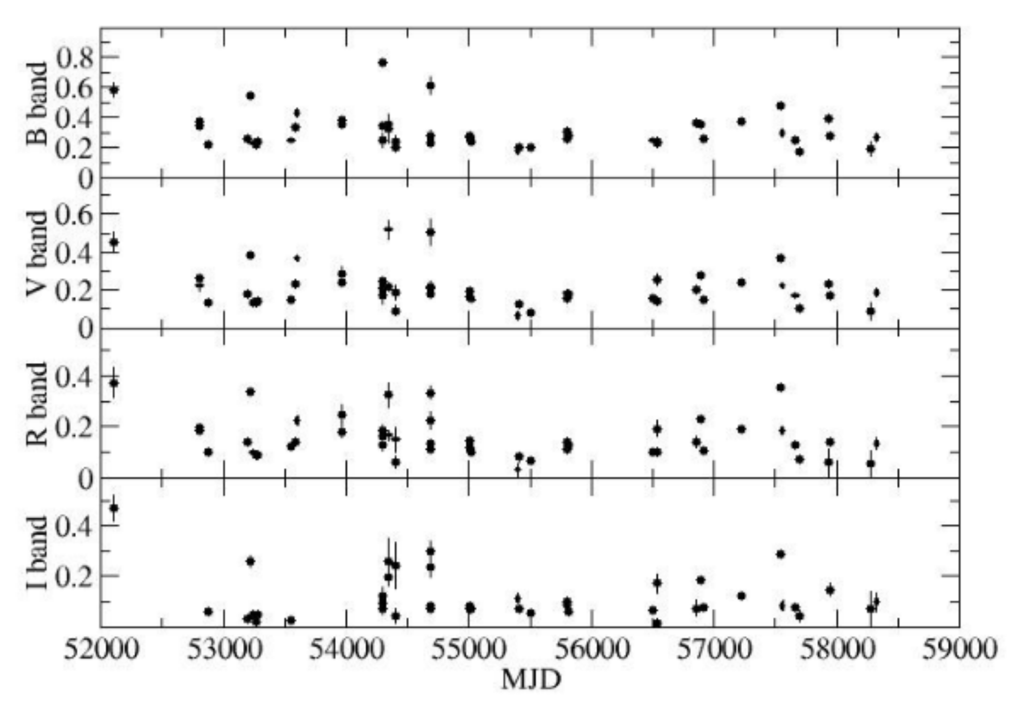
More specifically the reasons the observatory did not operate due to weather were:

- <u>High humidity:</u> It refers to the number of nights during which the dome was closed because the humidity level was higher than the allowed limit of 80%.
- <u>Clouds:</u> These are nights when the clouds prevented normal operation but the humidity was in the allowed range.
- <u>Strong wind:</u> It refers to the number of nights during which the dome was closed because the wind velocity was higher than the operational limit of 70 km/h (or > 50 km/h if pointed directly into the wind).
- <u>High dust concentration</u>: When the dust level was higher than 800 particles per cubic feet.

The number of nights the 1.3m telescope was closed due to technical problems was less than 1%

Atmospheric Extinction

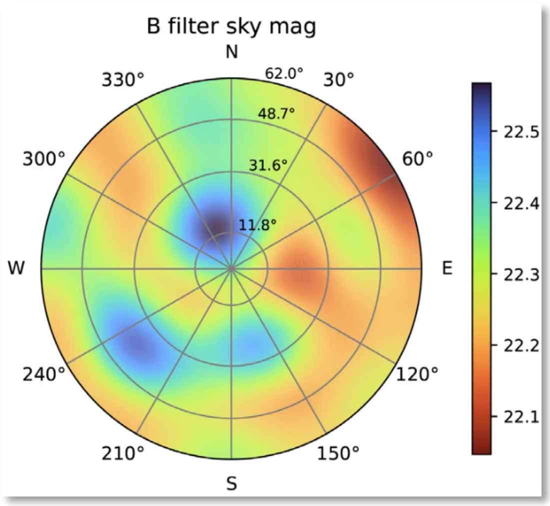
Atmospheric extinction is the astronomical parameter that evaluates sky transparency. Sources causing degradation of the sky transparency are clouds (water vapor) and aerosols (dust particles included). The extinction values and their stability throughout the night are essential for determining the accuracy of astronomical measurements. The nights with low and constant extinction are classified as photometric.

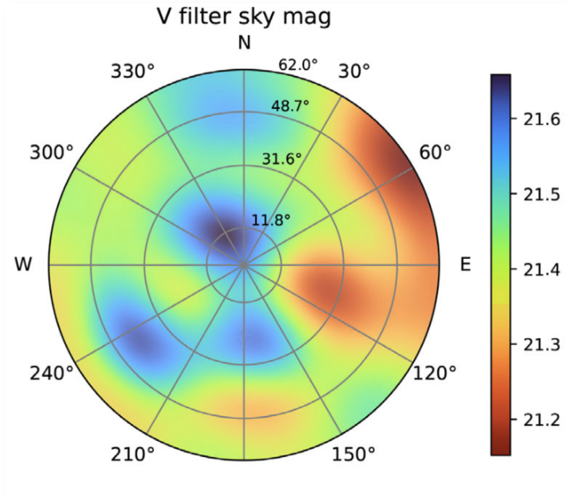


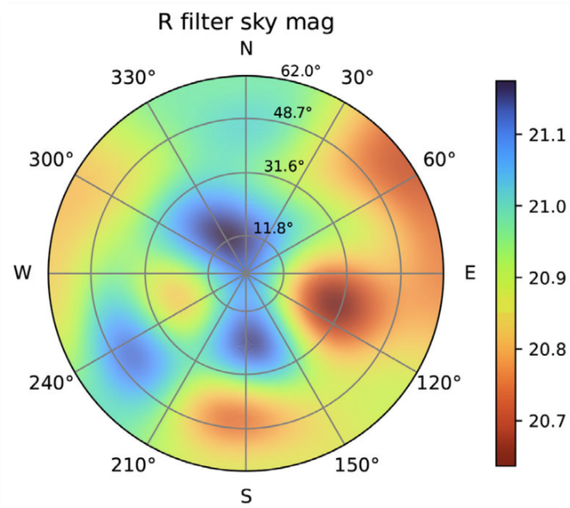
The extinction at the Skinakas Observatory during photometric nights are (in mag/airmass): 0.26 ± 0.06 for B, 0.17 ± 0.03 for V, 0.13 ± 0.04 for R, and 0.09 ± 0.06 for I.

Night Sky Brightness

Night sky BVR brightness observations were conducted during 12 nights from early June to late October 2016 and revealed that Skinakas Observatory is a relative dark site, with the exception of the direction towards the city of Heraklion (North East). The average night sky surface brightness towards zenith was found to be B=22.80±0.10, V=21.92±0.09, R=21.39±0.07 mag/arcsec^2. Comparison with a similar study which was performed in 2008 did not show a statistically significant change. The brightness maps are presented bellow while the full report is available [here.](#)







An older internal report on the night sky spectrum at Skinakas, along with an estimate of the contribution of the light pollution lines to the sky brightness can be found [here](#).

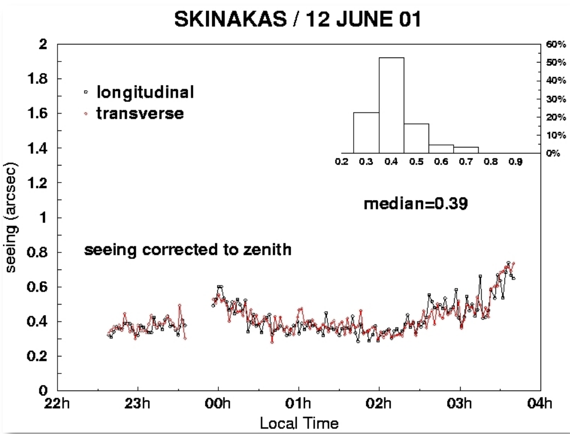
Seeing conditions

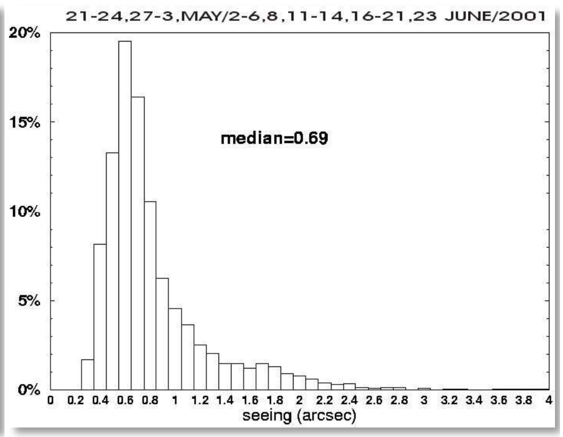
The Skinakas Summit is an excellent site for astronomical observations. As it can be seen in the satellite photo to the right, showing the island of Crete and Africa in yellow at the bottom of the photo, since the winds are typically from the north and the closest land mass to the north is the island of Santorini, some 150km away, the flow of air reaching the Skinakas peak is laminar. Only when there are strong winds from the south, sometimes including dust from the Sahara Desert, there is turbulence.

Image of Crete from the International Space Station taken on 13 Oct. 2019.

Using a two-aperture Differential Image Motion Monitor (DIMM), the seeing over Skinakas was measured in 2000 and 2001. For a total of 45 nights, the median seeing was found to be less than 0.7 arcsec.

Subsequent sporadic measurements over the years confirm that the overall seeing conditions have not changed. Analysis of more recent observations is underway and will become available in the 2023 annual report.





A more detailed analysis on the Skinakas weather conditions is presented in an internal report by Dr. P. Reig and E. Palaiologou and it is available here.

THE 1.3 M TELESCOPE

The optical system of the 1.3 m telescope was manufactured by Karl Zeiss (Germany), and the mechanical parts by DFM Engineering (USA). It has an f/8 focal ratio giving a scale of 0.021 arcsec/μm in direct mode (Table 1). With the use of the focal reducer, the scale is multiplied by 1.87. The telescope works together with an off-axis guiding unit, which provides tracking with an accuracy of 0.2 arcsec.

The main mirror was re-aluminized in 1998, 2004, 2011, and 2019 while some key technical characteristics are presented in the tables bellow:

PRIMARY MIRROR (M1)	
PHYSICAL DIAMETER	1300 (1290) mm
APERTURE	1230 mm
THICKNESS	200 mm
CURVATURE RADIUS	7380 mm
FOCAL LENGTH	3690 mm
CENTRAL HOLE	350 mm
WEIGHT	5700 N

SECONDARY MIRROR (M2)	
PHYSICAL DIAMETER	456 mm
FREE DIAMETER	446 mm
EFFECTIVE (EF) DIAMETER	412 mm
RADIUS OF CURVATURE	-3953 mm
FOCAL LENGTH	-1976 mm
OUTER “EF” DIAMETER	552.5 mm

SYSTEM	
FOCAL LENGTH	9857.0 mm
FOCAL RATIO	7.64
DISTANCE M1 to M2	2453.4 mm

Instrumentation

General overview:

A number of instruments are permanently available on the 1.3 m telescope. These include an auto-guider, three optical CCD cameras with complete filter sets, a long slit optical spectrograph providing low/intermediate resolution (R=1000-8000), a near-IR wide field camera, and an optical polarimeter. All the digital cameras and the optical elements associated with them are installed and attached to the telescope through the Guiding and Acquisition Module (GAM). Therefore, Skinakas offers the observers the possibility to carry out intermediate-low dispersion spectroscopy, wide-field imaging, and polarimetry. A movable diagonal mirror and the fast-cooling of the CCD cameras allow the observer to switch among the various instrumental configurations in a very short time (~30 minutes). However, changing to the near-IR camera requires daytime engineering work. When the near-IR camera is mounted, no other instrument option is available.

The Tables below summarize the observing capabilities of the 1.3 m telescope.

Optical Imaging				
CCD	**Size (pixel)**	**Scale ("/pixel)**	**Filters**	**Field of view (')**
Andor iKon-L 936	2048x2048	0.28	Jonhson Stromgren interference	9.5 x 9.5

Polarimetry				
CCD	**Size (pixel)**	**Scale (''/pixel)**	**Filters**	**Field of view (')**
Robopol ANDOR DW436	2048x2048	0.435	B, V, R, I SDSS r', g', i'	13 x 13

Spectroscopy					
CCD	**Size (pixel)**	**Scale (''/pixel)**	**Wavelength Range (Å)**	**Resolution**	**Slit width('')**
Andor iKon-L 936	2048x2048	0.529	3500 - 10000	1000 < R R< 8000	2, 4, 13

Infrared Imaging				
Instrument/focal plane array	**Size (pixel)**	**Scale (''/pixel)**	**Filters**	**Field of view (')**
Rockwell Science Center, Inc. HgCdTe	1024x1024	0.38	Broad (J,H,K) Fe,Br-γ,CO,H	6.5 x 6.5

CCD cameras

The observatory has four ANDOR 2048x2048 pixels CCDs with 13.5 μm pixel size. All four CCDs use thermoelectric water cooling (Peltier effect) to achieve an operational temperature of between -70 to -90ºC. Three CCD are used for direct imaging (*Andor iKon L-936, #CCD-20241*), spectroscopy (*Andor iKon L-936, #CCD-20240*), and polarimetry (*Andor DW436*) on the 1.3m and the fourth on the 30cm telescope (*Andor DZ436*).

With the optical characteristics of the 1.3 m telescope, these values translate into a field of view of 9.5 arcmin x 9.5 arcmin for direct imaging, 13 arcmin x 13 arcmin in the polarimetry mode, and 18 arcmin x 18 arcmin for spectroscopy.

In addition, an SBIG auxiliary CCD with 1536x1024 pixels and 9 μm pixel size is used in the auto-guider.

A near-IR camera, manufactured by Fraunhofer IOF was commissioned in 2006. It is an f/7.7 Offner design with a Rockwell Hawaii Array of 1024x1024 and pixel size 18.5μm, providing an image resolution of 0.38arcsecs per pixel, and a 6.5 arcmin x 6.5 arcmin field of view. It covers the spectral range between 1 and 2.4μm. The near-IR camera has not been used during the period of the report.

Filters

The observers can choose among a full set of narrow and broad-band photometric filters. The broad-band filters available are the Johnson-Couisins U, B, V, R, I and the SDSS u', g', r', i', z'. The narrow-band filters are the full Strömgren set u, v, b, y, Hβ(narrow), Hβ(wide) and more than 15 interference filters. In the infrared, the observatory offers three broad-band filters J, H, and K, and five narrow-band filters: FeII (16440 Å), H_2 (21220 Å), H_2 (21440 Å), Br-γ (21660 Å), and CO (22950 Å). The Tables below gives the list of filters together with some technical information.

Standard Johnson-Cousins filters			
Type	**Central Wavelength (Å)**	**FWHM (Å)**	**Peak Transmission (%)**
U	3640	320	63
B	4350	980	72
V	5380	980	88
R	6300	1180	82
I	8940	3370	96

List of Strömgren filters			
Type	**Central Wavelength (Å)**	**FWHM (Å)**	**Peak Transmission (%)**
u	3500	330	57
v	4110	170	67
b	4685	183	83
y	5493	235	84
Hβ wide	4890	145	80
Hβ narrow	4869	32	80

Near-IR Filter Characteristics	
Type	**Central Wavelength / FWHM**
FeII	1644 nm /17 nm
H_2	2122 nm /22 nm
H_2	2144 nm /22 nm
Br-γ	2166 nm /22 nm
CO	2295 nm /231 nm
J-band	1250 nm /160 nm
H-band	1635 nm /290 nm
Ks-band	2150 nm /320 nm

List of interference filters				
Type	**Central Wavelength (Å)**	**FWHM (Å)**	**Peak Trans. (%)**	**Refraction index**
[OII]3727	3727	25	60	2
[OIII]4363	4363	10	35	2
HeII4686	4687	20	46	2
Hβ4861	4864	28	65	2.1
[OIII]5007	5010	28	63	2.1
[OIII]5007	5007 (April 2013)	25	52	2.1
[NII]5755	5755	10	52	2
HeI5876	5877	20	54	2
Hα6563	6563	10	52	2
Hα+[NII]	6575	20	48	2
Hα+[NII]	6570	75	80	2.1
[NII]	6584	20	60	2
[SII]6716	6716	10	47	2
[SII]6720	6720	27	80	2.1
[SII]6731	6731	10	57	2
[SII]6735	6735	30	48	2
[SIII]	9069	20	70	2
Continuum	6096	134	-	-

Spectrograph

For spectroscopic observations, the focal reducer is used as a slit spectrograph with slit widths 80, 160, 320, and 640 μm. A range of grating results in dispersion from 530 Å/mm to 25 Å/mm.

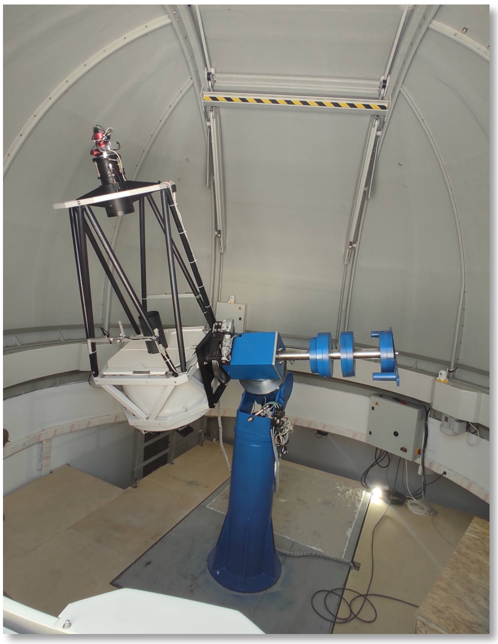
Gratings for the Focal Reducer				
Grating (lines/mm)	**Blaze Wavelength (nm)**	**Wavelength in 1st order for max. intensity**	**Dispersion (Å/mm)**	**Mounted**
3600	250	231	25.41	No
2400	430	397.3	37.8	Yes
1302	550	508.1	70.44	Yes
1302	480	443.5	70.27	Yes
1200	700	646.7	76.39	Yes
651	530	489.7	137.6	Yes
600	750	692.9	150.8	Yes
600	500	461.9	148.4	Yes
325.5	550	508.1	269.0	No
325.5	430	397.3	267.3	Yes
162.75	500	461.9	529.1	No

Polarimeter

RoboPol is a specialized photopolarimeter designed specifically for the 1.3 m telescope at Skinakas and commissioned in the spring of 2013. It was conceived, designed, and developed by the RoboPol Collaboration, which is comprised of the University of Crete and the Foundation for Research and Technology – Hellas in Greece, the California Institute of Technology in the United States, the Max-Planck Institute for Radioastronomy in Bonn, Germany, the Nicolaus Copernicus University in Poland, and the Inter-University Centre for Astronomy and Astrophysics, in Pune, India.

RoboPol was designed with high observing efficiency and automated operation as prime goals. It uses no moving parts other than the filter wheel. Instead, a combination of half-wave plates and Wollaston prisms are used to separate photons with orthogonal linear polarizations retard them, and simultaneously produce four images on the CCD detector for each source in the focal plane. The photon counts in each "spot" are used to calculate the Stokes parameters of linear polarization. This novel, 4-channel design eliminates the need for multiple exposures with different half-wave plate positions, thus avoiding unmeasurable, dominant systematic errors due to sky changes between measurements. A mask in the telescope focal plane prevents unwanted photons from the nearby sky and sources from overlapping with the central target on the CCD, further increasing the sensitivity of the instrument. Its large, 13’x13’ field of view allows relative photometry using standard catalogs and the polarimetric mapping of large regions in the sky.

THE 0.6 M TELESCOPE



The 60 cm Cassegrain telescope, called Ganymede, following an agreement between the Univ. of Crete and the Univ. of Tübingen, was installed at the Observatory in 2006, using an old existing dome. It operated until 2012 when the dome was destroyed by adverse weather conditions. As mentioned in Section 4.1 of this report, the new building and 5.3m Baader dome where the telescope will be housed again was completed in May 2022. The optics and electronics of the telescope were upgraded in 2021 and in June 2022 it commenced again normal operations.

The telescope characteristics are: Aperture of primary mirror: 60cm, Field-of-View: ~0.33 deg x 0.33 deg (~20 arcmin x20 arcmin for a 2048x2048 CCD camera. Primary and secondary mirror’s reflectivity: 95% at 550 nm: QE of CCD: 90% between 400-900 nm. Pixel scale: 0.8 ''/pixel. Sensor type (CCD, APS/CMOS, other): ST10XME SBIG.

The telescope is also equipped with a full suite of the standard optical filters.

We anticipate that in addition to standard imaging/monitoring science projects the telescope will be used for EU-SST projects in the future. Its absolute pointing is better than 1 arcmin and the relative (post processing) better than 1 arcsec. Slew rate for changing the pointing direction is 4º/sec and the pointing stability ~1arcsec in 4 hr.

THE 0.3 M TELESCOPE

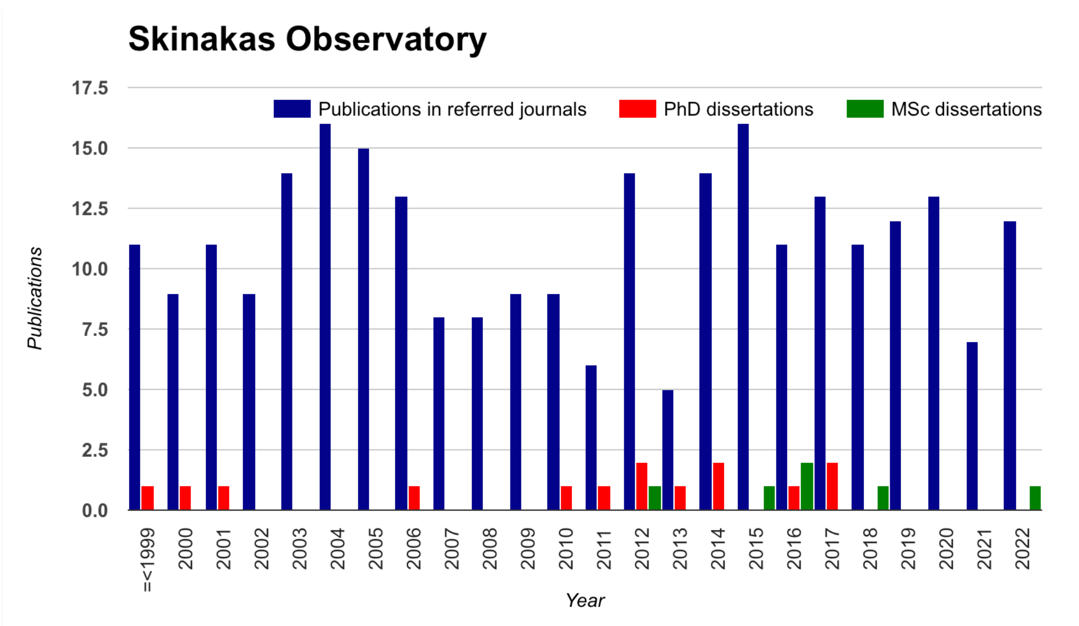
The 30 cm Schmidt-Cassegrain telescope (f/3.2) was the first one installed on Skinakas Observatory in 1986 and it was equipped with the first CCD camera ever used for astronomy in Greece.

It has a computer controlled German mount built by Eckard Alt and an off-axis guiding system. It provides a high-quality wide field of view and has been used extensively in studies requiring monitoring and supernovae remnants as well as for public outreach activities. In its current configuration the telescope is equipped with an ANDOR DZ 436 CCD with a 2048 x 2048 chip and 13.5 μm pixel size, resulting in pixel scale of 3 arcsec and a field of view of 1.7 square degrees.

The telescope is used in direct imaging mode. A six-slot filter wheel allows the observations in six different photometric bands. It should be noted that same filters available for the 1.3 m telescope can be used in the 0.3 m telescope. It was used to produce a large fraction of the images of extended objects presented in the book «Αστεροσκοπείο Σκίνακα: Με θέα το Σύμπαν» (“Skinakas Observatory: A view to the Universe”) edited by Crete University Press in 2010. A new version of the book, this time is English, is currently in production, as part of the Interreg project “GEOSTARS”.

Skinakas Observatory Publications

Until the end of 2022 observations from the telescopes at Skinakas Observatory have resulted in a total of 265 publications in refereed journals, which have received ~7200 citations. In addition, 15 PhD and 6 MSc dissertations have been produced using data from Skinakas Observatory. A histogram of those publications as a function of time, follows:



A total of **12 refereed papers** using data from Skinakas Observatory, **including one in Nature and 1 in Science**, were published in 2022.

A few select publications using Skinakas data, which have been well cited, follow:

- "Full orbital solution for the binary system in the northern Galactic disc microlensing event Gaia16aye", Wyrzykowski, Ł., Mróz, P., Rybicki, K. A. et al. **2020**, Astronomy & Astrophysics, 633, 98
- "RoboPol: a four-channel optical imaging polarimeter", Ramaprakash, A. N.; Rajarshi, C. V.; Das, H.K., **2019**, MNRAS, 485, 2355
- "RoboPol: optical polarization-plane rotations and flaring activity in blazars", Blinov, D., Pavlidou, V., Papadakis, I.E. et al. **2016**, MNRAS, 457, 2252
- "Be/X-ray Binaries", P. Reig, **2011**, Astrophysics & Space Sciences, 332, 1
- "Very fast optical flaring from a possible new Galactic magnetar" Stefanescu, A., Kanbach, G., Słowikowska, A. et al., **2008** Nature, 455, 503
- "Correlated fast X-ray and optical variability in the black-hole candidate XTE J1118+480", Kanbach, G., Straubmeier, C., Spruit, H. C., Belloni, T., **2001**, Nature, Volume 414, Issue 6860, 180
- "OPTIMA: A Photon Counting High-Speed Photometer", Straubmeier, C., Kanbach, G., Schrey, F., **2001**, Experimental Astronomy, 11, 157
- "Are spiral galaxies optically thin or thick?", Xilouris, E.M., Byun, Y.I., Kylafis, N.D., Paleologou, E.V., Papamastorakis, J., **1999**, A&A, 344, 868

A complete list of all publications from Skinakas Observatory is available at:

https://skinakas.physics.uoc.gr/en/index.php/research

16.2. The 2022 Refereed Publication List

The **75** refereed publications of the members of IA in Crete during 2022, as well the **5** of the IA-FORTH research fellows are presented bellow:

1. Acciari, V. A., Aniello, T., Ansoldi, S., Antonelli, L. A., Arbet Engels, A., Artero, M., Asano, K., Baack, D., Babić, A., Baquero, A., Barres de Almeida, U., Barrio, J. A., Batković, I., Becerra González, J., Bednarek, W., Bernardini, E., Bernardos, M., Berti, A., Besenrieder, J., Bhattacharyya, W., Bigongiari, C., Biland, A., Blanch, O., Bökenkamp, H., Bonnoli, G., Bošnjak, Ž., Busetto, G., Carosi, R., Ceribella, G., Cerruti, M., Chai, Y., Chilingarian, A., Cikota, S., Colombo, E., Contreras, J. L., Cortina, J., Covino, S., D'Amico, G., D'Elia, V., Vela, P. D., Dazzi, F., De Angelis, A., De Lotto, B., Del Popolo, A., Delfino, M., Delgado, J., Mendez, C. D., Depaoli, D., Di Pierro, F., Di Venere, L., Do Souto Espiñeira, E., Dominis Prester, D., Donini, A., Dorner, D., Doro, M., Elsaesser, D., Fallah Ramazani, V., Fariña, L., Fattorini, A., Font, L., Fruck, C., Fukami, S., Fukazawa, Y., García López, R. J., Garczarczyk, M., Gasparyan, S., Gaug, M., Giglietto, N., Giordano, F., Gliwny, P., Godinović, N., Green, J. G., Green, D., Hadasch, D., Hahn, A., Hassan, T., Heckmann, L., Herrera, J., Hoang, J., Hrupec, D., Hütten, M., Inada, T., Iotov, R., Ishio, K., Iwamura, Y., Jiménez Martínez, I., Jormanainen, J., Jouvin, L., Kerszberg, D., Kobayashi, Y., Kubo, H., Kushida, J., Lamastra, A., Lelas, D., Leone, F., Lindfors, E., Linhoff, L., Lombardi, S., Longo, F., López-Coto, R., López-Moya, M., López-Oramas, A., Loporchio, S., Machado de Oliveira Fraga, B., Maggio, C., Majumdar, P., Makariev, M., Mallamaci, M., Maneva, G., Manganaro, M., Mannheim, K., Mariotti, M., Martínez, M., Mas Aguilar, A., Mazin, D., Menchiari, S., Mender, S., Mićanović, S., Miceli, D., Miener, T., Miranda, J. M., Mirzoyan, R., Molina, E., Moralejo, A., Morcuende, D., Moreno, V., Moretti, E., Nakamori, T., Nava, L., Neustroev, V., Nievas Rosillo, M., Nigro, C., Nilsson, K., Nishijima, K., Noda, K., Nozaki, S., Ohtani, Y., Oka, T., Otero-Santos, J., Paiano, S., Palatiello, M., Paneque, D., Paoletti, R., Paredes, J. M., Pavletić, L., Peñil, P., Persic, M., Pihet, M., Prada Moroni, P. G., Prandini, E., Priyadarshi, C., Puljak, I., Rhode, W., Ribó, M., Rico, J., Righi, C., Rugliancich, A., Sahakyan, N., Saito, T., Sakurai, S., Satalecka, K., Saturni, F. G., Schleicher, B., Schmidt, K., Schmuckermaier, F., Schweizer, T., Sitarek, J., Šnidarić, I., Sobczynska, D., Spolon, A., Stamerra, A., Strišković, J., Strom, D., Strzys, M., Suda, Y., Surić, T., Takahashi, M., Takeishi, R., Tavecchio, F., Temnikov, P., Terzić, T., Teshima, M., Tosti, L., Truzzi, S., Tutone, A., Ubach, S., van Scherpenberg, J., Vanzo, G., Vazquez Acosta, M., Ventura, S., Verguilov, V., Viale, I., Vigorito, C. F., Vitale, V., Vovk, I., Will, M., Wunderlich, C., Yamamoto, T., Zarić, D., Hodges, M., Hovatta, T., Kiehlmann, S., Liodakis, I., Max-Moerbeck, W., Pearson, T. J., Readhead, A. C. S., Reeves, R. A., Lähteenmäki, A., Tornikoski, M., Tammi, J., D'Ammando, F., & Marchini, A., "Investigating the Blazar TXS 0506+056 through Sharp Multiwavelength Eyes During 2017-2019.", 2022, The Astrophysical Journal, 927, 197.
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A list of additional 5 refereed papers published by IA-FORTH research fellows, who spend only a fraction of their research time visiting the Institute in Crete.

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