FORTH
INSTITUTE OF ASTROPHYSICS

Institute of Astrophysics
FORTH
2021 Annual Report

www.ia.forth.gr

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1. Introduction

The present document summarizes the activities of the members of the Institute of Astrophysics (IA) at the Foundation for Research and Technology – Hellas (FORTH), during the 2021 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 this period, members of the IA engaged in active research in the fields of Theoretical and Observational Astrophysics. Six of the affiliated faculty (including one emeritus professor) of the Department of Physics at the University of Crete also taught undergraduate and graduate courses. Their research has been funded by national and international research grants, and in 2021 resulted in **66** papers published in refereed journals, that is **3.3** papers per PhD researcher per year.

In addition, new competitive grants of ~**790,000 Euros** were awarded to members of the Institute. Significant efforts were also devoted to the operation and improvement of the infrastructure and hardware at Skinakas Observatory.

This document was prepared in February 2022, 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.

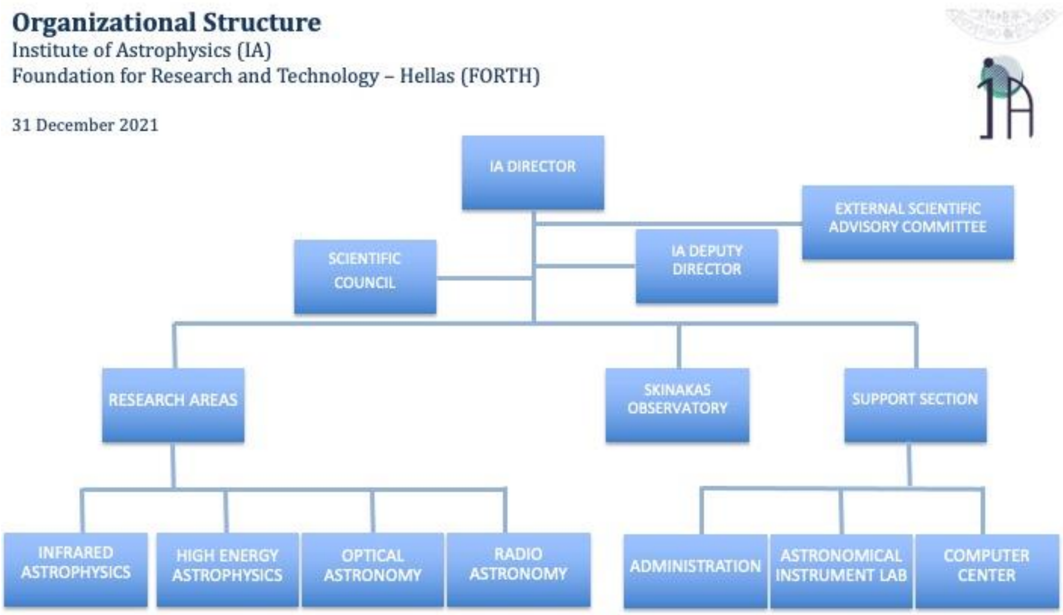
The current Scientific Council of the Institute (SCI) was formed on April 21, 2021 and it consists of:

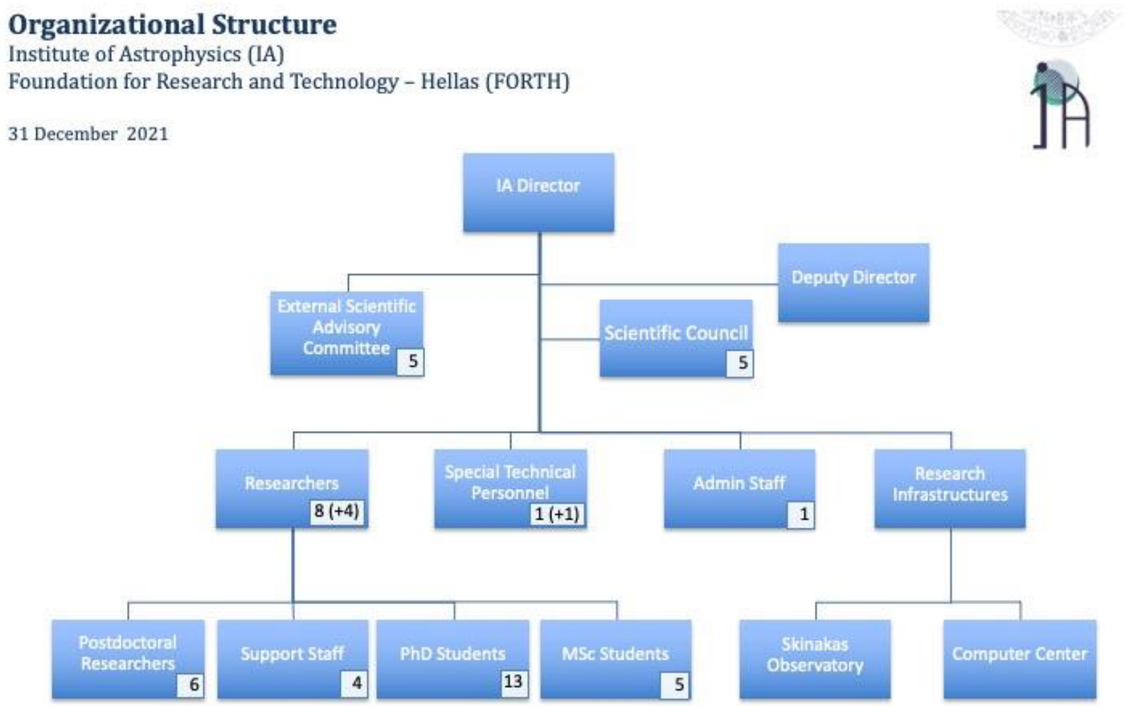
- Ioannis (John) Antoniadis
- Tanio Diaz Santos
- Iossif Papadakis
- Pablo Reig, Chair
- Andreas Zezas

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, 2021, the core personnel of IA consisted of 3 permanent researchers and 5 affiliated faculty from the Department of

Physics of the University of Crete. The personnel also include 2 professors emeriti and 10 post-doctoral researchers, as well as 7 support staff. In addition, 13 PhD students, 9 MSc students, and 11 undergraduate students were trained by members of IA. To the above local members, we should add 4 Affiliated Research Fellows and an Honorary Fellow 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)

Three (3) Permanent Researchers
- Ioannis (John) Antoniadis (Associate Researcher / Researcher C)
- Tanio Diaz Santos (Associate Researcher / Researcher C)
- Pablo Reig (Research Director / Researcher A)

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

Ten (10) postdoctoral researchers in non-tenure track positions:
- Dr. David Aguilera Dena (since February 2021)
- Dr. Dmitry Blinov
- Dr. Carolina Casadio
- Dr. Sebastian Kiehlmann
- Dr. Konstantinos Kouroumpatzakis (since March 2021)
- Dr. Ioanna Leonidaki
- Dr. Grigoris Maravelias
- Dr. Eva Ntormousi (since July 2021)
- Dr. Georgios Pavlou (since November 2021)
- Dr. Vincent Pelgrims

Five (5) Support Staff on soft money:
- Mr. Giannis Kapetanakis - IT support
- Mr. Vangelis Pantoulas - Engineering support
- Mr. Stylianos Roumpakis - Pipeline software support (since Jun. 2021)
- 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)

Thirteen (13) PhD students:

- Mr. Savvas Chanlaridis (with I. Antoniadis) - since Jan. 2021
- Mr. Román Fernández Aranda (with T. Diaz Santos) - since Feb. 2021
- Ms. Maria Kopsacheili (with A. Zezas) - since 2016
- Ms. Anna Konstantinou (with K. Tassis & E. Ntormousi) - since Jul. 2021
- Mr. Georgios Korkidis (with V. Pavlidou) - since 2020
- Mr. Ioannis Kypriotakis (with K. Tassis) - since 2017
- Mr. Elias Kyritsis (with A. Zezas) - since 2020
- 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 2018
- Mr. Raphael Skalidis (with K. Tassis) - since 2018
- Mr. Alexandros Tsouros (with V. Pavlidou) - since 2020

Nine (9) MSc students:

- Mr. Charalampos Daoutis (with A. Zezas) - since Sep. 2021
- Mr. Konstantinos Droudakis (with A. Zezas) - since Sep. 2021
- Mr. Charalampos Psarakis (with P. Reig) - since Sep. 2021
- Ms. Katia Gkimisi (with K. Tassis) - since Sep. 2020
- Ms. Lydia Markopoulioti (with T. Diaz Santos) - since Sep. 2020
- Ms. Anna Konstantinou (with K. Tassis) - Sep. 2019 to Mar. 2021
- Mr. Charalampos Frantzeskos (with A. Zezas) – Sep. 2020 to Nov. 2021
- Mr. Angelos Karakonstantakis (with I. Papadakis) - Sep. 2020 to Nov. 2021
- Mr. Giorgos Savathrakis (with A. Zezas) - Sep. 2020 to Nov. 2021

Eleven (11) Undergraduate students:

- Ms. Foteini Bouzelou (with K. Tassis)
- Mr. Margaritis Chatzis (with N. Kylafis)
- Mr. Charalampos Daoutis (with A. Zezas)
- Mr. Konstantinos Droudakis (with A. Zezas)
- Ms. Rea Kontouli (with E. Ntormousi)
- Mr. Nikolaos Loudas (with N. Kylafis)
- Ms. Electra Manoura (with I. Papadakis)
- Mr. Marios Papoutsis (with I. Papadakis)
- Mr. Harabalos Psarakis (with P. Reig)
- Mr. Konstantinos Psarras (with A. Zezas)
- Mr. Theodoros Tsantirakis (with A. Zezas)

3.2. Personnel Changes and Notable Events

During 2021, the following personnel changes took place:

Dr. Ioannis (John) Antoniadis, who had been awarded an HFRI/SNF excellence grant in 2020 and was also elected in a tenure track position at IA-FORTH, commenced his appointment at the level of Associate Researcher (aka Researcher C) in March 2022.

Dr. Eva Ntormousi returned to IA-FORTH as an HFRI postdoctoral fellow in July 2021. Three more postdoctoral researchers joined IA: in February 2021, Dr. David Aguilera Dena joined the group of Dr. Antoniadis, Dr. Konstantinos Kouroumpatzakis, who had graduated, joined the group of Prof. Zezas in March 2021, and Dr. Georgios Pavlou joined the group of Prof. Pavlidou in November 2021.

Three PhD students joined the Institute during the year: Mr. Savvas Chanlaridis (with I. Antoniadis), Mr. Román Fernández Aranda (with T. Diaz Santos), Ms. Anna Konstantinou (with K. Tassis & E. Ntormousi). In addition, Ms. Katerina Papadaki joined ICS-FORTH in a common project with IA co-supervised by G. Tzagkarakis and K. Tassis. Three MSc students also joined IA in the fall of 2021: Mr. Charalampos Daoutis and Mr. Konstantinos Droudakis (both with A. Zezas) and Mr. Charalampos Psarakis (with P. Reig).

During 2021, four (4) MSc students defended their thesis:

- Charalampos Frantzeskos - thesis title: "Classification of X-ray binary systems using the machine learning methods of random forest and artificial neural networks" - supervisor A. Zezas.
- Angelos Karakonstantakis - thesis title "Study of long-term X-ray time lags in AGN" - supervisor I. Papadakis
- Giorgos Savathrakis - thesis title: "Identification of clusters in observational and mock galaxy catalogs" - supervisor A. Zezas.
- Anna Konstantinou - thesis title: "Study of the impact of the interstellar cloud shapes on CMB polarization foregrounds" - supervisor K. Tassis.

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

A new 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.

Only the 1.3 m telescope was operating full-time at Skinakas Observatory in 2021. This telescope is a modified Ritchey-Chrétien telescope with a 1.3 m aperture (focal ratio of f/7.6), which was built by DFM Engineering and Zeiss and became operational in 1995. The 30 cm telescope (focal ratio f/3.2) was also operating, but for a limited time period, while the 60 cm telescope (focal ratio f/8 to f/3) was being upgraded in Germany since its new dome will be completed in 2022 (see below).

The RoboPol[2] polarimeter, first established in 2013, continued nominal operations.

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 some delays in construction and delivering of its optics. The commissioning is scheduled for the end of 2022.

The major infrastructure activity at the Observatory was the continuation of the construction of a new building with a 5.3m dome which will house the 60cm robotic telescope. At the end of November 2021, when the observatory closed for the winter, the new building and its dome, provided by Baader Planetarium GmbH, were in place with only minor details (such as the completion of electrical connectivity and cosmetic details) were left to be finished by May 2022.

Moreover, funding was secured for two major projects, which are expected to transform the operational capabilities of the facility in the near future.

One is related to the construction of a new visitor center, which includes an 85-seat lecture room as well as an additional 5.3 m dome. Funding for the project, which will cost nearly 1million Euros, has been approved and it will be realized by the town of Anogeia.

The second is the construction of the "Total-Coverage Ultra-Fast Response to Binary Mergers Observatory (TURBO)". This project, which commences in 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, TURBO will start to obtain continuous, multi-band imaging of over ~150 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.

The new 5.3m dome at Skinakas

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

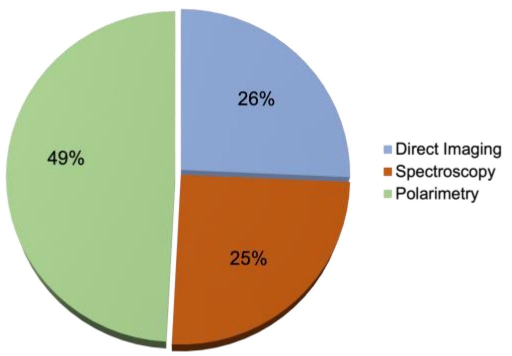
Students from the University of Minnesota, New Mexico, and Crete, as well as the citizen scientists will participate.

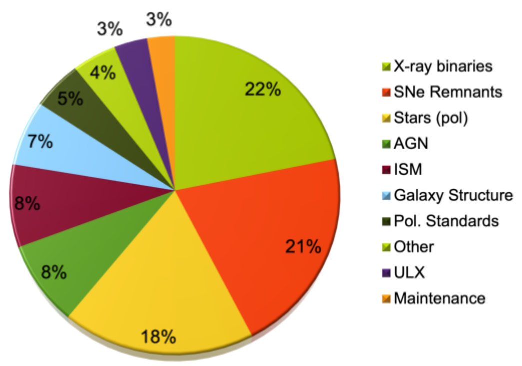
Furthermore, in May 2021, Skinakas Observatory was validated by the European Union Space Surveillance and Tracking (EU-SST) Campaign #4, as an optical ground station, which can be used to monitor satellites in orbit around the Earth. In parallel, ESA selected Skinakas and will fund, in 2022, its upgrade 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. We anticipate that both these new aspects in the usage of the observatory 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 2021 observing period were:

- Polarimetric monitoring of stars to establish a set of polarimetric standards
- 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 **179** nights that Skinakas was operating during 2021 is presented in the following pie charts.





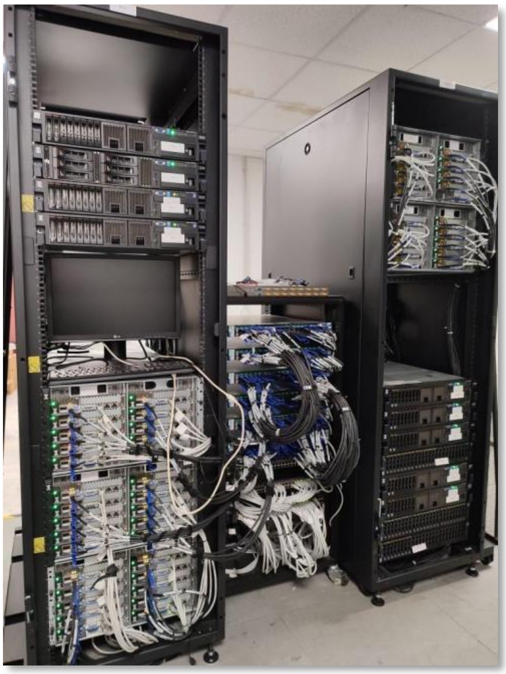
A total of **7 refereed papers** using data from Skinakas Observatory were published in 2021.

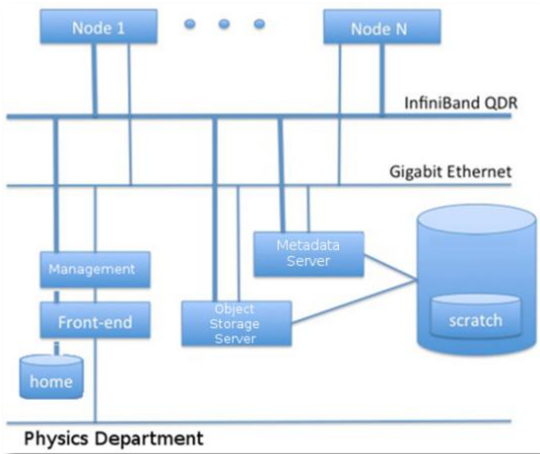
As it was the case in 2020, the tradition of open nights had to be canceled in 2021 due to the COVID-19 pandemic. Instead, several virtual visits were scheduled during the summer months.

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 in 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 The Turbulent Assembly of Hot DOGs

Super-massive black holes (SMBHs), that is black holes with at least one million times the mass of the Sun, are typically found at the center of galaxies. While black holes are, by definition, the darkest regions of the Universe as light cannot escape their gravity, they can paradoxically also be the most luminous. When SMBHs grow, the gas that is feeding them forms an accretion disk before crossing the event horizon that can become so bright as to outshine all the stars in a galaxy together. These luminous growing SMBHs are called "quasars", and can be found across the Universe in a range of luminosities.

Artist's rendering of W2246-0526. Credit JPL/Caltech

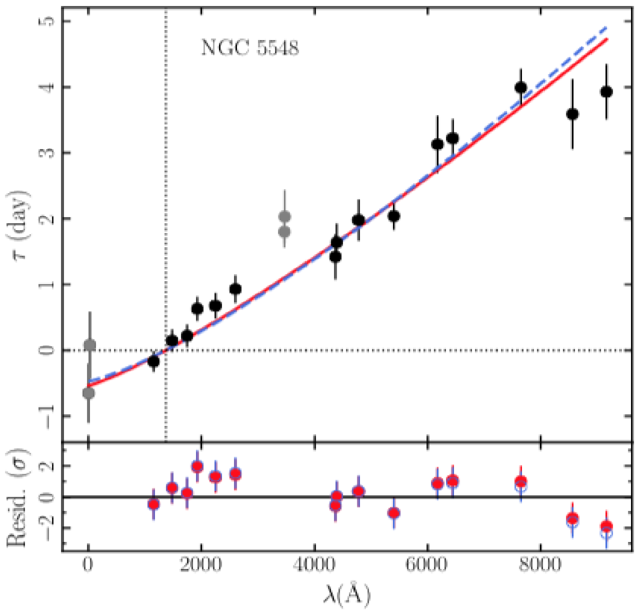
Extremely luminous, hot, dust-obscured galaxies (EL Hot DOGs) are some of the most luminous quasars discovered to date. These objects, which shine with the intensity of more than 100 trillion Suns, lived at a time when the Universe was less than one seventh of its current age. A group of astronomers led by Tanio Díaz-Santos, a researcher at the Institute of Astrophysics at FORTH in Crete, used the Atacama Large Sub/millimeter Array (ALMA) to image a small sample of 7 EL Hot DOGs in the far-infrared spectrum of light in order to study the distribution of gas and dust near the SMBHs as well as in their host galaxies. These observations have allowed them to acquire critical information about the gas dynamics and the physical properties of their interstellar medium.

In a recent study, the investigators have discovered that the random motions of the ionized gas in EL Hot DOGs are consistently very large, which indicates the interstellar medium is very turbulent -- something that can be likely explained by the infall of companion satellite galaxies and the energetic feedback from their central SMBHs. However, the morphology and rotation of the gas is not uniform among the EL Hot DOG population, as it usually is in obscured quasars found in the local Universe. This lack of uniformity in the gas and dust properties have led the investigators to think that the EL Hot DOG phase may be recurrent in the life of the most massive galaxies living at the knots of the cosmic web in the early Universe. This would be in contrast with the current paradigm of the formation of quasars in the nearby Universe, where this phase is believed to happen only once, as a consequence of the merging of two massive spiral galaxies. While these results are tantalizing, more observations are needed to confirm the difference in the origin and evolution between near and far obscured quasars.

Article: "Kinematics and star formation of high-redshift hot dust-obscured quasars as seen by ALMA", T. Diaz Santos et al., 2021, A&A, 654, 37 – October 2021

5.2 MODELING THE UV/OPTICAL CONTINUUM TIME-LAGS IN AGN

A group of astronomers, including Prof. Iossif Papadakis of the Institute of Astrophysics and the Department of Physics of the University of Crete, have recently explained the correlated optical/Ultraviolet (UV) variations that are observed in Active Galactic Nuclei (AGN).



The delays between the observed variations in the UV and optical bands and the X-rays, plotted as a function of wavelength, in the case of the active nucleus in the galaxy NGC 5548. The solid lines show the theoretical predictions which agree very well with the observations.

Approximately 10 percent of nearby galaxies host active nuclei, which emit enormous amount of light (equivalent to the light of the whole galaxy) from regions which are not much larger than our Solar system. AGN are the most powerful, persistent objects in the Universe. We currently believe that their enormous luminosity is powered by the accretion of gas to supermassive black holes which reside at their center (their mass being million to billion times larger than the mass of our Sun). The gas forms a disc, which is very small in size and cannot be resolved by any telescope on Earth. Astronomers are therefore forced to test their theories via other means, like the variations we observed in the optical and UV bands.

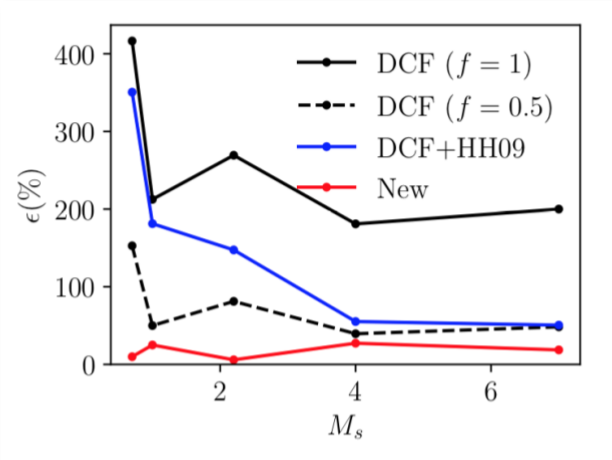
So far, the results appeared to suggest that the discs must be significantly larger than what the theory would suggest. This discrepancy was one of the most serious problems regarding our understanding of the power mechanism in AGN.

Recently, Prof Papadakis and his collaborators studied the response of an accretion disc in the case when it is illuminated by an intense X-ray source, taking into account all the general and special relativistic effects, as well as the important atomic physics effects which determine the amount of X-rays that the disc will absorb. They modeled the expected variations and delays between them (in the optical/UV band) and they showed that, despite previous claims, the observations are fully consistent with the standard accretion disc models. In addition, to providing an explanation for the apparent discrepancies between observations and theoretical models, the results from this work have also important implications regarding the physical processes, the spin of the supermassive black holes and the geometry between the X-ray source and the accretion discs in these enigmatic systems

Article: "Modelling the UV/optical continuum time-lags in AGN", Kammoun E., Papadakis I. E., & Dovciak, M. 2021, MNRAS, 503, 4163 – October 2021

5.3 A New Method to Infer the Magnetic Field of the ISM

A large-scale magnetic field (ranging from a fraction of a μG to hundreds of mG) permeates the interstellar medium (ISM) of our Galaxy and is involved in a variety of astrophysical properties (e.g., star formation, cosmic ray propagation). Characterizing the magnetic field properties is necessary in order to understand these processes.



The relative deviation of the estimated magnetic field strength from the true value in five different MHD simulation models of sonic Mach number (Ms).

Dust polarization has been proven one of the most powerful observables for studying the field properties in the ISM, although it probes only the magnetic field orientation and not its strength. For this reason, various methods which infer the magnetic field strength have been developed. The most widely applied method has been developed by Davis (1951) and Chandrasekhar & Fermi (1953) (DCF). This method relies on the assumption that the observed spread in the distribution of polarization angles is due to the propagation of the so-called Alfvén magnetohydrodynamic waves. Observations, however, indicate that non-Alfvénic (compressible) modes may be important in the ISM dynamics.

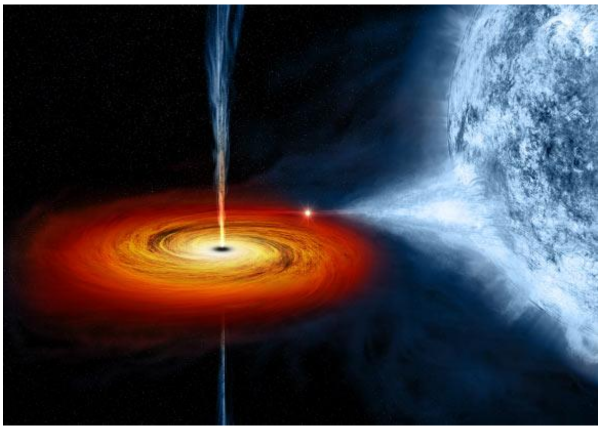
Rafael Skalidis, a PhD student at the Institute of Astrophysics and his supervisor Prof. Kostantinos Tassis propose a new method for estimating the magnetic field strength which includes the compressible modes. They have tested their method in MHD numerical simulations and compared it with the classical DCF method.

In the figure above it is shown with the black solid line (f=1) the relative deviation of the DCF estimated magnetic field strength from the true value in five different MHD simulation models. The black dotted line shows the DCF estimates corrected for line of sight and turbulent effects (f=0.5). The blue line corresponds to DCF combined with the method of Hildebrand et al. 2009 and Houde et al. 2009, which corrects for line of sight and instrumental effects. The red line corresponds to the relative deviation of the true magnetic field strength and the value obtained with the new method. The proposed method outperforms the previous methods, which are based solely on Alfvénic modes, and achieves a mean relative deviation of 17% without the need for a correction.

Article: "High-accuracy estimation of magnetic field strength in the interstellar medium from dust polarization", R. Skalidis, K. Tassis, 2021, A&A, 647, 186 – March 2021 - A follow up study by R. Skalidis, et al. 2021, A&A, 656, A118 was highlighted by A&A.

5.4 The Source of Hard X-rays in Black Hole Binaries

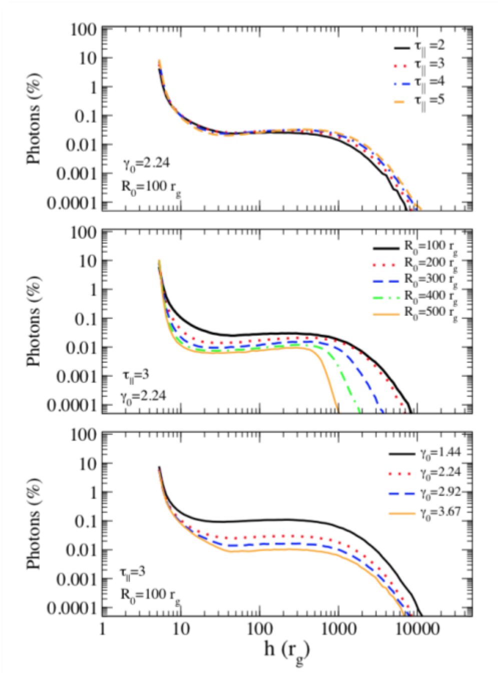
The models that seek to explain the reflection spectrum in black hole binaries usually invoke a point-like primary source of hard X-rays. This source illuminates the accretion disk and gives rise to the discrete (lines) and continuum-reflected components. Because of the complexity of the physics involved, many authors consider a simple geometry in which the illuminating continuum is assumed to be emitted isotropically from a point source on the rotational axis at a certain height above the black hole. This model is known as the lamp post model.



Artist's rendering of a black hole binary (NASA)

However, the lamp post model is an idealized case of the real physical source, which is likely extended, variable, and highly anisotropic.

Constraining the nature and geometry of the source of the hard X-rays that illuminates the disk is of paramount importance because it will allow us to consider more realistic models. It is well-stablished that black holes in binary systems emit powerful jets of matter at relativistic velocities (see artist's rendering).



Fraction of input photons that illuminate the disk as a function of the height h from where they escape the jet.

P. Reig and N. Kylafis researchers of the Institute of Astrophysics and the University of Crete have recently demonstrated that the jet itself can be indeed the disk-illuminating source.

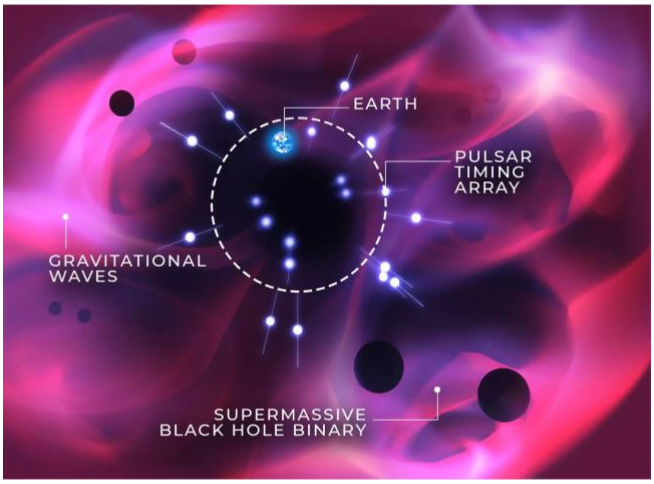
Using complex numerical methods, they found that, regardless of the optical depth, jet width, and jet velocity, a significant fraction of the Comptonized photons is back-scattered and hit the disk. The majority of photons that hit the disk escape within a few gravitational radii, as expected in the lamp post model. More importantly, there is a significant contribution of photons that escape at larger radii (see figure to the left.**)**.

Article: "Illumination of the accretion disk in black hole binaries: An extended jet as the primary source of hard X-rays", Reig, P. & Kylafis, N. D. , 2021, A&A, 646, A112 - February 2021

5.5 Detection Of A Strong Candidate Signal For The Stochastic Gravitational Wave Background At Nhz Frequencies

The European Pulsar Timing Array (EPTA) is a scientific collaboration bringing together teams of astronomers around the largest European radio telescopes, as well as groups specialized in data analysis and modelling of gravitational wave signals. Recently, the EPTA published a detailed analysis of a candidate signal for the since-long sought gravitational wave background due to in-spiraling supermassive black-hole binaries. Although a detection cannot be claimed yet, this represents another significant step in the effort to finally unveil gravitational waves at very low frequencies, of order one billionth of a Hertz. In fact, the candidate signal has emerged from an unprecedented detailed analysis and using two independent methodologies. Moreover, the signal shares strong similarities with those found from the analyses of other teams.

The results were made possible thanks to the data collected over 24 years with five large-aperture radio telescopes in Europe. They include the 100-m Radio Telescope of the Max Planck Institute for Radio Astronomy near Effelsberg in Germany, the 76-m Lovell Telescope in Cheshire/United Kingdom, the 94-m Nançay Decimetric Radio Telescope in France, the 64-m Sardinia Radio Telescope at Pranu Sanguni, Italy and the 16 antennas of the Westerbork Synthesis Radio Telescope in the Netherlands. In the observing mode of the Large European Array for Pulsars, the telescopes of the European Pulsar Timing Array are tied together to synthesize a fully steerable 200-m dish to greatly enhance the sensitivity of the array towards gravitational waves.



Radiation beams from the pulsars’ magnetic poles circle around their rotational axes, and they are observed as pulses when they pass our line of sight, like the light of a distant lighthouse. Pulsar timing arrays are networks of very stably rotating pulsars, used as galactic-scale gravitational wave detectors. In particular, they are sensitive to very low frequency gravitational waves in the billionth-of-a-Hertz regime. This will extend the gravitational wave observing window from the high frequencies (hundreds of Hertz) currently observed by the ground-based detectors LIGO/Virgo/KAGRA. While those detectors probe short lasting collisions of stellar-mass black holes and neutron stars, Pulsar Timing Arrays can probe gravitational waves such as those emitted by systems of slowly in-spiraling supermassive black-hole binaries hosted at the centres of galaxies. The addition of the gravitational waves released from a cosmic population of these binaries forms a gravitational wave background.

The EPTA can measure small fluctuations in the arrival times of the pulsars’ radio signal at Earth, caused by the spacetime deformation due to a passing-by very low frequency gravitational wave. In practice, these deformations manifest as sources of a very low frequency noise in the series of the observed times of arrival of the pulses, a noise which is shared by all the pulsars of a Pulsar Timing Array.

However, the amplitude of this noise is incredibly tiny (estimated to be tens to a couple of hundreds of a billionth of a second) and in principle many other effects could impart that to any given pulsar in the Pulsar Timing Array.

To validate the results, multiple independent codes with different statistical frameworks were then used to mitigate alternate sources of noise and search for the gravitational wave background. Importantly, two independent end-to-end procedures were used in the analysis for cross-consistency. Additionally, three independent methods were used to account for possible systematics in the Solar-system planetary parameters used in the models predicting the pulse arrival times, a prime candidate for false-positive gravitational wave signals.

The European Pulsar Timing Array analysis with both procedures found a clear candidate signal for a gravitational wave background and its spectral properties (i.e. how the amplitude of the observed noise varies with its frequency) remain within theoretical expectations for the noise attributable to a gravitational wave background. The European Pulsar Timing Array first found indications for this signal in their previously published data set in 2015, but as the results had larger statistical uncertainties, they were only strictly discussed as upper limits. The new data now clearly confirm the presence of this signal, making it a candidate for a gravitational wave background.

Einstein's General Relativity predicts a very specific relation among the spacetime deformations experienced by the radio signals coming from pulsars located in different directions in the sky. Scientists call that the spatial correlation of the signal, or Hellings and Downs curve. Its detection – which was not possible in this study – will uniquely identify the observed noise as due to a gravitational wave background.

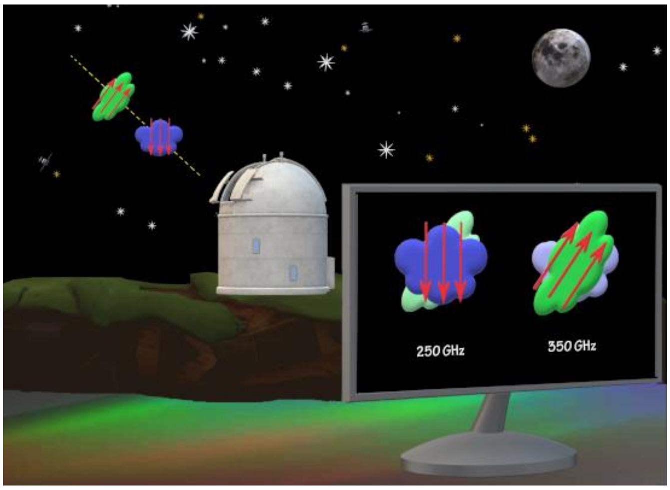
Article: "Common-red-signal analysis with 24-yr high-precision timing of the European Pulsar Timing Array: inferences in the stochastic gravitational-wave background search" 2021; The EPTA collaboration (incl. J. Antoniadis), MNRAS, 508, 4 , 4970 - October 2021

5.6 HUNTING FOR THE SIGNATURE OF THE FIRST MOMENTS OF THE UNIVERSE JUST GOT MORE COMPLICATED

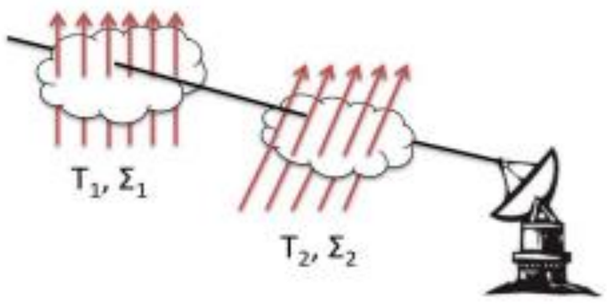
Polarized light emitted by Galactic interstellar dust acts as a veil obscuring our view of microwave emission from the early Universe - the cosmic microwave background (CMB), often called the Big Bang "ashes". An important breakthrough in our understanding of the complexity of this foreground emission has been achieved by an international collaboration of scientists from the Institute of Astrophysics of the Foundation for Research and Technology – Hellas (IA-FORTH) and the University of Crete in Greece, Princeton University, Institute for Advanced Study, and Caltech in the USA, and the University of Oslo in Norway.

The study, led by IA-FORTH's Dr. Vincent Pelgrims, used data from ESA's Planck mission and neutral Hydrogen emission to show that the rich 3-dimensional structure of interstellar gas has a strong effect on polarization from dust.

"When more than one clouds intersect a line of sight", Dr. Pelgrims said, "and these clouds have different emission spectra and misaligned magnetic fields, then the angle at which this radiation is polarized turns as we move from one frequency to the next." This effect was predicted in 2015 by IA-FORTH scientists and U. Crete faculty Konstantinos Tassis and Vasiliki Pavlidou (see Fig. 1), but this is the first time its signature is explicitly detected in observational data. It also demonstrates the difficulties and pitfalls in the proper treatment of Galactic foregrounds since a simple scaling of the polarized emission at one frequency to infer the emission at another frequency (an assumption frequently used in the past) is incorrect and should not be applied.

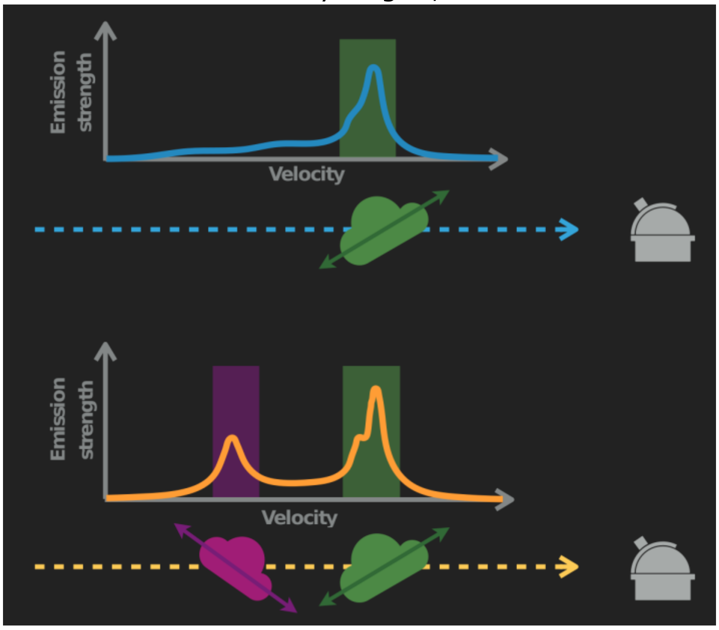


"This discovery was only now made possible thanks to breakthrough studies of the interstellar medium by our overseas co-authors: the work of Dr. Gina Panopoulou, Hubble Fellow at Caltech, and U. Crete alumna, which allowed us to determine which lines of sight intersect multiple clouds; along with the findings by Dr. Susan Clark, Fellow of the Institute for Advanced Study, and Dr. Brandon Hensley, Spitzer Fellow at Princeton, which enabled us to indirectly infer the direction of magnetic fields in different interstellar clouds" said Prof. Pavlidou.



When a single line of sight crosses two clouds with misaligned magnetic fields and different properties (temperature, amount of dust, dust composition), the polarization angle of the total dust emission is not the same in all frequencies, but turns as we go from one frequency to the next.

These analyses used the emission from neutral hydrogen, the most abundant ingredient in interstellar clouds, to trace the location of the clouds. The spectrum of this emission reveals the number of distinct clouds along each sightline, and its morphology can be used as a proxy for the magnetic field direction (See Fig. 2). With this information at hand for each direction in the sky, the scientists could select all sightlines that were susceptible to the effect, by intersecting more than one clouds with misaligned magnetic fields. Next, they looked at the difference in polarization angle between two frequencies that Planck observed, and where emission from interstellar dust dominates: 217 GHz, and 353 GHz. They found that in the selected sightlines the difference in polarization angle was much more pronounced than elsewhere in the sky. "Not only that," added Dr. Pelgrims, "but we were able to show that the larger the misalignment between clouds, the larger the difference in polarization angle between frequencies" .



Emission from neutral hydrogen can be used to determine how many clouds intersect a line of sight, and its morphology can be used to infer the magnetic field direction in each cloud.

"Now that we have demonstrated that the effect is visible in the Planck data, the need to find ways to account for it when cleaning microwave maps before using them to study the early Universe got more urgent", said Prof. Tassis. "Thankfully, the PASIPHAE experiment, which we expect to have running this year, will do exactly that." PASIPHAE is an international collaboration between IA-FORTH and U. Crete in Greece, Caltech in the U.S., IUCAA in India, SAAO in South Africa, and the University of Oslo in Norway. It will measure with unprecedented efficiency and accuracy the polarization of millions of stars in our Galaxy. Combining the polarization measurements with the amazingly accurate distances we now have for all those stars thanks to ESA's Gaia mission, we can distinguish between stars in front of clouds, in between clouds, and behind clouds. This allows us to disentangle the imprint of each cloud on stellar polarizations, and directly derive the magnetic field direction in each cloud, thus producing the first 3D map of the magnetic field of our Galaxy.

Article: V. Pelgrims, S. E. Clark, B. S. Hensley, G. V. Panopoulou, V. Pavlidou, K. Tassis, H.K. Eriksen, I. K. Wehus "Evidence for line-of-sight frequency decorrelation of polarized dust emission in Planck data" 2021, A&A, 647, A16

6. Research Areas

In the following, we present the research areas in which members of the IA contributed in 2021. 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:

The growth of structure and its link to cosmological models: 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 allow 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.

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:

The EPTA second data release (DR2): 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".

Detection of a candidate GW signal: Using a small set of the preliminary results from DR2, we 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. These results were later 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).

Large European Array for Pulsars (LEAP): 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 in nearby galaxies: 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 2021 we published the most complete census of ULX populations in the local Universe and we explored their connection with the star-formation rate, stellar mass, metallicity, and stellar population age of their host galaxies. We also investigated individual intriguing sources, such as the extremely luminous ULX pulsar in the M82 galaxy, which showed evidence for a 60-day super-orbital period.

Active Galactic Nuclei

(Researchers involved: D. Blinov, 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.

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.

Star Formation and Galaxy Mergers in the Local Universe

(Researchers involved: V. Charmandaris, T. Diaz-Santos, K. Kouroumpazakis, 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 also interested in the spatially resolved characterization of the ISM properties of nearby (U)LIRGs using the upcoming James Webb Space Telescope as part of an Early Release Science (ERS) program.

<u>Galaxy interactions and mergers</u>: 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 (IFU) observations obtained with the Spitzer Space Telescope, the Herschel Space Observatory and soon with the James Webb Space Telescope (JWST). 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.

<u>Star-formation and AGN activity in normal, Milky-way type, nearby galaxies</u>: 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. As part of this study, we released 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.

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.

Cluster formation and destruction, and supernova remnants in active galaxies: Studies of individual stars and star-clusters in nearby galaxies mainly with the Hubble Space Telescope give us a picture of their history. Based on these data, we can decipher when the stars in each area of a galaxy were formed, which in turn provides us information on the processes that shaped the present picture of a galaxy. In addition, we can obtain crucial information on the mechanisms of star-formation and the factors which affect them. This information is also important for understanding their populations of X-ray binaries and supernova remnants. Indeed, multi-wavelength studies of the supernova remnant populations in nearby galaxies using data from the Chandra X-ray observatory and narrow-band imaging data and spectroscopy from the Skinakas observatory, as well as other observatories (e.g. NOAO, CTIO), are used to understand the populations of SNRs in different wavelengths in a variety of environments. Our main interests are in the interaction of the shock-front with the ambient ISM, the dependence of the multiwavelength emission of SNRs on their age and local ISM, and their use as a proxy for the current formation rate of massive stars. In fact, massive stars are important tools for understanding stellar evolution. Observations of massive-star populations in nearby galaxies allow us to constrain their recent star-formation history, their dependence on parameters such as age and metallicity, and their connection with the compact object populations in these galaxies as witnessed in X-ray observations.

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 X-ray data from all major X-ray and radio telescopes as well as, supporting multiwavelength data from the Hubble Space telescope, and 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:

<u>Black hole X-ray binaries</u>: 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.

<u>Accreting pulsars</u>: 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.

<u>Variability time scales in Be/X-ray binaries (BeX):</u> 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.

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.

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 are 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. To assess the magnitude of the effect, a mini survey of three regions of the northern sky with very low dust emission/extinction were performed. Probing the polarization at the low dust extinction regime is important in order to calibrate the expected efficiency of the PASIPHAE survey and set the required time and sensitivity thresholds. In addition, our group has developed a new technique for estimating the strength of the plane-of-sky magnetic field in interstellar clouds using our earlier discovery that elongated structures in such clouds (striations in molecular clouds, fibres in HI clouds) are imprints of magnetosonic waves.

Imprint of MHD waves in interstellar molecular clouds: Building on previous work that demonstrated that the long parallel structures (striations) that appear in the outskirts of molecular clouds are the result of fast magnetosonic waves, we have identified and analysed an isolated cloud where such waves establish standing waves: the

Musca molecular cloud in the southern hemisphere. By analysing the normal modes present in that cloud, we found that, contrary to the standard paradigm that wanted this cloud to be a prototypical filament, Musca is in fact a sheet-like structure seen edge-on.

Demonstration of tomographic mapping of interstellar magnetic field direction: In a pathfinding study for the upcoming PASIPHAE survey, our group demonstrated the technique of Galactic magnetic tomography: using opto-polarimetric measurements of stars with known distances, we were able to measure, for the first time, the direction of the plane-of-sky magnetic field of two distinct clouds at different distances along the same line of sight.

Opto-polarimetric searches for low-energy counterparts of unidentified Fermi sources: Highly polarized point sources were looked for within the positional error circles of some of the most prominent high-Galactic-latitude gamma-ray sources that are yet to be associated with known systems at lower wavelengths.

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. A paper presenting a new methodology for the derivation of their multi-variate luminosity functions of SNRs and also introducing their excitation function is accepted for publication. As part of this effort, we are also developing tools for the distinction of shock-excited regions from photoionized (HII) regions using machine-learning methods. In addition we are developing a population synthesis model for SNRs in order to model their luminosity and excitation functions.

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.

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.

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)
- ERC Consolidator Grant "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)
- H2020 RISE, entitled "ASTROSTAT-II: Development of novel statistical tools for the analysis of astronomical data", (P.I.: A. Zezas, budget: €556,800, duration: 2019 – 2025)
- H2020 INFRAIA, entitled "Opticon-Radionet Pilot", (Local contact: V. Charmandaris, budget: €40,000, duration: 2021 – 2025)
- ERASMUS+, entitled "Large Scientific Infrastructures enriching online and digital Learning", (Local contact: V. Charmandaris, budget: €53,300, duration: 2021 – 2023)
- Interreg Greece-Cyprus GEOSTARS, (P.I.: A. Zezas, budget: €410,000, duration: 2019 – 2022)
- HFRI "Cosmic rays at the highest energies", (P.I.: V. Pavlidou, budget: €199,500, duration: 2020 – 2023)
- HFRI "European Pulsar Interior Composition Survey", (P.I.: I. Antoniadis, budget: €194,400, duration: 2020 – 2023)
- HFRI "Magnetized galaxies through cosmic time: Simulating the galactic magnetic field across scales and epochs", (P.I.: E. Ntormousi, budget: €194,400, duration: 2021 – 2023)
- HFRI "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)
- HFRI 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)
- IKY "Galactic SNe Remnants: Exploring an unexploited treasure", (fellow: I. Leonidaki, budget: €26,400, duration: 2020 – 2021)
- 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 – 2022)
- FORTH Synergy Grant "Computational Intelligence for Multimodal Astrophysical Tomography", (P.I.: K. Tassis, budget: €73,600, duration: 2021 – 2023)

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

- ❑ 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" initiative.

9. COMMITTEES AND SERVICE

During the 2021 calendar year period covered by this report, members of the IA served in a number of national and international committees. Specifically:

Prof. V. Charmandaris is a member of the Scientific Council of INSU/CNRS since 2019 and was a member of the Astronomy Working Group of ESA from 2019 to 2021. 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. He was elected as Vice Chair of the Board of Directors of the Opticon Radionet Pilot in 2021. In 2020 he was elected President of the Hellenic Astronomical Society and was also 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 and as a member of the Management Committee of the European COST action PHAROS on neutron star physics.

Professor K. Tassis is serving as the Management Panel Chair of the PASIPHAE Collaboration.

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.

10. Conference & Workshop Organization

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

- "Looking at the polarized Universe: past, present, and future", 24-28 May 2021
- "Lensing Odyssey 2021", 20-24 Sep. 2021
- "12th Gaia Science Alerts workshop", 8-12 Nov. 2021

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.

On June 3, 2021 Prof. J. Silk, the 2020 "Nick Kylafis Lecturer", gave his lecture entitled "The Future of Cosmology" online since visiting IA was still not possible due to complications of COVID-19 pandemic.

The 2021 "Nick Kylafis Lectureship" was awarded to Prof. Ewine van Dishoeck, Professor of Molecular astrophysics at Leiden University, The Netherlands "for her seminal contributions in the fields of theoretical astrophysics and astrochemistry". Prof. van Dischoek visited IA-FORTH on October 21 and 22, 2021. Her lecture was entitled "Building stars, planets and the ingredients for life in space".

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 2021 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

12. Public Outreach

Due to restrictions related to the COVID-19 pandemic the PO activities were very limited. No open nights at Skinakas Observatory were offered to the public in 2021. Instead, virtual visits and special events using ZOOM were offered to schools from all over Greece as well as the general public.

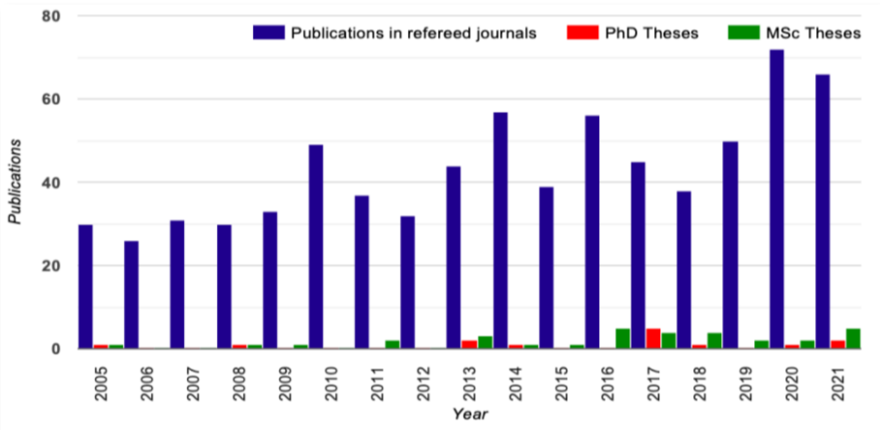
IA-FORTH in collaboration with the Dept. of Physics of the Univ. of Crete and the Society of Physicists of Crete organized the **1st online School of Astrophysics of Crete**. The school took place during the months of March to May 2021 and it was addressed to high school students from Crete who were 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 153 students from 48 high schools of Crete attended the 8 online lectures.

13. Visitors

A total of 14 scientists visited IA in 2021 in order to collaborate with our staff and/or give seminars. These researchers were: Prof. Pere Bley (International Univ. of Valencia, Spain), Prof. Tim de Zeeuw (Leiden Univ., The Netherlands), Dr. David Elbaz (CEA/Saclay, France), Dr. Anastasiia Filmonova (Nikhef, The Netherlands), Dr. Konstantinos Kovlakas (Univ.of Geneva, Switzerland), Dr. Ioannis Liodakis (Univ. of Turku, Finland), Prof. Maurizio Paollilo (Univ. of Napoli, Italy), Prof. Kallia Petraki (Sorbonne Univ., France), Dr. Luka Popovic (Belgrade Astronomical Observatory, Serbia), Dr. Jean-Luc Stark (CEA/Saclay, France), Dr. Anton Srtigachev (Bulgarian Academy of Sciences, Bulgaria), Prof. Ewine van Dischoek (Leiden Univ., The Netherlands), Dr. Alejandro Vigna Gomez (Univ. of Copenhagen, Denmark), Prof. Andrzej Zdziarski (Polish Academy of Sciences, Poland),

14. Publication Statistics

During 2021 the members of IA produced **66** publications that appeared in print in refereed journals (according to NASA/ADS). This corresponds to **3.3** publications per PhD researcher. The full 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:

Institute of Astrophysics
Foundation for Research and Technology – Hellas
Vassilika Vouton
GR-70013 Heraklion
Greece

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E-mail: info@ia.forth.gr

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 this observatory was chosen in the early 1980a 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 1760 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 Observatory, observations started in 1987.

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 2013 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 they are expected to be completed by Spring 2022. This dome will host again the 60 cm robotic telescope on time for the 2022 observing season.

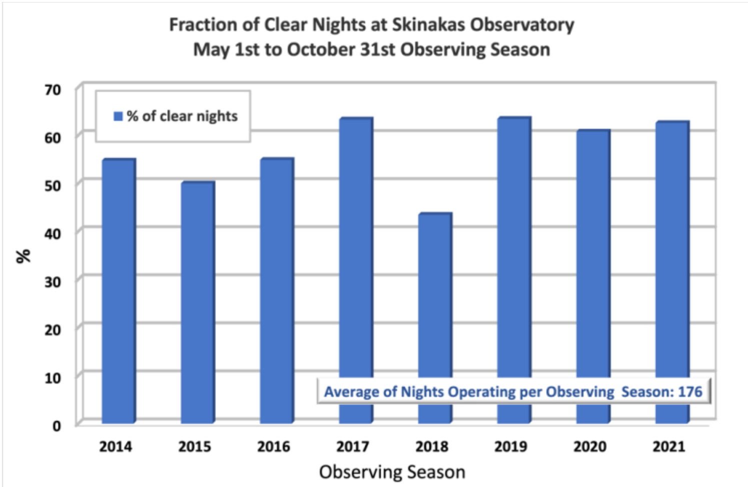
Facilities at sea level

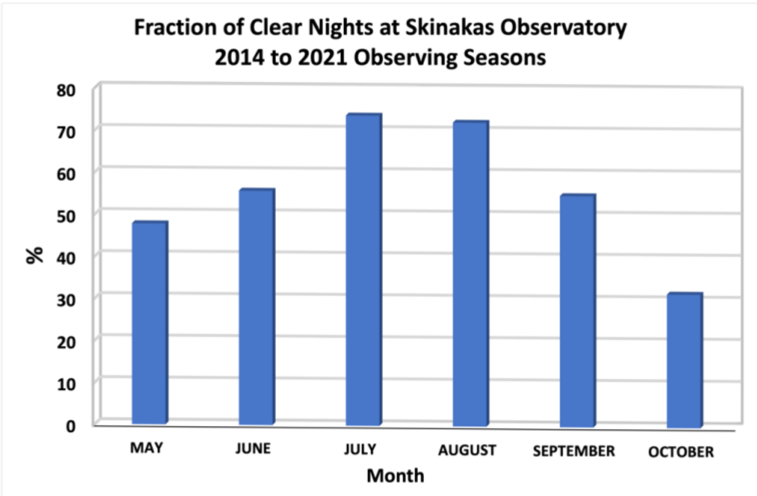
Offices for staff are located on the premises of the Department of Physics of the University of Crete. An instrumentation lab with an optical table and a computing room are also part of the sea-level facilities. The observatory owns two vehicles used for the transportation of material and personnel.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

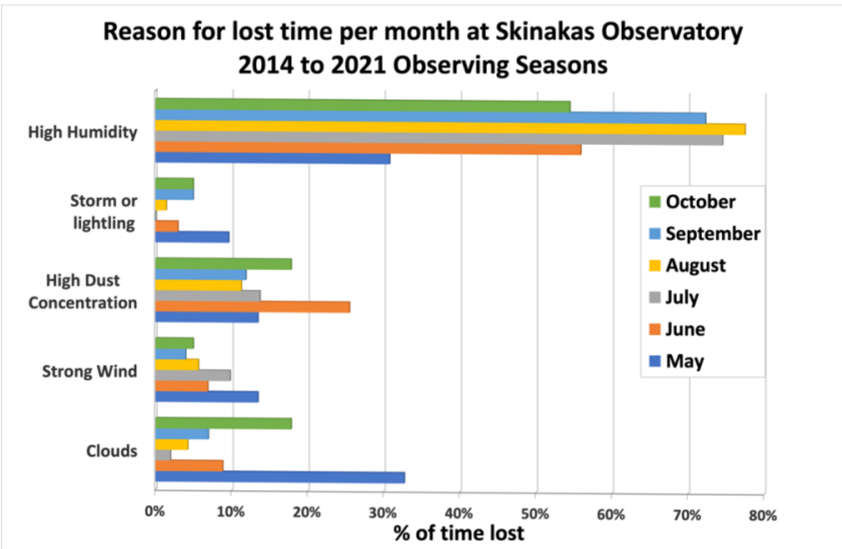
Scientific Operations

Typically, the Observatory operates from late April until late 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 eight years (2014 to 2021). 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.







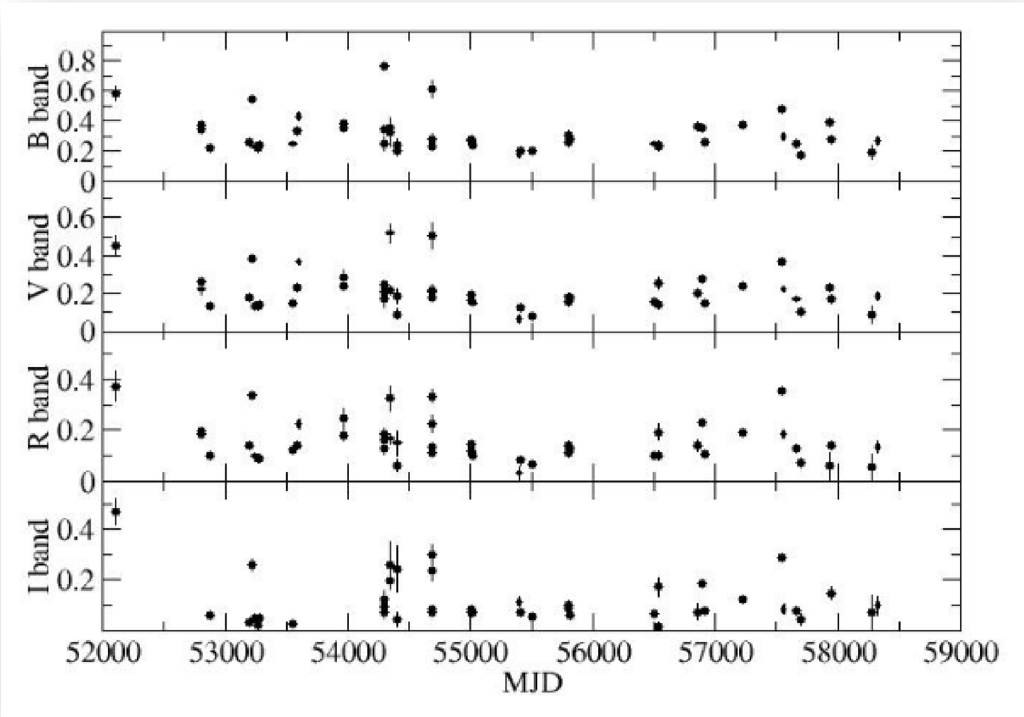
More specifically the reasons the observatory did not operate due to weather were:

- High humidity: 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%.
- Clouds: These are nights when the clouds prevented normal operation but the humidity was in the allowed range.
- Strong wind: 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).
- High dust concentration: 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

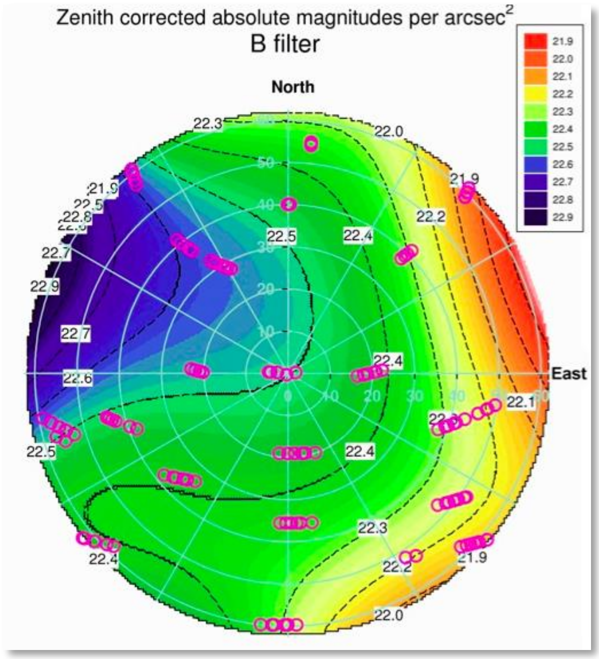
Atmospheric extinction is the astronomical parameter that evaluates sky transparency. Sources causing degradation of the sky transparency are clouds (water vapor) and aerosols (dust particles included). The extinction values and their stability throughout the night are essential for determining the accuracy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

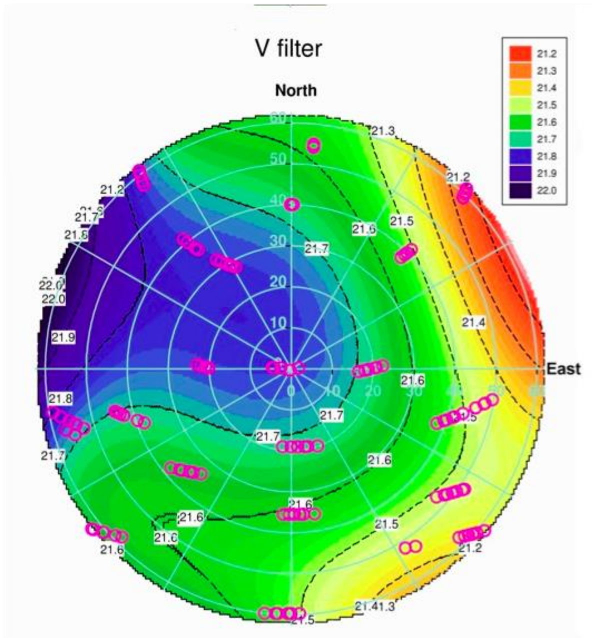


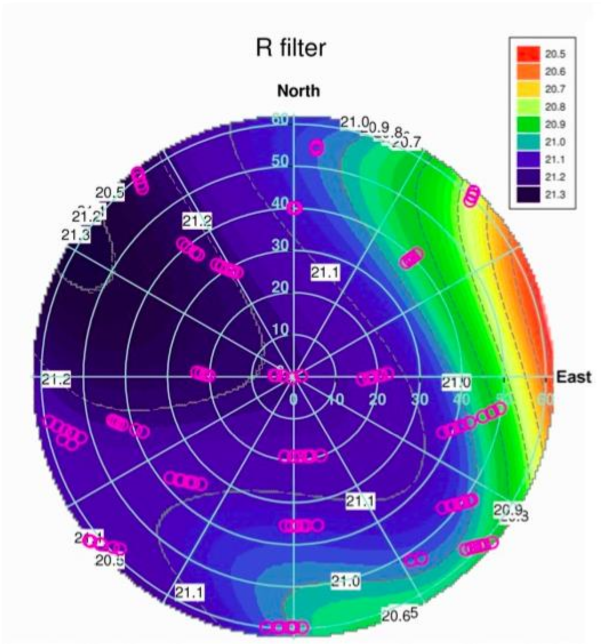
The extinction at the Skinakas Observatory during photometric nights are (in mag/airmass): 0.26 ± 0.06 for B, 0.17 ± 0.03 for V, 0.13 ± 0.04 for R, and 0.09 ± 0.06 for I.

Night Sky Brightness

Night sky BVR brightness observations were conducted in August 2008 and revealed that Skinakas Observatory is a 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=22.36±0.16, V=21.60±0.14, R=21.07±0.14 in absolute magnitudes per square arcsecond. For further details, see here.







An 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.

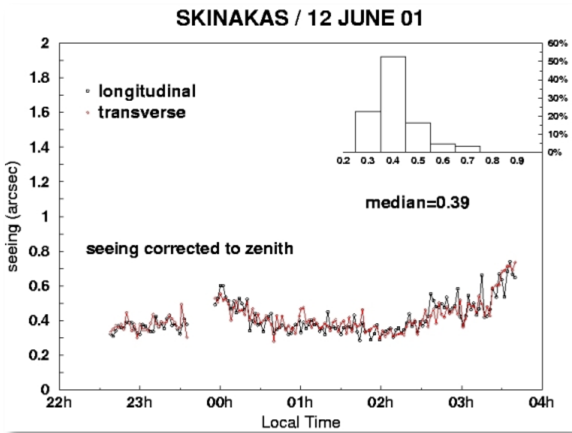
Seeing conditions

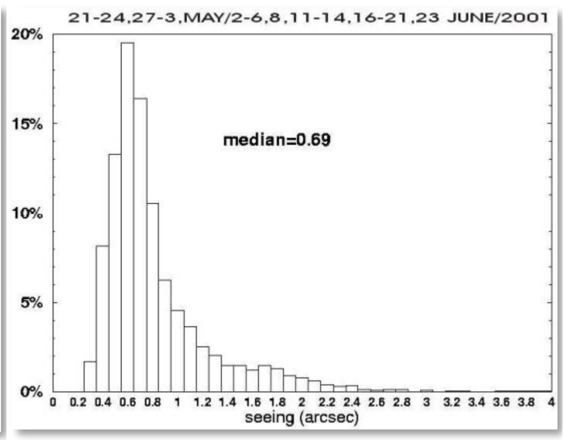
The Skinakas Summit is an excellent site for astronomical observations. As it can be seen in the satellite photo to the right, showing the island of Crete and Africa in yellow at the bottom of the photo, since the winds are typically from the north and the closest land mass to the north is the island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

Using a two-aperture Differential Image Motion Monitor (DIMM), the seeing over Skinakas was measured during observations 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.

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





A more detailed analysis on the Skinakas weather conditions was prepared in an internal report by Dr. P. Reig and E. Palaiologou and it's 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 0.02 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	570 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	555 mm

SYSTEM	
FOCAL LENGTH	9857.0 mm
FOCAL RATIO	8
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 CCD requires daytime engineering work. When the 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	0.38	B, V, R, 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/CCD	**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 Skinakas observatory has three ANDOR 2048x2048 pixels CCDs with 13.5 μm pixel size. All three CCDs use thermoelectric cooling (Peltier effect) to achieve an operational temperature of between -70 to -90ºC. These CCD are used for direct imaging (*Andor iKon L-936, #CCD-20241*), spectroscopy (*Andor iKon L-936, #CCD-20240*), and polarimetry (*Andor DW436*).

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, a SBIG auxiliary CCD with 3072x2048 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 a 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. 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, 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 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 will be fully completed in April 2022. The optics and electronics of the telescope were upgraded in 2021 in order to commence again operations during the 2022 season.

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 mirrors 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 the EU-SST projects. 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

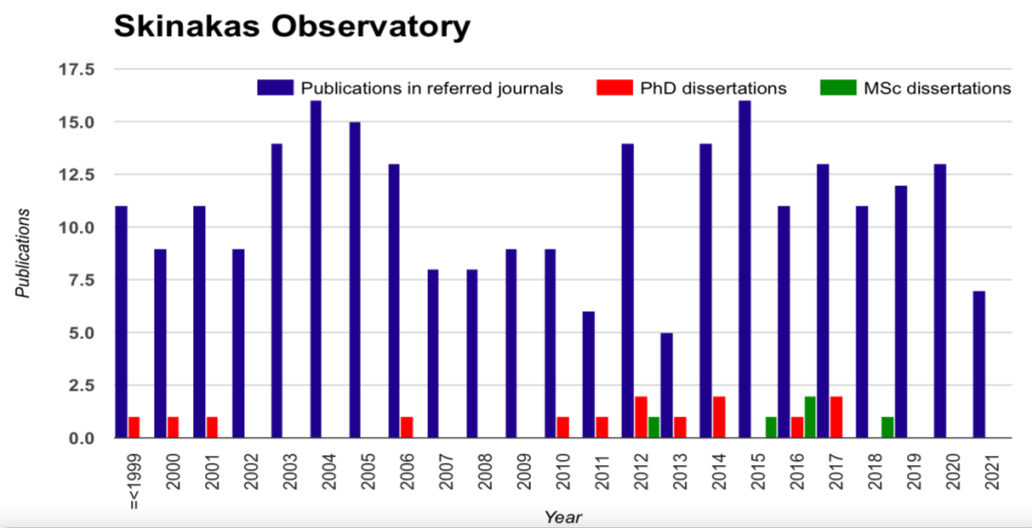
The 30 cm Schmidt-Cassegrain telescope (f/3.2) was the first one installed on Skinakas Observatory in 1986 and it was equipped with the first CCD camera ever used for astronomy in Greece.

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 is 0.38 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") 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 2021 observations from the telescopes at Skinakas Observatory have resulted in a total of 254 publications in refereed journals, which have received ~6700 citations. In addition, 15 PhD and 5 MSc dissertations have been produced using data from Skinakas Observatory. A histogram of those publications as a function of time, follows:



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 2021 REFEREED PUBLICATION LIST

The refereed publications of the members of IA during 2021 follow:

1. Acciari, V.A., Ansoldi, S., Antonelli, L.A., Engels, A.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., Bellizzi, L., Bernardini, E., Bernardos, M., Berti, A., Besenrieder, J., Bhattacharyya, W., Bigongiari, C., Biland, A., Blanch, O., Bonnoli, G., Bošnjak, Ž., Busetto, G., Carosi, R., Ceribella, G., Cerruti, M., Chai, Y., Chilingarian, A., Cikota, S., Colak, S.M., Colombo, E., Contreras, J.L., Cortina, J., Covino, S., D'Amico, G., D'Elia, V., Da Vela, P., Dazzi, F., De Angelis, A., De Lotto, B., Delfino, M., Delgado, J., Mendez, C.D., Depaoli, D., Di Pierro, F., Di Venere, L., Do Souto Espińeira, E., Dominis Prester, D., Donini, A., Dorner, D., Doro, M., Elsaesser, D., Fallah Ramazani, V., Fattorini, A., Ferrara, G., Fonseca, M.V., Font, L., Fruck, C., Fukami, S., 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., Heckmann, L., Herrera, J., Hoang, J., Hrupec, D., Hütten, M., Inada, T., Inoue, S., Ishio, K., Iwamura, Y., Jiménez, I., Jormanainen, J., Jouvin, L., Kajiwara, Y., Karjalainen, M., Kerszberg, D., Kobayashi, Y., Kubo, H., Kushida, J., Lamastra, A., Lelas, D., Leone, F., Lindfors, E., 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., Maraschi, L., Mariotti, M., Martínez, M., Mazin, D., Menchiari, S., Mender, S., Mićanović, S., Miceli, D., Miener, T., Minev, M., Miranda, J.M., Mirzoyan, R., Molina, E., Moralejo, A., Morcuende, D., Moreno, V., Moretti, E., Neustroev, V., 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., Perennes, C., Persic, M., Prada Moroni, P.G., Prandini, E., Priyadarshi, C., Puljak, I., Rhode, W., Ribó, M., Rico, J., Righi, C., Rugliancich, A., Saha, L., Sahakyan, N., Saito, T., Sakurai, S., Satalecka, K., Saturni, F.G., Schleicher, B., Schmidt, K., Schweizer, T., Sitarek, J., Šnidarić, I., Sobczynska, D., Spolon, A., Stamerra, A., Strom, D., Strzys, M., Suda, Y., Surić, T., Takahashi, M., 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., Vigorito, C.F., Vitale, V., Vovk, I., Will, M., Wunderlich, C., Zarić, D., de Palma, F., D'Ammando, F., Barnacka, A., Sahu, D.K., Hodges, M., Hovatta, T., Kiehlmann, S., Max-Moerbeck, W., Readhead, A.C.S., Reeves, R., Pearson, T.J., Lähteenmäki, A., Björklund, I., Tornikoski, M., Tammi, J., Suutarinen, S., Hada, K. and Niinuma, K., "*Multiwavelength study of the gravitationally lensed blazar QSO B0218+357 between 2016 and 2020".* Monthly Notices of the Royal Astronomical Society, 2021
2. Alonso-Herrero, A., García-Burillo, S., Hönig, S.F., García-Bernete, I., Ramos Almeida, C., González-Martín, O., López-Rodríguez, E., Boorman, P.G., Bunker, A.J., Burtscher, L., Combes, F., Davies, R., Díaz-Santos, T., Gandhi, P., García-Lorenzo, B., Hicks, E.K.S., Hunt, L.K., Ichikawa, K., Imanishi, M., Izumi, T., Labiano, A., Levenson, N.A., Packham, C., Pereira-Santaella, M., Ricci, C., Rigopoulou, D., Roche, P., Rosario, D.J., Rouan, D., Shimizu, T., Stalevski, M., Wada, K., and Williamson, D., "*The Galaxy Activity, Torus, and Outflow Survey (GATOS). II. Torus and polar dust emission in nearby Seyfert galaxies".* Astronomy and Astrophysics, 2021. **652** p.A99
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10. Bonfini, P., <u>Zezas, A.,</u> Ashby, M.L.N., Willner, S.P., Maragkoudakis, A., <u>Kouroumpatzakis, K.,</u> Sell, P.H., and Kovlakas, K., "*The star formation reference survey - IV. Stellar mass distribution of local star-forming galaxies".* Monthly Notices of the Royal Astronomical Society, 2021. **504** p.3831

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