FORTH
INSTITUTE OF ASTROPHYSICS

INSTITUTE OF ASTROPHYSICS
FORTH
2019 & 2020 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 2019 and 2020 calendar years.

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

During the period of this report, 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 during the 2019–2020 period resulted in **122** papers published in refereed journals, that is **3** papers per PhD researcher per year. It should be noted that among those publications one appeared in Science, one in Nature and one in Nature Astronomy.

In addition, new competitive grants of **~1.1 million Euros** were awarded to members of the Institute. Significant efforts were also devoted to the improvement of the infrastructure and hardware at Skinakas Observatory.

This document was prepared in March 2021, based on contributions from all members.

2. STRUCTURE

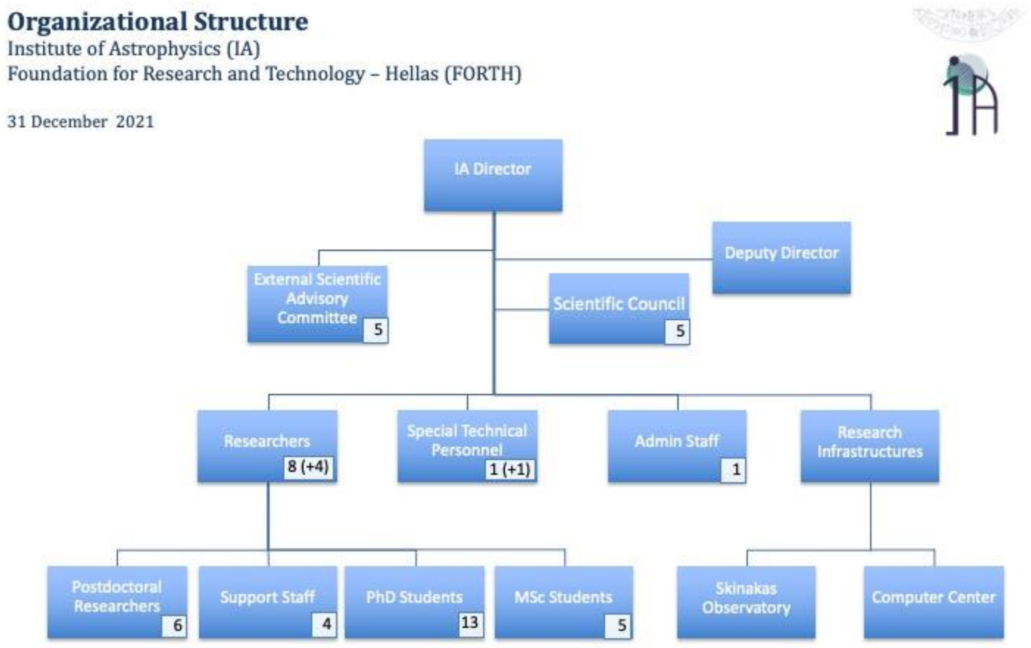
As of March 6, 2019, Director of the Institute is Prof. Vassilis Charmandaris.
The current Scientific Council of the Institute (SCI) was formed on April 20, 2019, and it consists of:

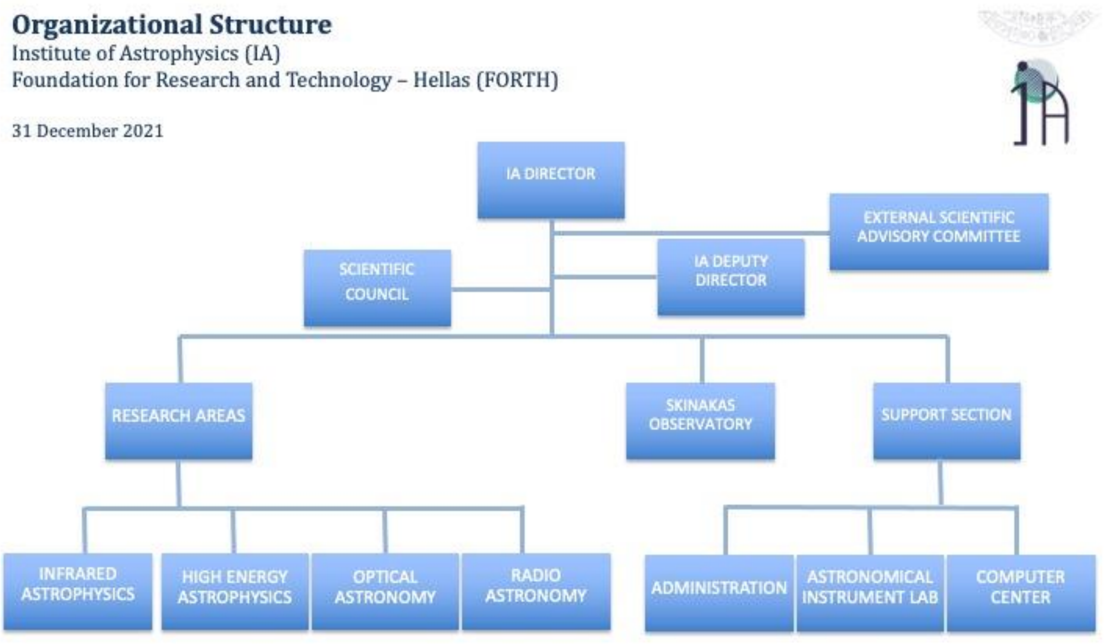
- Iossif Papadakis, Chair
- Vasiliki Pavlidou
- Konstantinos Tassis
- Pablo Reig
- Andreas Zezas

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 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, 2020, the core personnel of IA consisted of 2 researchers, and 5 affiliated faculty from the Department of Physics of the University of Crete. The personnel also include 2 professors emeriti and 6 post-doctoral researchers, as well as 7 support staff. In addition, 11 PhD students, 10 MSc students, and 21 undergraduate students were trained by members of IA.

To the above local members, we should add 3 Affiliated Research Fellows from institutes outside Greece, who often visit IA and interact with the local personnel.

In detail these individuals were:

Director of the IA:
- Vassilis Charmandaris (Professor)

Two (2) Permanent Researchers:
- 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)

Three Affiliated Research Fellows:
- 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

Twelve (12) postdoctoral researchers in non-tenure track positions:
- Dr. Konstantina Anastasopoulou - Jan. 2020 to Sep. 2020
- Dr. Dmitry Blinov
- Dr. Paolo Bonfini - until Feb. 2020
- Dr. Carolina Casadio - since Mar. 2020
- Dr. Fabio Del Sordo - until Sep. 2020
- Dr. Sebastian Kiehlmann
- Dr. Ioanna Leonidaki
- Dr. Grigoris Maravelias
- Dr. Eva Ntormousi - until Sep. 2020
- Dr. Vincent Pelgrims
- Dr. Paul Sell - until Sep. 2019
- Dr. George Vernardos - Oct. 2019 to Aug. 2020

Four (4) Support Staff on soft money:
- Mr. Giannis Kapetanakis - IT support
- Mr. Vangelis Pantoulas - Engineering support since Jan. 2020
- Ms. Anna Steiakaki - Engineering support
- Ms. Eleftheria Tsentelierou - Executive secretary since Jan. 2020

Two (2) Support Staff of the Univ. of Crete for Skinakas Observatory:
- Mr. George Paterakis - (Telescope technical support)
- Dr. Eythymios Palaiologou - (Telescope software support)

Twelve (12) PhD students:
- Ms. Konstantina Anastasopoulou (with A. Zezas) - graduated Jan. 2020
- Mr. Konstantinos Kouroumpatzakis (with A. Zezas) - graduated Dec. 2020
- Ms. Maria Kopsacheili (with A. Zezas) - since 2016

- Mr. Georgios Korkidis (with V. Pavlidou) - since 2020
- Mr. Konstantinos Kovlakas (with A. Zezas) - graduated Dec. 2020
- Mr. Ioannis Kypriotakis (with K. Tassis) - since 2017
- Mr. Elias Kyritsis (with A. Zezas) - since Sep. 2020
- Mr. Nikolaos Mandarakas (with K. Tassis) - since 2019
- 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

Ten (10) MSc students:

- Mr. Ioannis Avgoustakis (with I. Papadakis) - until Nov. 2019
- Mr. Antonis Bertsias (with A. Zezas) - until Nov. 2019
- Ms. Katia Gkimisi (with K. Tassis) - since Sep. 2020
- Mr. Angelos Karakonstantakis (with I. Papadakis) - since Sep. 2020
- Ms. Anna Konstantinou (with K. Tassis) - since Sep. 2019
- Mr. Ilias Kyritsis (with A. Zezas) - until Mar. 2020
- Mr. George Korkidis (with V. Pavlidou) - until Mar. 2019
- Mr. Nikolaos Mandarakas (with V. Pavlidou) - until Nov. 2019
- Ms. Lydia Markopoulioti (with T. Diaz Santos) - since Sep. 2020
- Mr. Giorgos Savathrakis (with A. Zezas) - since Sep. 2020

Twenty (21) Undergraduate students:

- Mr. Konstantinos Avgoulas (with P. Reig)
- Ms. Foteini Bouzelou (with K. Tassis)
- Mr. Margaritis Chatzis (with N. Kylafis)
- Mr. Charalampos Daoutis (with A. Zezas)
- Mr. Thomas Doulgeris (with V. Charmandaris)
- Mr. Konstantinos Droudakis (with A. Zezas)
- Ms. Rea Kontouli (with E. Ntormousi)
- Mr. Angelos Karakonstantakis (with I. Papadakis)
- Mr. Antonis Kyriazis (with K. Tassis)
- Mr. Nikolaos Loudas (with N. Kylafis)
- Mr. Dimitris Maniadakis (with P. Reig)
- Ms. Electra Manoura (with I. Papadakis)
- Ms. Alexia Nix (with A. Zezas)
- Mr. Marios Papoutsis (with I. Papadakis)
- Ms. Alexandra Pouliasi (with V. Pavlidou)
- Mr. Charalampos Psarakis (with P. Reig)
- Mr. Konstantinos Psarras (with A. Zezas)
- Mr. Giorgos Savathrakis (with A. Zezas)
- Ms. Aikaterini-Niovi Triantafilaki (with P. Reig)
- Mr. Theodoros Tsantirakis (with A. Zezas)
- Ms. Lydia Markopoulioti (with K. Tassis)

3.2. Personnel Changes and Notable Events

During the 2019–2020 period, the following personnel changes took place:

In September 2019, all astrophysics personnel affiliated with the Institute of Electronic Structure and Laser (IESL) were formally transferred to IA. In 2019, Dr. A. Zezas was promoted to Full Professor. Dr. Tanio Diaz Santos was elected as Associate Researcher (aka Researcher C) and commenced his appointment in February 2020. In December 2020, Dr. E. Palaiologou retired from his position at the Univ. of Crete but he continues to support the activities of IA related to Skinakas

Observatory on a volunteer basis.

In September 2019, the postdoctoral appointments of Dr. F. del Sordo and Dr. E. Ntormousi ended and both moved to new postdoctoral positions in Italy. In August 2019, Dr. P. Shell moved to a lecturer position at the Univ. of Florida (USA), while Dr. Bonfini also moved to a new postdoctoral position at the Computer Science Dept. of the Univ. of Crete in December 2020. In April 2020, Dr. Carolina Casadio joined IA as postdoctoral researcher in the group of Prof. K. Tassis. Dr. Konstantina Anastassopoulou, who completed her thesis in February 2020, remained as postdoc with Prof. Zezas until September 2020, when she moved to a postdoctoral position at the Astronomical Observatory of Brera (Italy).

In 2019, two PhD students, Mr. Stylianos Romanopoulos (with V. Pavlidou) and Mr. Nikolaos Mandarakas (with K. Tassis), as well as one MSc student, Ms. Anna Konstantinou (with K. Tassis) joined IA. In 2020, two more PhD students, Mr. Georgios Korkidis (with V. Pavlidou) and Mr. Elias Kiritsis (with A. Zezas), as well as five MSc students, Mr. Charlampos Frantzeskos (with A. Zezas), Ms. Katia Gkimisi (with K. Tassis), Mr. Angelos Karakonstantakis (with I. Papadakis), Ms. Lydia Makropoulioti (with T. Diaz Santos) and Mr. Giorgos Savathrakis (with A. Zezas) joined the Institute.

In February 2020, Dr. Tanio Diaz Santos joined IA as Associate Researcher (Researcher C).

In November 2020, Dr. Ioannis (John) Antoniadis was elected as Associate Researcher (Researcher C) and was also awarded an HFRI/SNF excellence grant, as a result of his performance in an ERC grant application with IA-FORTH as a host, the year before. Dr. Antoniadis is expected to join IA in early 2021.

During 2020, 3 PhD students defended their thesis:

- Konstantina Anastasopoulou - thesis title: "Ultra-luminous X-ray sources and X-ray luminosity scaling relations in nearby galaxies" - supervisor A. Zezas.
- Konstantinos Kouroumpatzakis thesis title: "Comparison of Different Star-formation Measurement Methods and Their Correlation with X-ray Emission From Galaxies" - supervisor A. Zezas.
- Konstantinos Kovlakas - thesis title: "Populations of Ultraluminous X-ray Sources in Nearby Galaxies" - supervisor A. Zezas.

During the 2019-2020 period, 4 MSc students defended their thesis:

- Georgios Korkidis - thesis title: "Turnaround radius of galaxy clusters in N-body simulations" - supervisor V. Pavlidou. (2020)
- Elias Kyritsis - thesis title: "Spectral classification of stars based on Machine Learning methods" - supervisor A. Zezas (2020)
- Antonios Bertsias - thesis title: "Classification of X-Ray binary systems using machine learning methods" - supervisor V. Pavlidou. (2019)
- Nikolaos Mandarakas - thesis title: "Global alignments of radio-jets" - supervisor V. Pavlidou. (2019)

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

Awards:

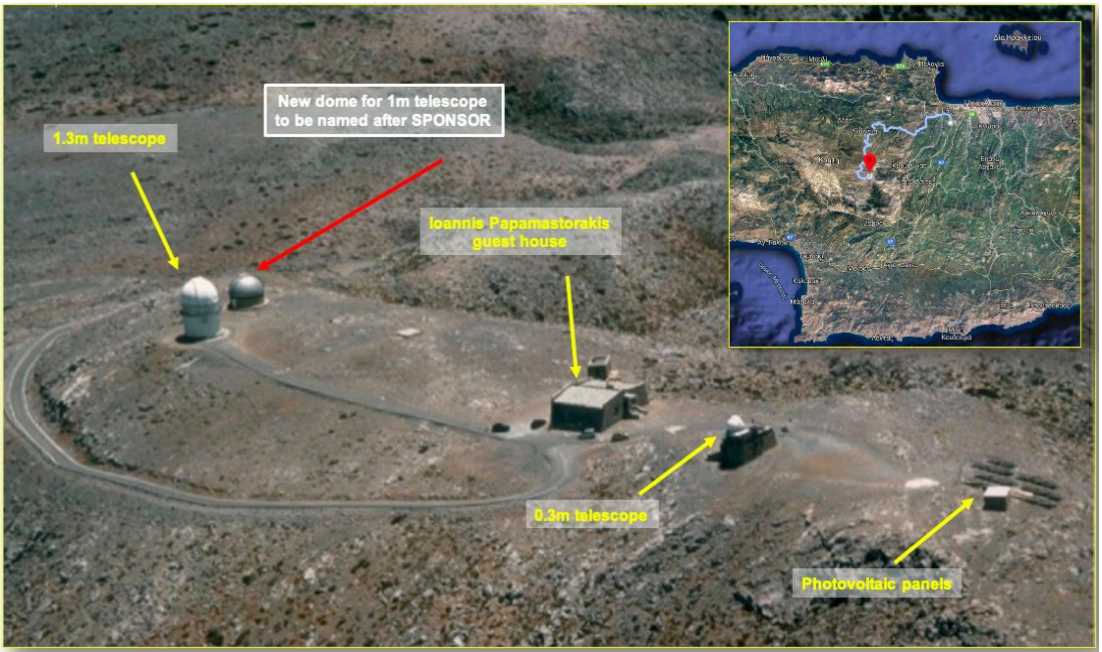
- Prof. N. Kylafis was awarded the 2019 "S. Pichorides Award for Excellence in Academic Teaching" of the Univ. of Crete.
- Prof. K. Tassis was awarded the 2019 FORTH prize in basic research.

- Mr. R Skalidis was awarded the 2019 Best PhD student Award by the Friends of FORTH.
- Dr. A. Tritsis, who had completed his PhD under the supervision of Prof. Tassis in 2018, was awarded the 2020 MERAC prize by the European Astronomical Society for the best PhD thesis in Theoretical Astrophysics.

4. FACILITIES

4.1. SKINAKAS OBSERVATORY

Skinakas Observatory[1] is a common research infrastructure of IA-FORTH and the University of Crete. 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.



An aerial view of Skinakas Observatory

Only the 1.3 m telescope was operating full-time at Skinakas Observatory in 2019 and 2020. 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 60cm telescope (focal ratio f/8 to f/3) was being upgraded in Germany since the new dome where it will be housed is expected to be completed in 2022 (see below).

The RoboPol[2] polarimeter, first established in 2013, continued its 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 normal operations of the industry and experienced some delays. A PhD student, I. Kypriotakis was recruited to participate in the design of the instrument, and spent many months at IUCAA during the reporting period. The commissioning is scheduled at the end of 2022.

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

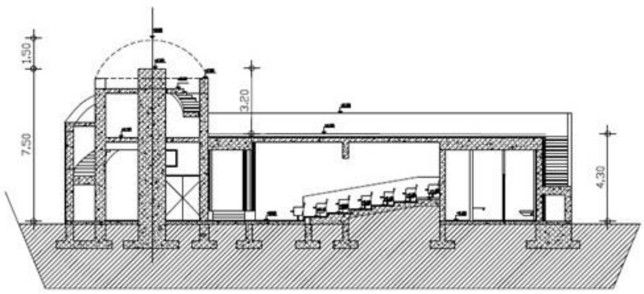
On September 29, 2019, the Rector of the University of Crete, Professor P. Tsakalides formally recognized the lifelong contribution of Ioannis Papamastorakis, Emeritus Professor at the Dept. of Physics of the Univ. of Crete and affiliated faculty of IA-FORTH, towards the creation and successful operation of Skinakas Observatory for nearly 35 years, by naming the Guest House of the Observatory as "Guest House Ioannis Papamastorakis". The event coincided with the 10 years anniversary since Prof. Papamastorakis retired from the Univ. of Crete.

The major infrastructure activities at the Observatory involved the complete administrative "regularization" of the land where the telescopes are situated. This laborious and bureaucratic process was necessary in order to commence the construction, in late 2020, of the new building with a 5.3 m dome which will house the 60 cm robotic telescope.

Moreover, the Univ. of Crete completed the construction plans and obtained the building permit for a new visitor center at Skinakas, which includes an 85-seat lecture room as well as an additional 5.3m dome. A proposal requesting funding for the new building was submitted by the town of Anogeia to the "Greece 2021" Committee.

Additional proposals requesting funding to purchase a new 1m class optical telescope were submitted to the Univ. of Crete, via its access to the national structural funds, to FORTH, via funding opportunities from the European Investment Bank, as well as to private donors. The proposal to the Univ. of Crete was successful and 325,000 Euros were earmarked towards the purchase of a new telescope.

In parallel, the staff of Skinakas Observatory commenced preparatory work in order to be evaluated by the European Union Space Surveillance and Tracking (EU-SST) as an optical ground station, which can be used to monitor satellites in orbit around the Earth. Additional efforts to join ESA projects, regarding space to ground optical communication with lasers projects, were underway.

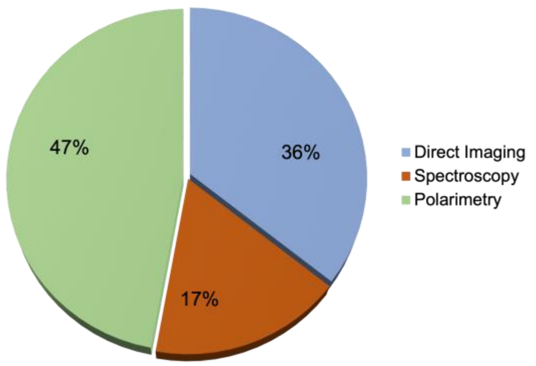


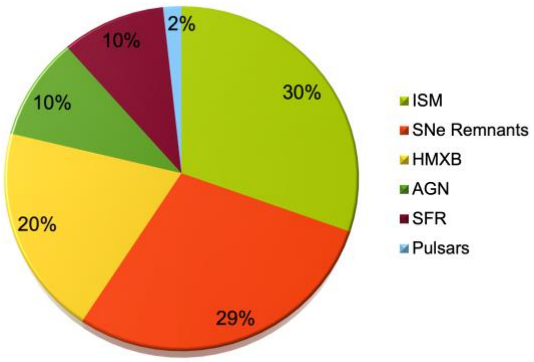
Side view of the proposed Skinakas visitor center

The main science projects during the 2019 and 2020 observing periods were:

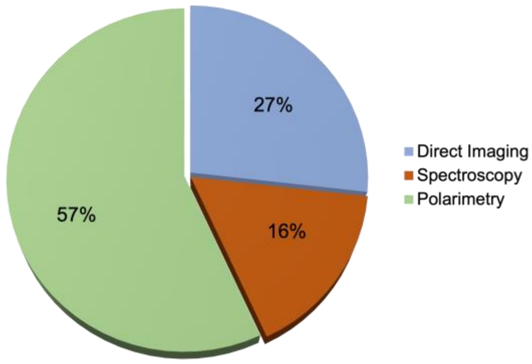
- Polarimetric monitoring of stars to establish a set of polarimetric standards
- Photometry monitoring of AGN
- Target of Opportunity opto-polarimetric follow-up of GRBs and other objects
- Polarimetry, Photometry, and Spectroscopy of Binaries with a compact star companion
- Narrow-band imaging of Galactic Supernova Remnants
- An Hα survey of nearby galaxies
- Follow-up spectroscopy of galaxies detected in the eROSITA survey

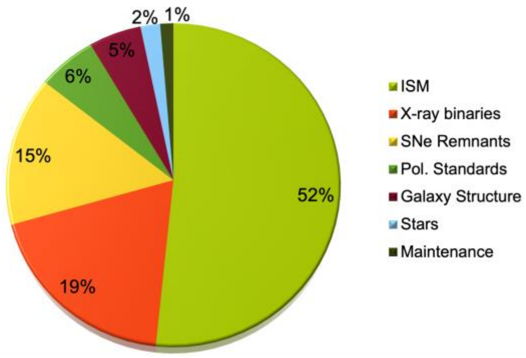
The time distribution of the **174** nights that Skinakas was operating during 2019 is presented in the following pie charts.





The time distribution of the **153** nights that Skinakas was operating during 2020 is presented in the following pie charts.





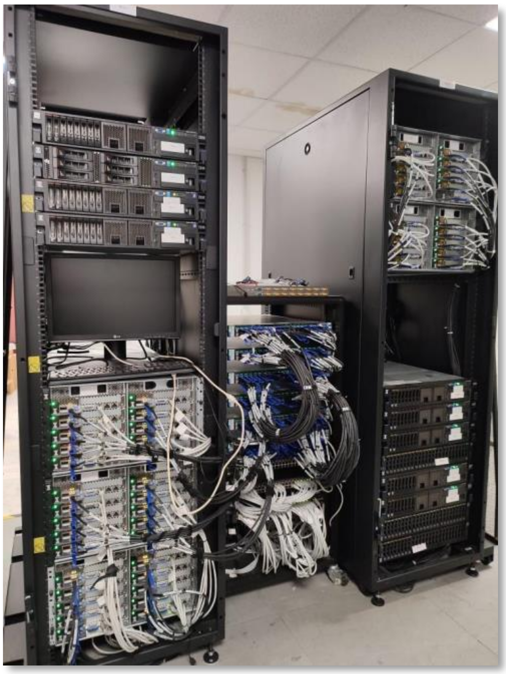
A total of **25 refereed papers** (12+13) using data from Skinakas Observatory were published in 2019 and 2020.

The tradition of "open nights" continued and the Observatory was open to the public for 7 nights, from May until September in 2019. They were very successful, with a "full-house" capacity each night. Due to the COVID-19 pandemic, the open nights had to be canceled in 2020.

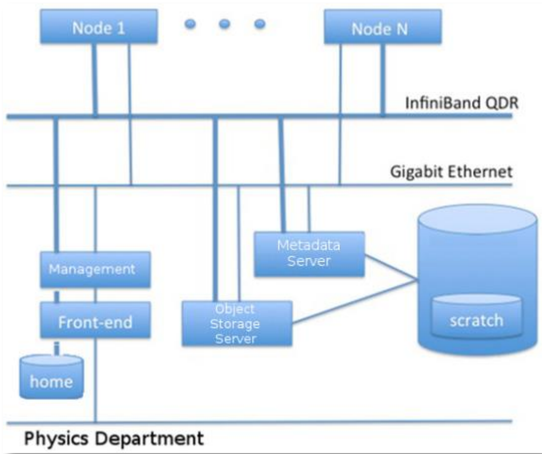
More details on Skinakas Observatory, the quality of the site, the telescopes, and the available instrumentation can be found in its recently updated web page at: http://skinakas.physics.uoc.gr/en/

4.2. METROPOLIS HPC CLUSTER

The IA provides the IT/engineering support for the operation of the "Metropolis" HPC cluster at 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 (4.7TB 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:

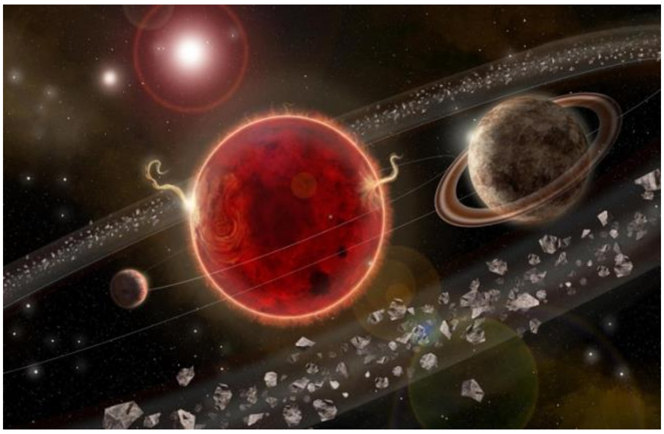
https://qcn.physics.uoc.gr/content/infrastructure/computing-facilities

5. RESEARCH HIGHLIGHTS

5.1. NEW ICY PLANET DETECTED IN OUR NEAREST EXOPLANETARY SYSTEM

Strong indications for the existence of a second planet in orbit around Proxima Centauri, the nearest star to the Sun, have been recently unveiled by an international team of scientists.

Proxima Centauri is a small red dwarf star about 4.3 light-years away from us. It is colder and smaller than our Sun, and since 2016 it has been known to host at least one planet, Proxima b. However, new data indicate the existence of a second planet, named Proxima c, orbiting in the same system. The discovery was announced by an international team of researchers, led by Fabio Del Sordo, postdoctoral researcher at the Institute of Astrophysics of FORTH, and Mario Damasso, National Institute of Astrophysics (INAF) in Torino, and it was published in Science Advances.



They used data obtained in 17 years of observations performed with the spectrographs HARPS, at La Silla Observatory, and UVES, at the Very Large Telescope on Cerro Paranal, in Chile. From these spectra, the team extracted 279 radial velocities aimed at monitoring the possible wobbling of Proxima Centauri as a consequence of planets orbiting around it. In this dataset, Damasso and Del Sordo unveiled a signal consistent with the existence of Proxima c, an exoplanet at least six times more massive than our Earth. The detection of Proxima c is very challenging due to its long orbital period of about 5.2 years and its small mass. Its estimated equilibrium temperature would be of about 40 K, or -230 degrees Celcius, as it orbits at around 1.5 Astronomical Units away from its host star: an icy planet, unlikely to host life as we know it.

What makes this exoplanet fascinating, beyond its proximity to our Solar System, is the possibility to observe it with various techniques, such as astrometry and direct imaging. In particular, the team illustrated the possibility of confirming the existence of Proxima c with astrometric observations underway with the Gaia satellite. When the Gaia end-of-mission dataset is released, astrometry will probably prove its existence, and tell us both its real mass and exact orbit.

With this discovery, Proxima becomes the nearest multi-planetary system to us, and new compelling questions immediately arise: What is the composition of Proxima c's atmosphere? Does it host a system of Saturn-like rings? How did it form?

New observations, analysis and modelling will hopefully soon shed light on this brand-new celestial object.

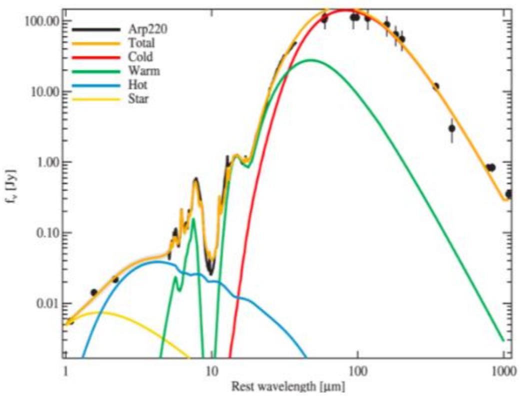
Article: M. Damasso, F. Del Sordo, et al., "A low-mass planet candidate orbiting Proxima Centauri at a distance of 1.5 AU." Science Advances 6, eaax7467 (2020)

5.2. UNDERSTANDING THE PHYSICS OF U/LIRGS WITH SPITZER

Luminous and ultraluminous infrared galaxies (LIRGs/ULIRGs) have been an active area of galaxy research since their discovery more than three decades ago. With its vast increase in sensitivity in the infrared, Spitzer played a major role in exploring these galaxies in the local Universe, and at high redshifts.

In a review published in Nature Astronomy, L. Armus and B.T. Soifer of Caltech (USA) and Vassilis Charmandaris of IA-FORTH and the Univ. of Crete, highlight some of the major discoveries made with the Infrared Spectrograph (IRS) on Spitzer, through observations of luminous and ultraluminous infrared galaxies from the local universe to cosmic noon. These include measuring the role of starbursts and actively accreting supermassive black holes as power sources, finding evidence for energetic feedback on the atomic and molecular interstellar gas and dust and identifying the physical properties of luminous infrared galaxies on and off the galaxy star-forming main sequence.

Studies of low-redshift LIRGs and ULIRGs with Spitzer produced powerful new infrared tools and spectral templates for understanding the energy sources, dynamics, and multi-phase interstellar media in normal and active galaxies at all redshifts. The rise of composite starburst and AGN sources in galactic mergers, direct evidence for energetic feedback on the host ISM, and connections between infrared source compactness and the galaxy main sequence were all Spitzer successes.



Modeling of the infrared Spectral Energy Distribution of Arp220 using CAFE (Marshall et al. 2018).

However, limitations in the spatial and spectral resolution of Spitzer left unanswered questions about how star formation proceeds under such extreme conditions, and how SNe and AGN interact with and affect gas on sub-kpc physical scales. Even using the high-resolution IRS spectra, dynamic studies were restricted to extremely fast-moving gas, giving us a biased view of feedback. The spatial resolution, even in the nearest ULIRGs, was ~1-2 kpc at best, averaging over tens or hundreds of star forming regions and providing limits to the sizes and energy densities in the centers of these galaxies. At high redshifts, estimates of the power sources in SMGs and DOGs were often based on single features averaged over entire galaxies, and with relatively low signal to noise.

The James Webb Space Telescope is poised to provide our clearest look yet at the detailed physics operating inside ULIRGs at $z < 2$, and enable us to build and explore samples of galaxies in place well before the peak epoch of star formation. The Mid Infrared Imager Instrument (MIRI) provides an example of the leap in capabilities expected on JWST. MIRI covers slightly less wavelength than the IRS on Spitzer, but it is roughly 50 times more sensitive and it has a spectral resolving power ~5 times higher, and a spatial resolution nearly 10 times better than Spitzer.

Article: L. Armus, V. Charmandaris, B. T. Soifer, "Observations of luminous infrared galaxies with the Spitzer Space Telescope", Nature Astronomy, Vol. 4, pages 467–477 (2020)

5.3. MODELING THE EVOLUTION OF A BINARY SYSTEM LEADING TO A NEUTRON STAR COLLISION

As a star evolves, depleting the hydrogen in its nucleus and becoming a supergiant, its size may increase by more than 500 times. If the star is in a binary system it enters the so-called common envelope phase, in which the evolved star engulfs its companion upon expansion. During this phase orbital kinetic energy of the inspiraling companion is converted to kinetic energy of the envelope of the giant star and it is a critical evolutionary stage forming short-period, compact-object binary systems, such as coalescing double compact objects, X-ray binaries, and cataclysmic variables.

An international team lead by Prof. Anastasios Fragos at the Univ. of Geneva, Switzerland in which Jeff Andrews and Andreas Zezas of IA-FORTH are also members, performed the first detailed hydrodynamical modeling of the inspiral of a 1.4 $M_\odot$ neutron star (NS) inside the envelope of a 12 $M_\odot$ red supergiant star. Their numerical work enables the self-consistent calculation of the drag force experienced by the NS and the back-reaction onto the expanding envelope as the NS spirals in.

They find that nearly all of the hydrogen envelope escapes, expanding to very large radii (~100 Astronomical Units) where it forms an optically thick envelope with temperatures low enough that dust formation occurs. The orbit of the NS is simulated until only 0.8 $M_\odot$ of the hydrogen envelope remains around the giant star's core. Their numerical results suggest that the inspiral of the NS will continue until another $\approx 0.3 M_\odot$ are removed, at which point the remaining envelope of the giant star will retract.

Artist's rendering of a binary star with a Neutron Star as one companion

Upon separation, a phase of dynamically stable mass transfer onto the NS accretor is likely to ensue, which may be observable as an ultraluminous X-ray source.

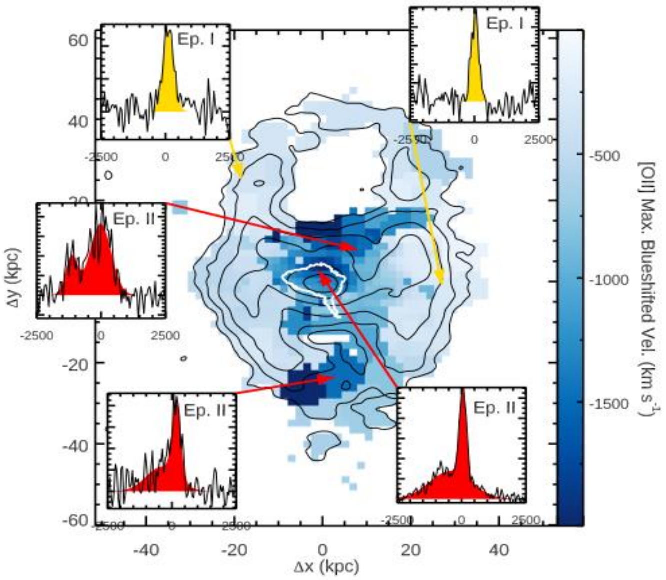
The resulting binary, comprised of a detached 2.6 $M_\odot$ helium star and an NS with a separation of 3.3-5.7 $R_\odot$, is expected to evolve into a merging double neutron-star, analogous to those recently detected as sources of gravitational waves by LIGO/Virgo.

Article: A. Fragos, J. Andrews, E. Ramirez-Ruiz, G. Meynet, V. Kalogera, R.E. Taam, A. Zezas "The Complete Evolution of a Neutron-star Binary through a Common Envelope Phase Using 1D Hydrodynamic Simulations", The Astrophysical Journal Letters, Vol. 883, 45 (2019)

5.4. CRASHING GALAXIES DRIVE HUGE SHOCKWAVES INTO DEEP SPACE

Research conducted by an international team of astronomers, published in the scientific journal Nature, revealed an enormous nebula around an extreme form of a merging galaxy.

The galaxy named Makani (Hawaiian for 'wind') is pushing a large fraction of its gas into the space between galaxies called the circumgalactic medium. The team observed a wind in a glowing halo of extended oxygen out to extreme distances (one of the largest such nebulae ever observed) at different speeds and locations, corresponding to the different times at which the galaxy began rapidly forming stars. This enabled them to track the detailed energetics of the event. Seeing this expansive outflow also provides a missing link to explaining how metals can be displaced far out into the intergalactic medium (the space between galaxies).



Velocity maps of the galactic wind. The velocities are from fits to Voronoi-binned [O II] data and are calculated from the red side of the cumulative velocity distribution function to specified percentiles as maximum blue shifted velocity $v_{max}=v_{98\%}=v_{50\%}-2\sigma$ *(see paper)*

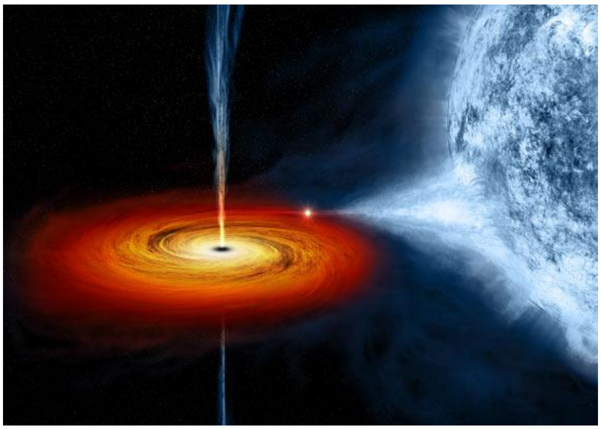
"What is also remarkable is that the aging and dying stars appear to be powerful enough on their own to do all of the work without the need for a supermassive black hole's help, though we expect one to be buried down in the center of the merging galaxies, maybe quite literally under a lot of dust and gas," remarked Dr. Paul Sell, who, as a member of a small collaboration, contributed to this research while a scientist at the Institute of Astrophysics of FORTH; Dr. Sell has since recently joined the faculty at the University of Florida, USA.

Though this galaxy weighs about as much as our Milky Way Galaxy, we don't see anywhere near such an extreme situation in our own Galaxy or even in other one relatively nearby. Seeing such heavy galaxies catastrophically colliding is pretty rare, especially those that have lots of cold gas from which to form new stars. The funneling and collision of the cold gas deep in the gravitational well of the merging galaxies produces a very large number of stars in a short time and in a small space. The heaviest stars formed from this burst of star formation quickly die, sending out strong winds and shockwaves that blow the gas out of the galaxy, shooting it at high speeds out into deep space.

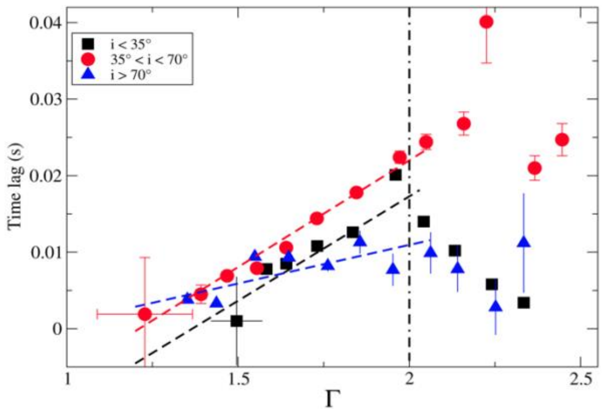
Article: D. Rupke, … P. Sell, et al., "A 100-kiloparsec wind feeding the circumgalactic medium of a massive compact galaxy", Nature Vol. 574, pages 643–646 (2019)

5.5. INCLINATION EFFECTS ON THE X-RAY EMISSION OF GALACTIC BLACK-HOLE BINARIES

Galactic black-hole X-ray binaries (BHBs) emit a compact, optically thick, mildly relativistic radio jet when they are in hard and hard-intermediate states. In these states, BHBs exhibit a correlation between the time lag of hard with respect to softer photons and the photon index of the power law component that characterizes the X-ray spectral continuum above ~10 keV. The correlation, however, shows large scatter. In recent years, several works have brought to light the importance of taking into account the inclination of the systems to understand the X-ray and radio phenomenology of BHBs. We have investigated the role that the inclination plays on the correlation between the time lag and photon index.



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



Average correlation between the time lag and photon index for Low-inclination BHBs (i ≤ 35°; black squares), Intermediate-inclination BHBs (35 ° < i ≤ 70°; red dots), and High-inclination BHBs (i >70°; blue triangles).

P. Reig and N. Kylafis of IA-FORTH computed energy spectra and light curves of BHBs using the Monte Carlo technique that reproduces the process of Comptonization in the jet. The authors can account for the inclination effects by recording the photons that escape from the jet at different angles. From the simulated light curves and spectra, they obtained model-dependent photon index and time lags, which they compared with those obtained from the real data.

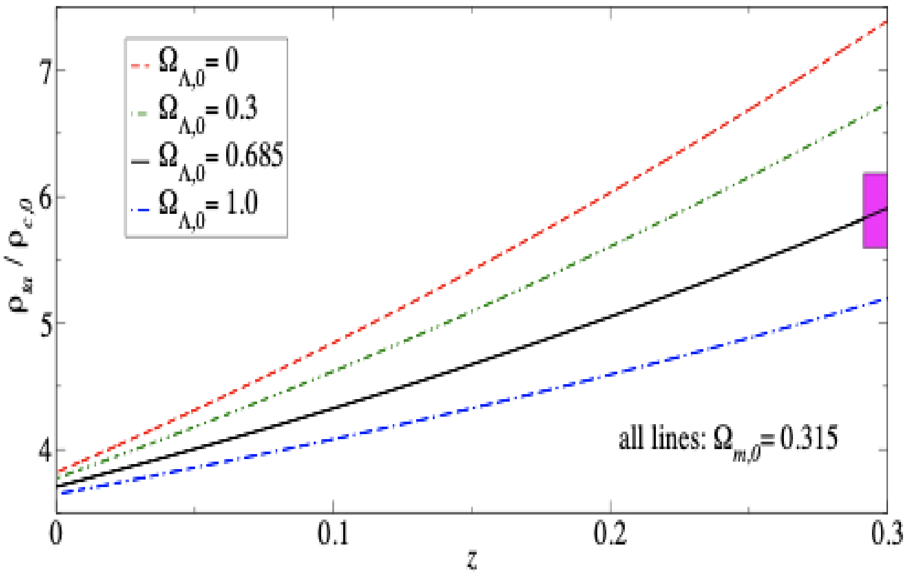
The large dispersion observed in the time lag – photon index correlation in BHBs can naturally be explained as an inclination effect. High-inclination systems display, on average, a flatter correlation. Comptonization in the jet explains the steeper dependence of the lags on the photon index in low- and intermediate-inclination systems than in high-inclination systems.

The most remarkable result of this work is the fact that it can reproduce the observed correlations between time lag and photon index for systems with different inclination angles, with the same set of models, by simply looking at the jet with different viewing angles.

Article: P. Reig, N. Kylafis, Inclination effects on the X-ray emission of Galactic black-hole binaries, A&A, 625, A90 (2019).

5.6. A NEW PROBE OF DARK ENERGY

Large scale structures, such as groups of galaxies, galaxy clusters, and superclusters, have long been the workhorses of observational cosmology. Now a new way to observe them promises to provide new insights to one of the most mysterious ingredients of our Universe: dark energy. In an expanding Universe of any composition, the average matter density within the scale on which a structure detaches from the Hubble flow, usually termed the turnaround density, is universal: the same for all cosmic structures at a given redshift, independently of their mass or their growth history. In a recent publication, IA-FORTH scientists, led by Prof. V. Pavlidou, showed that the low-redshift evolution of the turnaround density constrains the cosmological parameters and it can be used to derive a local constraint on $\Omega_{\Lambda,0}$ alone, independent of $\Omega_{m,0}$. The turnaround density thus offers a promising new method for exploiting upcoming large cosmological datasets.



Evolution of the turnaround density with redshift z, for Ω_m = 0.315 and different values of Ω_Λ. The magenta shaded box shows the accuracy that can be achieved by measuring the turnaround density in 100 clusters at z = 0.3 with fractional uncertainty of 50% in each, and is indicative of the discriminating power of such an experiment.

Article: V. Pavlidou, G. Korkidis, T. Tomaras and D. Tanoglidis, Turnaround density as a probe of the cosmological constant, A&A, 638, L8 (2020).

6. RESEARCH AREAS

In the following, we present the research areas in which members of the IA contributed in the period of the report. 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 manifestation of accretion of material onto the supermassive black-holes (SMBHs; from several millions to several billion times the mass of the Sun) found at the centers of massive galaxies, a phenomenon producing the so-called active galactic nuclei (AGN). The result of this accretion is the production of intense radiation over the whole electromagnetic spectrum and often the ejection of material in the form of collimated relativist radio jets or larger scale gas outflows.

COSMOLOGY

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

Specific Background:

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

Current efforts:

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

QUASAR ACTIVITY AND EARLY GALAXY ASSEMBLY

(Researchers involved: T. Diaz-Santos)

Specific Background:

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

Current efforts:

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

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 2020 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:

<u>AGN variability</u>: 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.

<u>ROBOPOL blazars</u>: 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, 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.

Galaxy interactions and mergers: Galaxy mergers trigger vigorous star formation and are responsible for activating their central SMBHs. Energetic feedback from these sources can generate high-velocity gas outflows heating up and carrying away a large fraction of the gas mass within the host galaxy, thereby rapidly truncating future star formation. We study galaxy mergers in the IR via spatially resolved mapping and integral field unit (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.

Star-formation and AGN activity in normal, Milky-way type, nearby galaxies: Our group is leading studies of the star-forming activity in a representative sample of galaxies in the local Universe. The goals of this project are to: (a) compare different methods for measuring the star-formation rate and address the factors that influence these measurements; (b) measure the connection between recent and past star-forming activity in galaxy-wide as well as sub-galactic scales; (c) study the connection between star-forming activity and AGN activity. As part of this study, we have also embarked on the assembly of the Heraklion Extragalactic Catalogue (HECATE). This is the most complete, value-added catalogue of galaxies in the local Universe, including information on their stellar content (star-formation rate, stellar mass), metallicity, AGN activity. Such a catalogue is extremely useful for statistical investigations of nearby galaxies, but also for the fast identification and characterization of the hosts of transient events (e.g., gravitational-wave sources, gamma-ray bursts, tidal disruption events, supernovae etc).

Star-formation and X-ray binary populations in nearby galaxies: X-ray binaries are a key tool for understanding the evolution of binary stellar systems and the formation of their end-points such as sources of gravitational waves and short gamma-ray bursts. Studies of the discrete X-ray source populations (in particular accreting sources) in nearby galaxies allow us to: (a) probe areas of the parameter space that are not present in our neighborhood (e.g., different metallicity or star-formation history), and (b) obtain large statistical samples and explore rare types of systems. We have embarked in a systematic study of the X-ray binary populations and their integrated X-ray emission in nearby galaxies and their connection with their parent stellar populations (star-formation history, metallicity, etc) and star-cluster parameters. In 2019 and 2020 we published several systematic studies of the X-ray binary populations in individual nearby galaxies (including a seminal study on the formation efficiency of the X-ray binaries in the SMC) or small samples of galaxies. 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 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: 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.

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

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

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.

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. 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.

EXTRASOLAR PLANETARY SYSTEMS

(Researchers involved: F. Del Sordo, 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: 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 principal component analysis of imaging and spectroscopic data affected by source confusion. These methods are particularly relevant for the X-ray and gamma-ray regime. In addition, we are working on methods for the analysis of LogN-LogS distributions at the Poisson limit accounting for source confusion. In the general context of our efforts in the area of Astrostatistics we also held a regular Astrostatistics seminar aiming at the introduction of students and researchers to statistics techniques and an Astrostatistics school.

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.

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.

- ERC Consolidator Grant "A-Bingos", entitled "Accreting Binary populations in Nearby Galaxies: Observations and Simulations", (P.I.: A. Zezas, budget: €1,242,000, duration: 2014 – 2019)
- Stavros Niarchos Foundation Grant in support of the project "PASIPHAE" (P.I.: K. Tassis, budget: $1,457,000, duration: 2016 – present)
- H2020 RISE, entitled "ASTROSTAT: Development of novel statistical tools for the analysis of astronomical data", (P.I.: A. Zezas, budget: €526,500, duration: 2016 – 2020)
- Marie Curie Individual Fellowship "ORIGAMI", entitled: "The Origin of the Galactic Magnetic Field", (fellow: Ntormousi, budget: €153,000, duration: 2017 – 2019)
- 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)
- 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)
- 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)
- IKY "Galactic SNe Remnants: Exploring an unexploited treasure", (fellow: I. Leonidaki, budget: €26,400, duration: 2020 – 2021)

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
  - 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 period of this report, members of the IA served in a number of national and international committees. Specifically:

Professor V. Charmandaris was a member of the Haut Comité Scientifique of Paris Observatory (France) from 2015 until 2020, a member of the Scientific Council of INSU/CNRS since 2019, and a member of the Astronomy Working Group of ESA since 2019. He also serves, since 2013, as the representative of Greece to the Board of Directors of the scientific journal "Astronomy & Astrophysics" and since 2017 he is a member of the Executive Committee. In 2020 he was elected President of the Hellenic Astronomical Society and he 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 and also served as the Chairman of the Department of Physics until September 2019.

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 was re-elected as a member of the Governing Council of the Hellenic Astronomical Society. She is also 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. In 2020 he was elected as a member of the Governing Council of the Hellenic Astronomical Society

Professor A. Zezas is serving as a member of the NuSTAR Users Committee as well as 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

- "Exploring the Infrared Universe: The Promise of SPICA", 20-23 May 2019
- "Workshop on Computational Intelligence in Remote Sensing and Astrophysics", 17-19 Jul. 2019
- "Summer school for astrostatistics in Crete", 18-21 Jul. 2019
- "Crete III: Through dark lanes to new stars - Celebrating the career of Prof. Charles Lada", 23-27 Sep. 2019

Due to the restrictions of the COVID-19 pandemic no conferences were organized in 2020.

On October 15-18, 2019, three members of the External Advisory Committee, P. Caseli, G. Helou and J. Spyromilio, visited IA for three days. They had close interactions with all members, visited Skinakas Observatory, and provided critical suggestions on the vision of the new institute.

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 IA-FORTH. Under the auspices of the Lectureship, one distinguished theoretical astrophysicist is invited annually at FORTH for a brief visit.

The inaugural 2019 "Nick Kylafis Lectureship" was awarded to Prof. Dr. Rashid Sunyaev, Director Emeritus, Max Planck Institute for Astrophysics (Germany). Prof. Sunyaev visited the Institute of Astrophysics on October 24 and 25, 2019. His lecture was entitled "Detecting very hot plasma in the clusters of galaxies".

The 2020 "Nick Kylafis Lectureship" was awarded to Prof. Joseph Silk, Professor of Physics at the Institut d'Astrophysique de Paris, Université Pierre et Marie Curie (France). Due to the restrictions of the COVID-19 pandemic the visit of Prof. Silk was postponed for the following year.

11. EDUCATION AND TRAINING

The affiliated faculty members of IA also offer a number of undergraduate and graduate astronomy courses as part of their teaching responsibilities in the Dept. of Physics. These are in addition to other physics courses they teach. For the calendar year period 2019-2020 these were:

- SPRING SEMESTER
  - "Astrophysics II" (Galactic and extragalactic astrophysics) (A. Zezas)

- FALL SEMESTER
  - "Astrophysics I" (stellar structure and evolution) - V. Charmandaris
  - 'Observational Cosmology" - I. Papadakis
  - "Astrophysics III" (Advanced radiative processes and radiative transfer) - V. Pavlidou

12. PUBLIC OUTREACH

All members of the IA were involved in a number of public outreach activities throughout the year. These consist of giving public lectures, mostly in the island of Crete, along with dedicated tours to the facilities of Skinakas Observatory, as well as TV and radio interviews. The group also supports the activities organized by the local amateur astronomical societies in Crete.

Skinakas Observatory opened its doors to the public in 2019 for five Sunday nights and five more special visits were offered to select groups. Hundreds of people visited the Observatory, where they were guided to the facilities by members of the IA and had the chance to look through the main 1.3 m telescope. In 2020 the open nights were canceled due to the COVID-19 pandemic.

Several members of IA-FORTH actively participated in the European Researchers' Night (September 2019), which has become one of the most important events in science for the local community of Heraklion (Crete). As in the previous years, the events of 2019 were very successful with large participation of the public. In the exposition of Skinakas Observatory participated three senior astronomers (K. Tassis, A. Zezas and P. Reig), one postdoc (E. Ntormousi), 4 PhD students (K. Kouroumpatzakis, M. Kopsacheili, K. Athanasopoulou and R. Skalidis) and one technician (A. Steiakaki). The show included short video projections of the observatory and a selection of pictures of cosmic objects obtained with the cameras of the observatory.

Due to the COVID -19 restrictions, the activities of the European Researchers' Night in 2020 consisted of radio and TV interviews to local media, newspaper articles describing the group's activities, and two videos presenting science projects the Skinakas Observatory is undertaking.

13. VISITORS

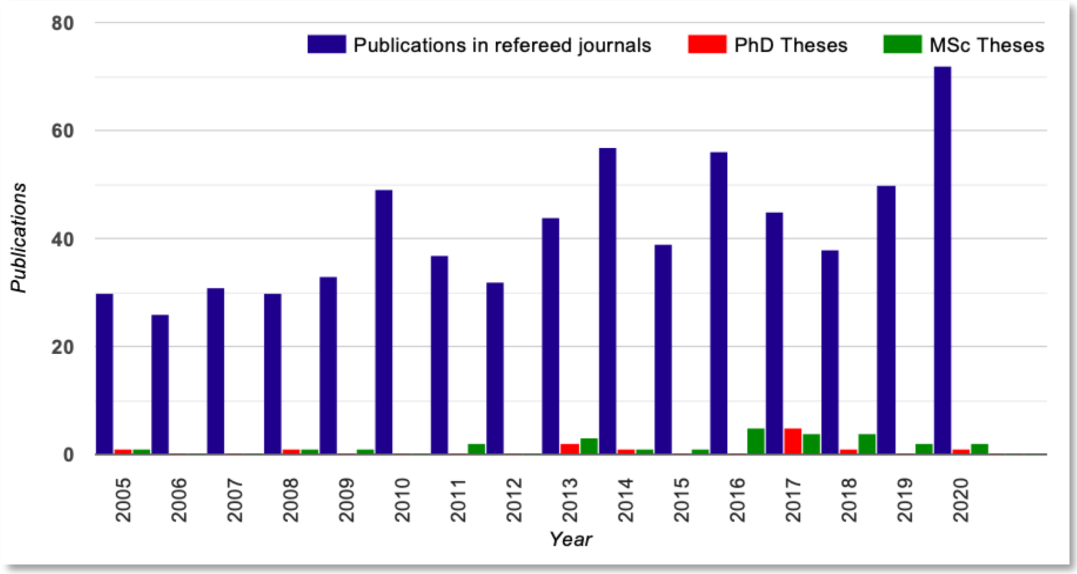
A total of **26** scientists visited IA during the 2019 and 2020 calendar years in order to collaborate with our staff and/or give seminars. These researchers were: Dr. John Antoniadis (MPIfR, Germany), Dr. Francois Boulanger (Ecole Normale Superieure), Dr. Carolina Casadio (MPIfR, Germany), Prof. Paola Caselli (MPE, Germany), Prof. Manos Chatzopoulos (Louisiana State Univ., USA), Prof. Francoise Combes

(Observatoire de Paris & College de France, France), Dr. Tanio Diaz Santos (Univ. Diego Portales, Chile), Dr. David Elbaz (CEA/Saclay, France), Dr. Torsten Ensslin (MPA, Germany), Prof. Dimitrios Giannios (Purdue Univ., USA), Dr. Vincent Guillet (Univ. Paris-Sud, France), Prof. Jenni Jormanainen (Bar Ilan Univ, Israel), Prof. Telemachos Mouschovias (Univ. of Illinois Urbana-Champaign, USA), Prof. Kallia Petraki (Sorbonne Univ, France), Dr. Jean-Luc Stark (CEA/Saclay, France), Prof. Alkistis Pourtsidou (Queen Mary Univ. of London, UK), Prof. Anthony Readhead (Caltech, USA), Dr. Hendrik Spruit (MPA, Germany), Dr. Jason Spyromilio (ESO, Germany), Prof. Rashid Sunyaev (MPA, Germany), Prof. Joachim Truemper (MPE, Germany), Prof. Nektarios Vlahakis (Univ. of Athens, Greece), Prof. Andrzej Zdziarski (Polish Academy of Sciences, Poland), Dr. Hans Zinnecker (Astrophysical Institute of Potsdam, Germany), Dr. Wenda Zhang (Czech Academy of Sciences, Czech Republic), and Dr. Yannis Zouganelis (ESA, Spain).

14. PUBLICATION STATISTICS

The researchers and affiliated members at the IA have produced **122** publications that appeared in print in international refereed journals (according to NASA/ADS) during the 2019-2020 calendar year period (50 publications during 2019 and 72 during 2020). This corresponds to **3** refereed publications per PhD researcher per year. A complete list of the publications is presented in the Appendix.

The histogram below 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

Phone: +30 2810 394200
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.

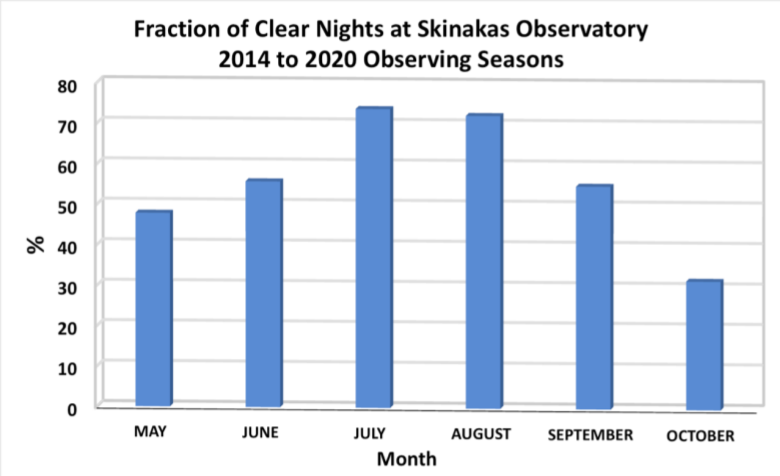
Facilities at sea level

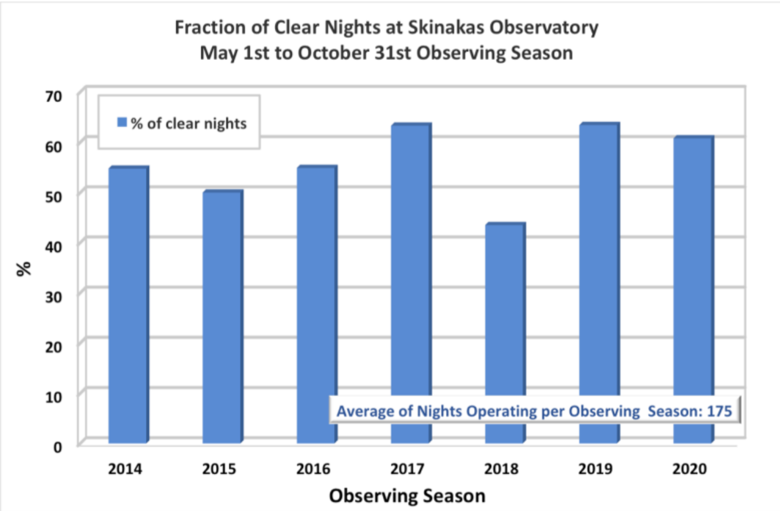
Offices for staff are located on the premises of the Department of Physics of the University of Crete. An instrumentation lab with an optical table and a computing room are also part of the sea-level facilities. The observatory owns two vehicles used for the transportation of material and personnel.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

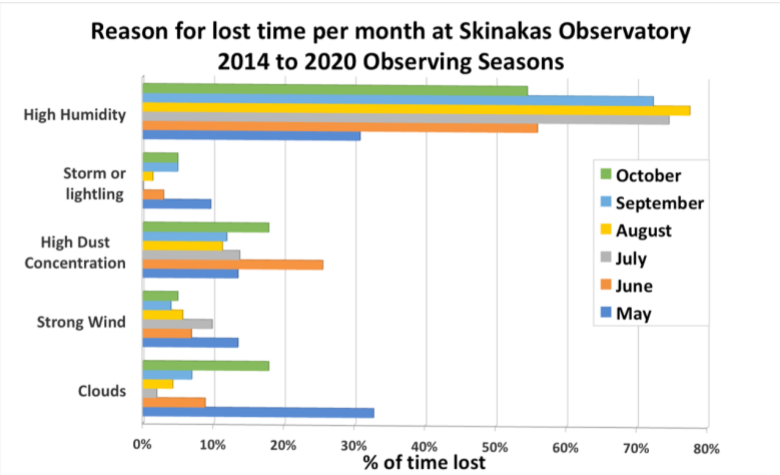
Scientific Operations

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 2020). The average number of nights the Observatory operates per season is 176 with the average full clear nights to be over 60% the past three years. The best months are July and August, with over 70% of the nights being clear. High humidity is the major reason for not observing (~50% of the cases) with clouds and then dust, due to southern winds, being the other two reasons.







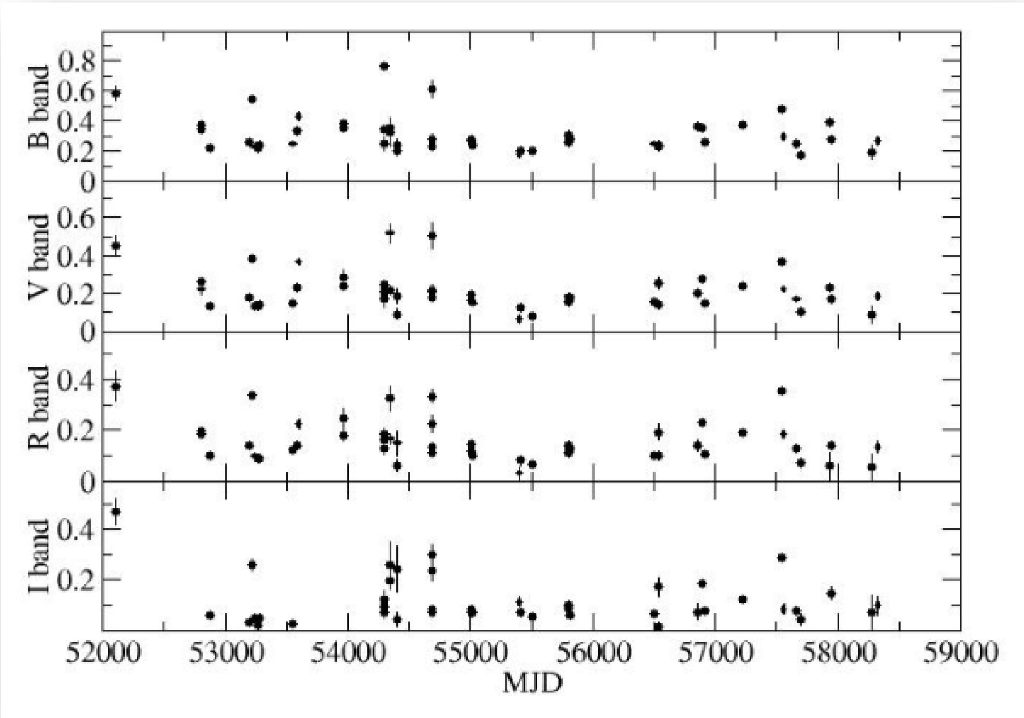
More specifically the reasons the observatory did not operate due to weather were:

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

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

Atmospheric Extinction

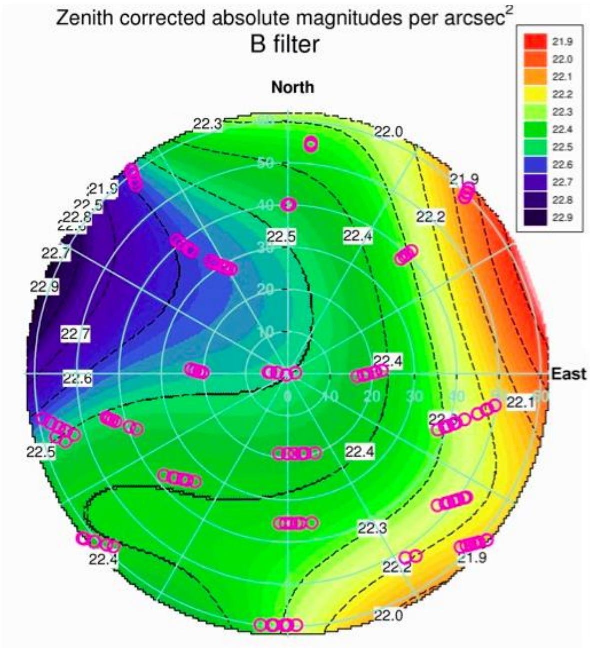
Atmospheric extinction is the astronomical parameter that evaluates sky transparency. Sources causing degradation of the sky transparency are clouds (water vapor) and aerosols (dust particles included). The extinction values and their stability throughout the night are essential for determining the accuracy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

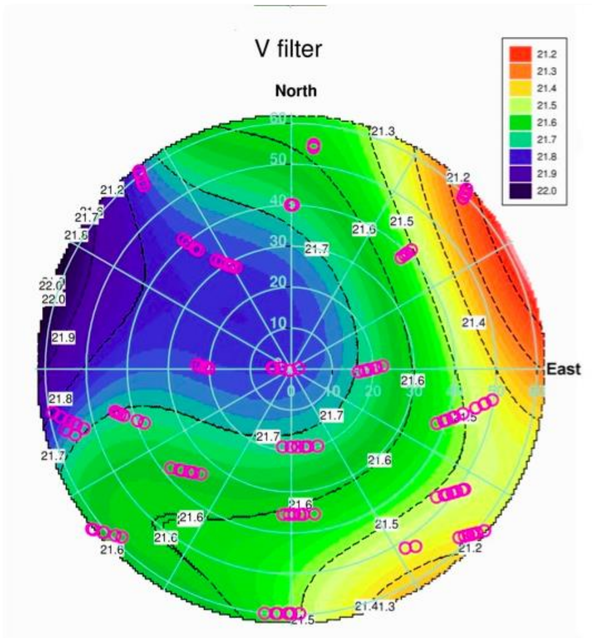


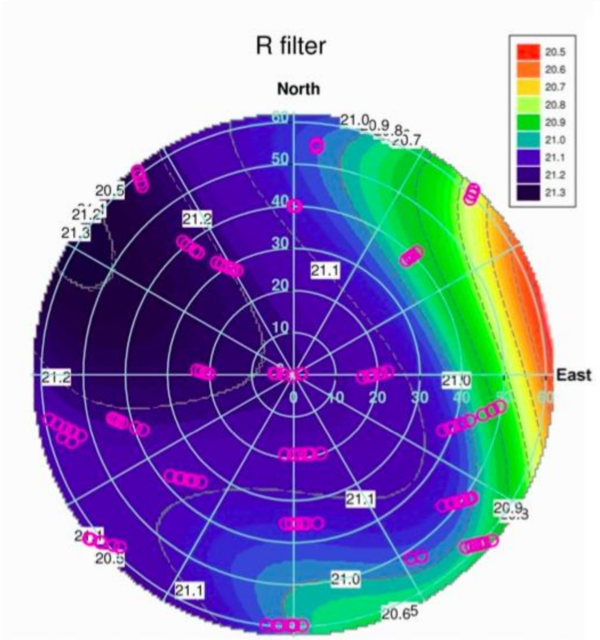
The extinction at the Skinakas Observatory during photometric nights are (in mag/airmass): 0.26 ± 0.06 for B, 0.17 ± 0.03 for V, 0.13 ± 0.04 for R, and 0.09 ± 0.06 for I.

Night Sky Brightness

Night sky BVR brightness observations were conducted 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.

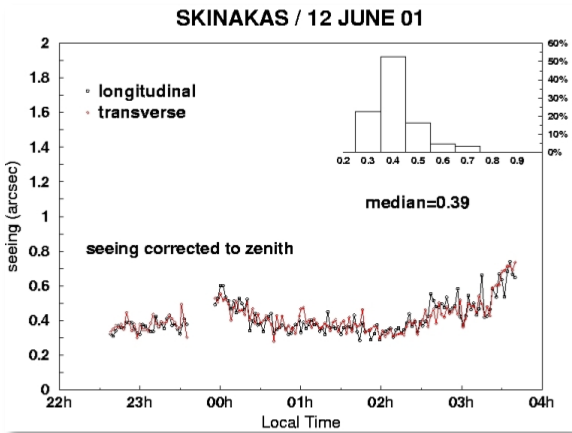
Seeing conditions

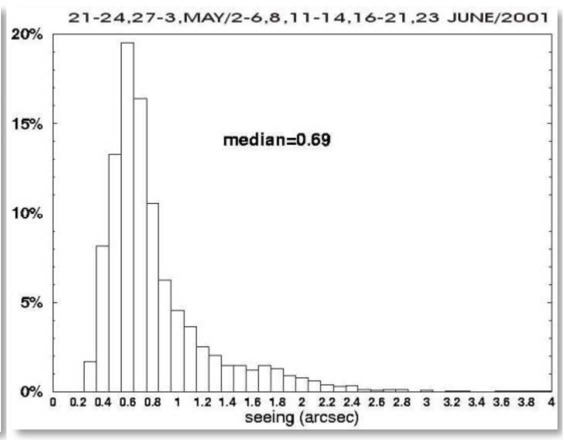
The Skinakas Summit is an excellent site for astronomical observations. As it can be seen in the satellite photo to the right, showing the island of Crete and Africa in yellow at the bottom of the photo, since the winds are typically from the north and the closest land mass to the north is the island 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 being upgraded in 2020 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 x 20 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

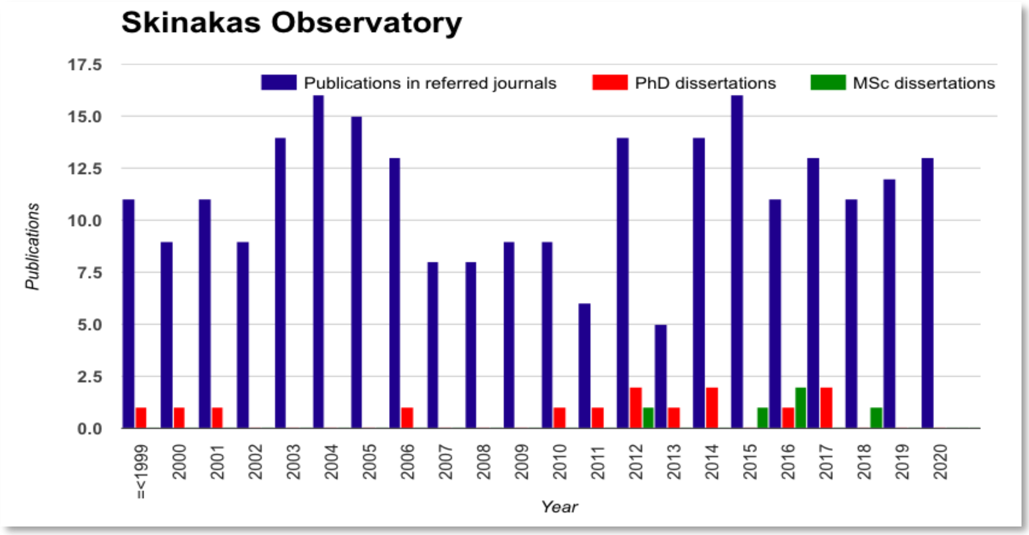
The 30 cm Schmidt-Cassegrain telescope (f/3.2) was the first one installed on Skinakas Observatory in 1986 and it was equipped with the first CCD camera ever used for astronomy in Greece.

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 2020 observations from the telescopes at Skinakas Observatory have resulted in a total of 247 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 2019 & 2020 REFEREED PUBLICATION LIST

Year 2019:

1. Anastasopoulou, K., Zezas, A., Gkiokas, V., and Kovlakas, K., "*Do sub-galactic regions follow the galaxy-wide X-ray scaling relations? The example of NGC 3310 and NGC 2276".* Monthly Notices of the Royal Astronomical Society, 2019. **483**(1) p.711-733
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3. Andrews, J.J. and Zezas, A., "*Double neutron star formation: merger times, systemic velocities, and travel distances".* Monthly Notices of the Royal Astronomical Society, 2019. **486**(3) p.3213-3227
4. Antoniou, V., Zezas, A., Drake, J.J., Badenes, C., Haberl, F., Wright, N.J., Hong, J., Di Stefano, R., Gaetz, T.J., Long, K.S., Plucinsky, P.P., Sasaki, M., Williams, B.F., Winkler, P.F., and Collaboration, S.X., "*Deep Chandra Survey of the Small Magellanic Cloud. III. Formation Efficiency of High-mass X-Ray Binaries".* Astrophysical Journal, 2019. **887**(1): 20
5. Bitsakis, T., Sanchez, S.F., Ciesla, L., Bonfini, P., Charmandaris, V., Cervantes Sodi, B., Maragkoudakis, A., Diaz-Santos, T., and Zezas, A., "*The integrated properties of the CALIFA galaxies: model-derived galaxy parameters and quenching of star formation".* Monthly Notices of the Royal Astronomical Society, 2019. **483**(1) p.370-380
6. Blinov, D. and Pavlidou, V., "*The RoboPol Program: Optical Polarimetric Monitoring of Blazars".* Galaxies, 2019. **7**(2): 46
7. Bonanno, A., Corsaro, E., Del Sordo, F., Palle, P.L., Stello, D., and Hon, M., "*Acoustic oscillations and dynamo action in the G8 sub-giant EK Eridani".* Astronomy & Astrophysics, 2019. **628**: A106
8. Bonanos, A.Z., Yang, M., Sokolovsky, K.V., Gavras, P., Hatzidimitriou, D., Bellas-Velidis, I., Kakaletris, G., Lennon, D.J., Nota, A., White, R.L., Whitmore, B.C., Anastasiou, K.A., Arevalo, M., Arviset, C., Baines, D., Budavari, T., Charmandaris, V., Chatzichristodoulou, C., Dimas, E., Duran, J., Georgantopoulos, I., Karampelas, A., Laskaris, N., Lianou, S., Livanis, A., Lubow, S., Manouras, G., Moretti, M.I., Paraskeva, E., Pouliasis, E., Rest, A., Salgado, J., Sonnentrucker, P., Spetsieri, Z.T., Taylor, P., and Tsinganos, K., "*The Hubble Catalog of Variables (HCV)".* Astronomy & Astrophysics, 2019. **630**: A92
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