Finnish Centre for Astronomy with ESO

Annual Report

2021

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FINNISH CENTRE FOR ASTRONOMY WITH ESO, ANNUAL REPORT 2021

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Based on a template by Andrea Hidalgo.

May, 2022

Cover: The centre of the Milky Way (courtesy: ESO)

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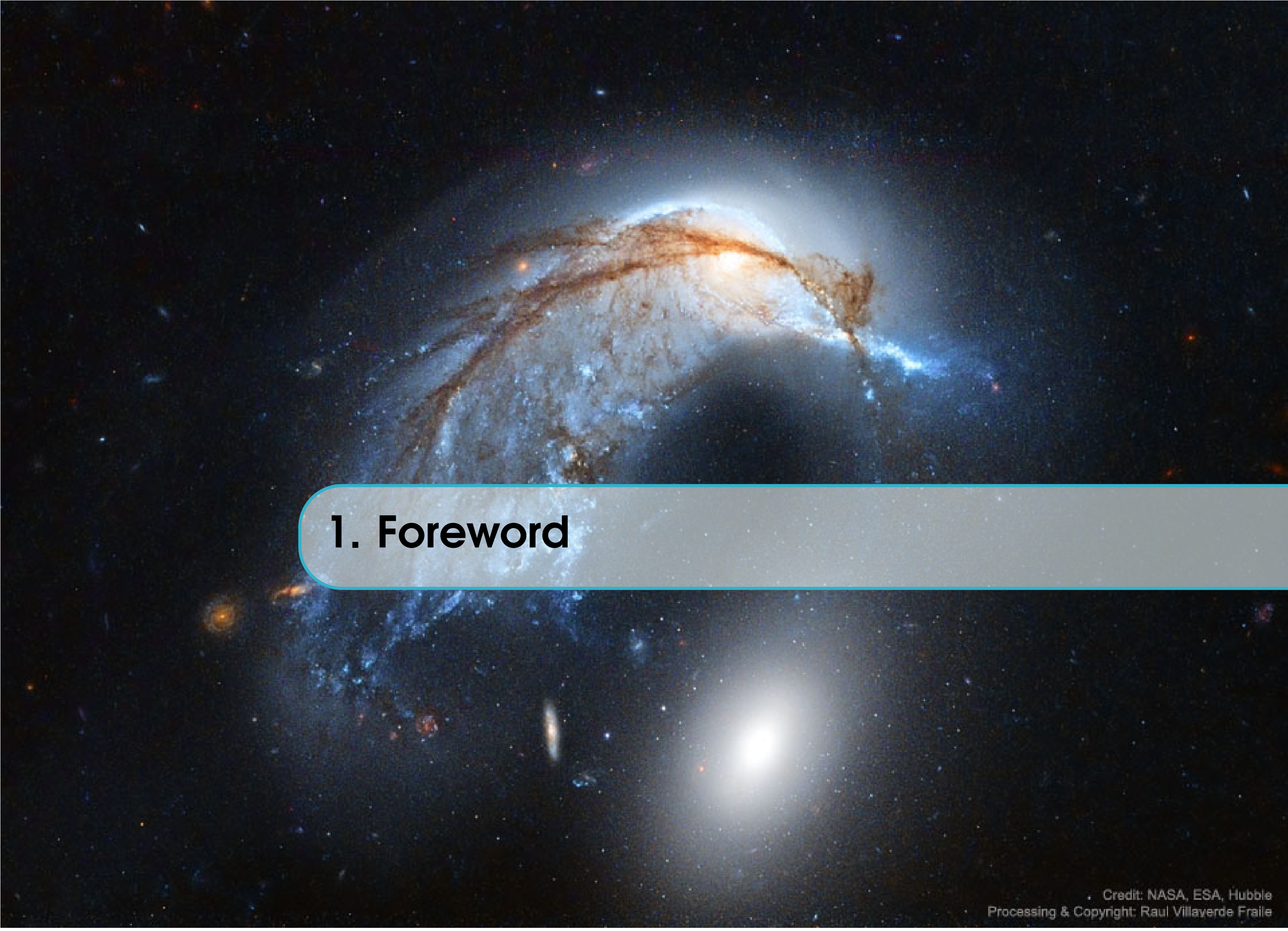
1. Foreword



Finland is a member of the European Southern Observatory (ESO) since 2004. ESO is a world leading astronomical research and technology organization, with 16 member states, headquarters in Garching, Germany, and three world-class observatories in Chile.

Finnish Centre for Astronomy with ESO (FINCA) is a national research institute for astronomical and astrophysical research in Finland. FINCA coordinates Finnish co-operation with ESO by networking into the ESO infrastructure and projects; practices and promotes high quality research in all fields of astronomy, and ESO-related technological development work; participates in researcher training in astronomy; and fosters and implements ESO-related co-operation of all the Finnish universities engaged in astronomical research. The ultimate goal of FINCA is to improve the scientific and industrial benefit of Finland's membership in ESO, and Finland's international competitiveness in astronomical research.

The year 2021 marked the 12th year of operation for FINCA, administratively a Special Unit of the University of Turku, and funded by the Ministry of Education and Culture, and by the participating universities (Aalto, Helsinki, Oulu and Turku). The highest decision-making body is the Board, chaired by Vice-Rector Kalle-Antti Suominen of the University of Turku, and comprising of two members from each participating university and one member from FINCA staff. The scientific activities of FINCA are overseen by an international Scientific Advisory Board (SAB), chaired by

Prof. Susanne Aalto (Chalmers University of Technology, Sweden),

The research at FINCA covers a large range in contemporary astronomy, from cosmology, active galaxies, and galaxy formation and evolution, through properties of nearby galaxies, to supernovae and their progenitor stars, stellar activity and star formation in our own Galaxy. In our research, we use radio to gamma-rays multi-wavelength observational data from large ground-based and space telescopes, especially from the four 8m ESO Very Large Telescopes (VLT), the Nordic Optical Telescope (NOT), and the Atacama Large (Sub)Millimeter Array (ALMA) in the optical, near-infrared and (sub)millimeter wavelengths. Observational research is supplemented by modelling, simulations and theoretical work, that are essential in understanding the physics behind the observations. Our research is characterized by strong collaboration both within FINCA, with other astronomy departments in Finland and internationally.

The corona situation continued to affect our research activities in 2021. International conferences were either canceled or moved on-line. Our successful visitor program, likewise, continued to be discontinued until emd of 2021 but is resuming activity from the beginning of 2022. ESO and ALMA at times suspended their operations, affecting their observation gathering capacity. Despite this, FINCA research was reported in 57 refereed scientific articles in 2021, and some of them are highlighted in this Report.

Our researcher training activities in 2021 focused on supervision of PhD and MSc students in the participating universities. Furthermore, we were able to organize 1) the annual course on remote optical/infrared observing with the NOT for MSc and PhD students and 2) the practical course for Finnish high school students on remote observations with the NOT, in hybrid mode at the Tuorla Science Center.

The construction of the ESO Extremely Large Telescope (ELT), a 39 m diameter giant for infrared and optical astronomy, is well underway, with Phase 1 instruments being constructed, Phase 2 instruments being in final design phase, all major contracts for the construction of the ELT been awarded, and construction started at Cerro Amazons. This keeps ESO on-track to remain in a world-leading position, when the ELT is expected to start operations in September 2027, only five years time from now, bringing an enormous leap forward in sensitivity and resolution.

Our acquired external funding has increased significantly in recent years. Especially, the research infrastructure (FIRI) grant from the Academy of Finland has enabled our participation in ESO instrument projects, FINCA is participating on behalf of the Finnish community in the ELT first-light instrument consortium MICADO (near-infrared adaptive optics imager), both by funding and by participating in the PSF reconstruction, in collaboration with the Department of Physics and Astronomy of the University of Turku, and the Lappeenranta University of Technology. MICADO is expected to be the only first-light instirument at ELT for some time after 2027. FINCA is also participating in a new instrument to the ESO 3.5-m New Technology Telescope (NTT), the Son Of X-Shooters (SOXS), with first light expected in 2023. Notably, the calibration unit of SOXS was built at the University of Turku, in collaboration with several local companies. FINCA will apply for more instrumentation funding from the Academy in future FIRI calls to strengthen the position of the Finnish community toward the ELT era, including participation in another ELT instrument, MOSAIC (optical and near-infrared multi-object spectrograph).

Jari Kotilainen,
FINCA Director

2. Staff and Organization

FINCA staff (Turku, unless otherwise indicated)	
Director :	Jari Kotilainen
Professor emeritus :	Mauri Valtonen
University Researchers :	Roberto De Propris Pasi Hakala Kari Nilsson
Academy Research Fellows	Talvikki Hovatta (Aalto/Turku) Elina Lindfors
Postdoctoral Researchers	Marco Berton (Aalto until 1.10.2021) Claudia Gutierrez Jenni Jormalainen Karri Koljonen (Aalto) Yannis Liodakis Derek McKay (Turku/Aalto) Venkatessh Ramakrishnan Quentin Salome (Aalto from 1.10.2021) Clare Wethers (until 1.10.2021) Stephen Williams

FINCA board

Members

Name	University
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Merja Tornikoski	Aalto
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Vitaly Neustroev	Oulu
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Juri Poutanen	Turku
Roberto De Propris (staff representative)	Turku

3. Research

3.1 Main research areas

The research at FINCA concentrates on observational astronomy carried out using radio to γ-rays, multi-wavelength data from large ground-based and space telescopes. Especially, we make use of ESO's large ground-based facilities in the optical and infrared (the four 8m ESO Very Large Telescopes; VLT) and in (sub)millimetre (Atacama Large Millimeter Array; ALMA), together with the Nordic Optical Telescope (NOT) on La Palma, in the northern hemisphere. Our observational research is supplemented by modelling, computer simulations and theoretical work, that are essential in understanding the physics behind the observations. The present science topics at FINCA cover a large range in contemporary astronomy from observational cosmology, distant active galaxies, and galaxy formation and evolution, through properties of nearby galaxies, to supernovae and their progenitor stars, stellar activity and star formation in our own Galaxy. In 2021, our research were reported in 57 refereed scientific articles, and some of them are highlighted below.

3.2 Research Highlights

3.2.1 Cosmology and Extragalactic Astrophysics

TXS1206+549: the most distant gamma-ray-detected narrow-line Seyfert 1 galaxy at redshift 1.34

Radio and gamma-ray loud narrow-line Seyfert 1 galaxies (NLS1) are unique objects to study the formation and evolution of relativistic jets, as they are believed to have high accretion rates and powered by low mass black holes contrary to that known for blazars. However, only about a dozen gamma-ray-detected NLS1s (gamma-NLS1) are known to date and all of them are at z≤ 1. **S. Rakshit, J. Kotilainen** and collaborators identified a new gamma-ray-emitting NLS1 TXS1206+549 at z = 1.344. A near-infrared spectrum taken with the Subaru Telescope showed Hβ emission line with FWHM of 1194 $\pm$ 77 km s^{-1} and weak [O III] emission line. The source is very radio-loud, unresolved, and has a flat radio spectrum. The broad-band spectral energy distribution of the source has the typical two hump structure shown by blazars and other gamma-NLS1s. The source exhibits strong variability from gamma-rays to infrared bands. All these characteristics show that TXS1206+549 is the most distant gamma-NLS1 known to date. (Rakshit et al. 2021 MNRAS, 504, L22)

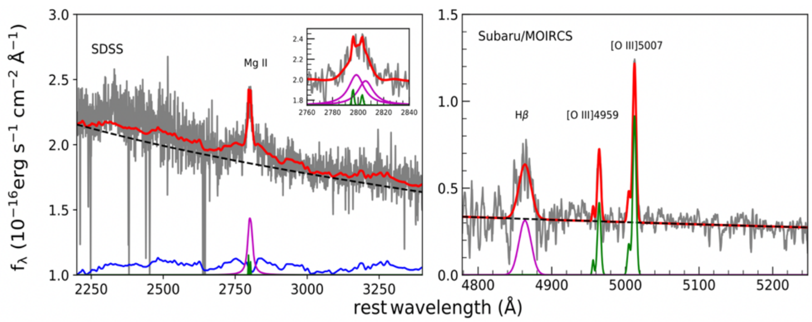


Figure 3.1: Spectrum of TXS1206+549. Left: Mg II line fit of the SDSS spectrum. The data (gray), best-fit model (red) and power law plus Balmer continuum (black dashed) are shown along with the decomposed broad (magenta) and narrow (green) components of Mg II, and Fe II in UV (blue). The inset plot shows the zoomed version of Mg II line fitting. Right: Hβ model fit to the Subaru spectrum. The data (gray), best-fit model (red), power law continuum (black dashed), decomposed broad line (magenta) and narrow lines (green) are shown.

Identifying changing jets through their radio variability

Supermassive black holes can launch highly relativistic jets with velocities reaching Lorentz factors of as high as $\Gamma > 50$. How the jets accelerate to such high velocities and where along the jet do they reach terminal velocity are open questions. Those are tightly linked to their structure as well as their launching and dissipation mechanisms which are among the most important questions in jet physics. **I. Liodakis** with collaborators (including FINCA staff **T. Hovatta**) we used radio light curves from 5 radio observatories, namely UMRAO, Metsahovi, ALMA, CARMA, and SMA, covering the 4.8-340 GHz range to quantify the jet's relativistic effects as a function of frequency. Due to synchrotron self-absorption, different radio frequencies allow us to look into different regions of the jets. Changes in the relativistic effects along the jets could then reveal jet acceleration, deceleration, or bending, offering a unique view in the inner workings of the jets not accessible with other observational methods. The majority of our sample consisted of constant velocity jets. However, we were able to identify 17/61 sources were either acceleration or jet bending are most likely taking place at parsec scales, while one source showed acceleration at subparsec scales and deceleration after. These results provide important constraints on models of jet acceleration and propagation.

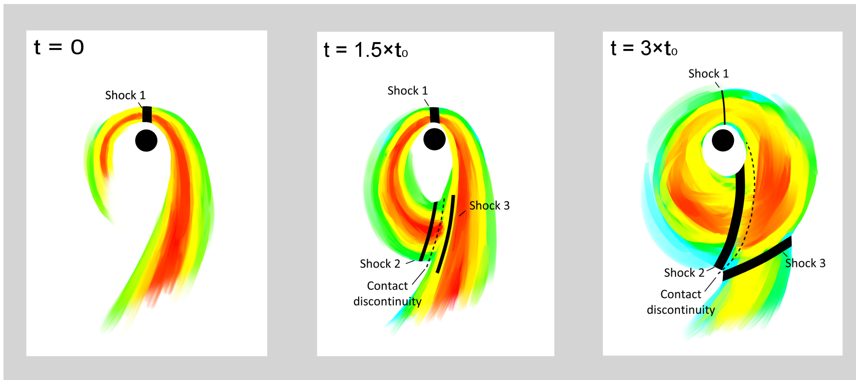


Figure 3.2: A schematic showing the stellar debris evolution during the formation of an accretion disk in a tidal disruption event. As the stellar stream makes a first pass around the supermassive black hole a shock is formed near the pericenter of the orbit. The stellar stream then collides with itself and forms more shocks near the apocenter. The shocks help circularize the stream into an accretion disk. The optical polarization observations matched the expectations for the shocks evolution at different phases of the event.

Optical polarization reveals colliding stellar stream shocks in a tidal disruption event

A tidal disruption event (TDE) occurs when a star passes very close to a SMBH in the centre of a typically quiescent galaxy. The tidal forces from the black hole disrupt the star, a portion of which is pulled inwards forming an accretion disk. This is observed as a flare from optical to X-rays with the spectrum typically peaking in the ultraviolet (UV) – soft X-rays lasting from months to years. Currently, the dominant models for the formation of the accretion disk from the stellar debris suggest either fast accretion disk formation and reprocessed X-ray to UV-optical emission or slow accretion disk formation by tidal shocks. **I. Liodakis** with collaborators (including FINCA staff **E. Lindfors, K. I. I. Koljonen, T. Hovatta, M. Berton, J. Jormanainen, K. Nilsson**) we observed TDE-AT2020mot using the optical polarimeters at Nordic Optical Telescope and Skinakas observatory. The optical polarization observations at N.O.T. were led by J. Jormainainen and a group of high-school students as part of the NOT-school organised by the Science Centre and the Finnish Centre for Astronomy with ESO, University of Turku. Our efforts resulted in the first polarization light curve study of a TDE and the discovery of the most polarized event so far. The high-degree of polarization cannot be explained by reprocessing models suggesting that TDEs detected by optical surveys are most likely powered by tidal stream shocks. The paper has been accepted for publication in Science.

A unique super-massive black hole binary candidate revealed by radio observations

T. Hovatta and **I. Liodakis** were involved in a study where periodic variations in the radio brightness of an active galactic nucleus PKS 2131-021 were identified. The observations used in the paper by O'Neill et al. (accepted for publication in ApJ Letters) spanned over 45 years and revealed sinusoidal variability with a period of 2.1 years in the rest-frame of the galaxy. The sinusoidal nature of the variations make the source a strong candidate for hosting two super-massive black holes with a small orbital separation. These kind of objects are expected in galaxy evolution models due to mergers of galaxies, but identifying candidates from observations is very challenging as they cannot be spatially resolved with any current instruments. Intriguingly, the sinusoidal period is not seen over a 20-year period in the middle of the observations, which demonstrates the challenges in identifying periodic variability in these types of active galaxies where the periodic component may be hidden by the stochastic variability induced in the relativistic jets. Future observations with gravitational wave experiments, such as pulsar timing arrays, may be able to confirm the binary nature of this target.

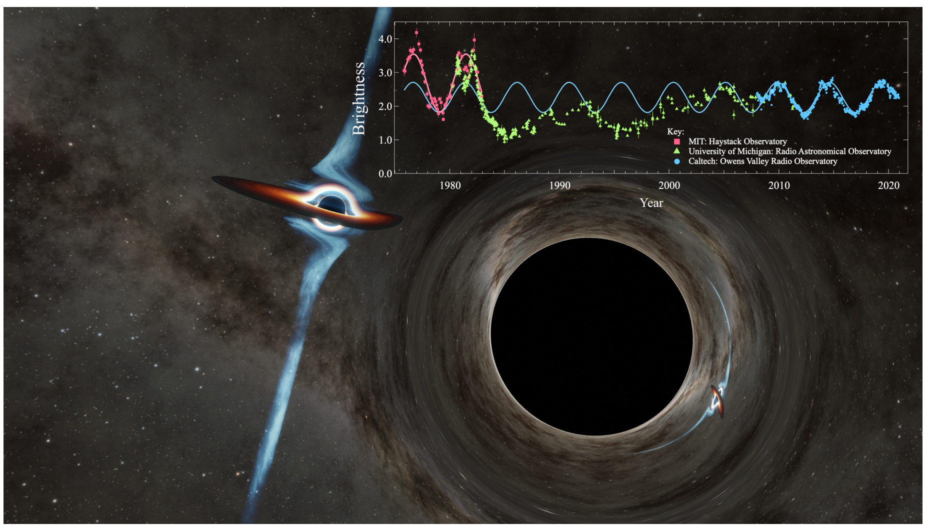


Figure 3.3: This artist's illustration shows two candidate supermassive black holes at the heart of a quasar called PKS 2131-021. In this view of the system, gravity from the foreground black hole (right) can be seen distorting the light of its companion, which has a powerful jet that is emitting radio waves. The sinusoidal brightness variations observed by different radio facilities are shown in the top right corner. Image credit: Caltech/R. Hurt (IPAC)

The peculiar narrow-line Seyfert 1 galaxy PKS 2004-447

Marco Berton and collaborators continued the study of narrow-line Seyfert 1 (NLS1s) galaxies. They are a class of active galactic nuclei (AGN) that, in some cases, can harbor powerful relativistic jets. One of them, PKS 2004-447, shows γ-ray emission, and underwent its first recorded multifrequency flare in 2019. However, past studies revealed that in radio this source could be classified as a compact steep-spectrum source (CSS), suggesting that, unlike other γ-ray sources, the relativistic jets of PKS 2004-447 had a large inclination with respect to the line of sight. Berton et al. presented a set of spectroscopic observations obtained of this object obtained with the FORS2 spectrograph mounted on the Very Large Telescope of ESO (see Fig. 3.4). These data were aimed at carefully measuring the black hole mass and Eddington ratio of PKS 2004-447, determining the properties of its emission lines, and characterizing its long term variability. They found that the black hole mass is $(1.5 \pm 0.2) \times 10^7$ $M_{\odot}$, and the Eddington ratio is 0.08. Both values are within the typical range of NLS1s. The spectra also suggested that the 2019 flare was caused mainly by the relativistic jet, while the accretion disk played a minor role during the event. In conclusion, they confirmed that PKS 2004-447 is one of the rare examples of γ-ray emitting CSS/NLS1s hybrid, and that these two classes of objects are likely connected in the framework of AGN evolution.

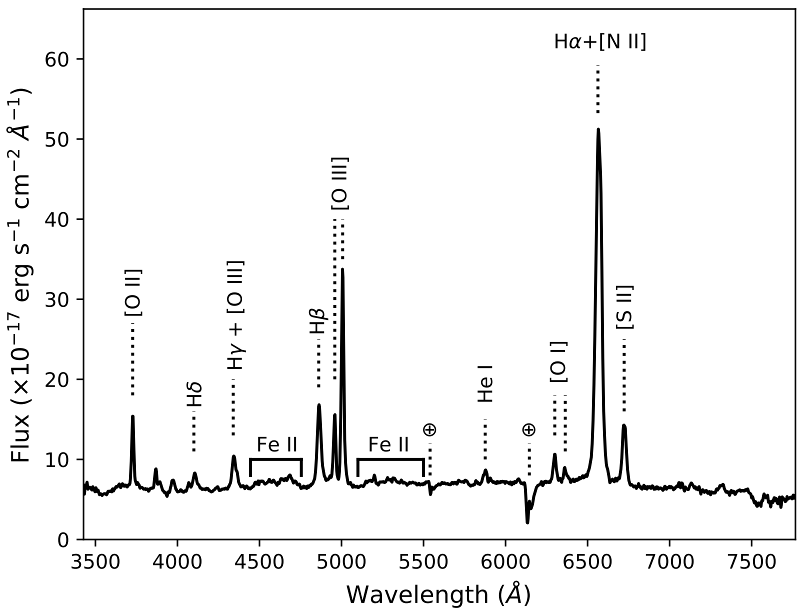


Figure 3.4: Redshift-corrected optical spectrum of PKS 2004-447, observed by FORS2. The most prominent emission lines are identified. The telluric absorptions are marked with the crossed circle. The presence of Fe II multiplets, detected here for the first time, confirmed the NLS1 nature of this source.

Blazars as sources of very high energy gamma-ray emission.

Blazars are the most numerous sources in the extragalactic Very High Energy (VHE,E>100GeV) gamma-ray sky. FINCAns Vandad Fallah Ramazani (visiting researcher),**Jenni Jormanainen, Elina Lindfors and Kari Nilsson** together with **Talvikki Hovatta and Yannis Liodakis** (associated members of the MAGIC collaboration) continued to have an active role in the international MAGIC collaboration that operates the two Imaging Air Cherenkov Telescopes at La Palma, Canary Islands, Spain.

In 2021 two new VHE gamma-ray blazar discoveries by the MAGIC telescopes were published. The first one, called B21420+326, is a powerful flat spectrum quasar a type of sources that can only be detected at VHE gamma-rays during bright flares. The second source, TXS1515-273, was a candidate extreme BL Lac source that are very rare, but MAGIC and simultaneous XMM-Newton X-ray observations revealed the source to be a typical high synchrotron peaked source. The paper was led by PhD student Serena Loporchio, who was visiting FINCA from January to June 2020, under the supervision of **Elina Lindfors** and Vandad Fallah Ramazani.

In 2021, the group has been also very actively participating in the preparatory science of the Cherenkov Telescope Array (CTA) Observatory. CTA will consist of two observatories, one at La Palma and second at ESO premises in Chile. In 2021, the consortium published two major papers "Sensitivity of the Cherenkov Telescope Array to a dark matter signal from the Galactic centre" and "Sensitivity of the Cherenkov Telescope Array for probing cosmology and fundamental physics with gamma-ray propagation". The latter uses blazars as probes and for such studies knowing the exact redshift of blazars is extremely important. Therefore, we have organized within CTA consortium a task force to perform large redshift surveys of blazars, using also ESO telescopes, and the first paper of the series was published in 2021 (Goldoni et al. 2021, including Lindfors, E.). In addition, **Elina Lindfors** served as the Science Coordinator of the Consortium and **Talvikki Hovatta** has been leading the preparation of the AGN variability consortium publication.

OJ287

Mauri Valtonen has coordinated an international observational campaign on the blazar OJ287 which is expected to show a huge optical flare in 2022. The flare results from the January 20, 2022, impact of the secondary black hole on the accretion disk of the primary in this binary black hole system. Observations have been carried out by optical photometry and polarimetry at multiple sites by, among others, Andrei Bergyugin of University of Turku. These data are combined with a monitoring program by Swift observatory extending the data to x-rays. At the same time, monitoring in radio frequencies is carried out by Metsähovi observatory, among others. Radio VLBI mapping has also been scheduled. The first indications of this campaign is that the main flare will be delayed from August to October 2022. This is good news for the campaign, as OJ287 is too close to sun in August to be observed in optical region while in October the observations will be easy. Since this is the last expected flare in OJ287 of the decade, we have a unique opportunity to collect more information on the astrophysical processes leading to the flares. They belong to the class of most energetic explosion events in the universe since the Big Bang.

The Ultraviolet Upturn at $z = 1$

Most (if not all) early-type galaxies exhibit excess flux at wavelengths shorter than 3000 Å compared to what is expected from the extrapolation of population synthesis models that, with standard assumptions (age of 11 Gyr, solar metallicity, star formation e-folding time of 0.3 Gyr) reproduce the observed optical/infrared colours of E/S0 galaxies and their evolution at least to $z = 2$ if not beyond. The broad consensus is that this excess flux is produced by blue horizontal branch (core helium burning) stars but such objects are not expected to exist within the old, metal-rich stellar populations of early-type galaxies. This therefore requires that E/S0 galaxies contain: (a) a significant population of metal-poor stars that can naturally evolve to the blue horizontal branch over cosmological timescales; (b) high metallicity stars must undergo increasing mass loss as they ascend the red giant branch for the first time in order to lose sufficient envelope mass to expose the hot inner layers of their atmosphere; (c) tight binaries strip each other of their envelopes as one or both stars

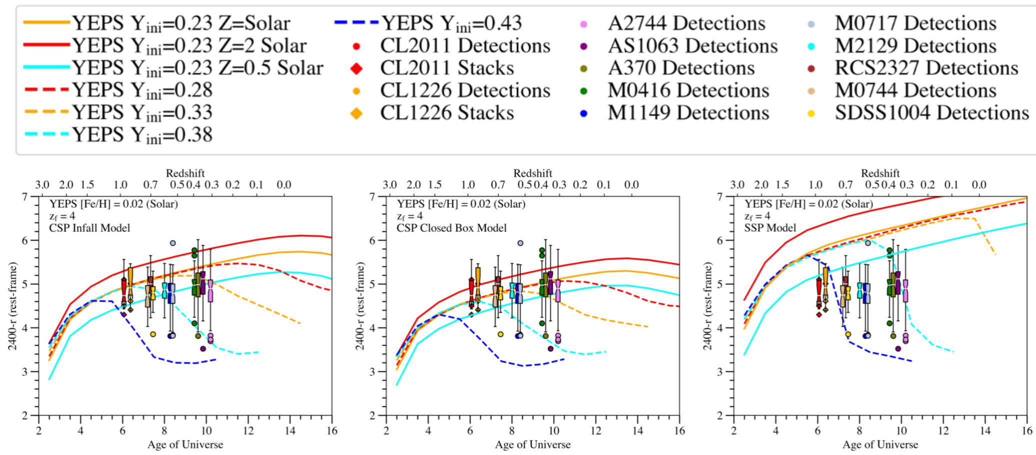


Figure 3.5: The observed 2400–r colour vs. redshift in models of different chemical formulations with varying helium abundances and different prescriptions for infall. Box plots show the observed colours for cluster galaxies

evolve and (d) there is a population of stars enriched in helium similar to the multiple populations now known to exist within Galactic globular clusters.

All these models make different predictions as to the redshift evolution of the ultraviolet flux. In a series of papers Ali et al. (including **De Propris** have shown that the ultraviolet flux remains constant in cluster galaxies out to $z = 0.6$ and declines beyond this, a finding most consistent with the presence of a minority population of helium rich stars. Ali et al. (2021, including **De Propris**) use a slighly redder bandpass in the near ultraviolet to measure the ultraviolet flux in clusters out to $z = 1$. As shown in Fig. 3.5 the colour of the ultraviolet flux clearly becomes redder beyond $z = 0.7$ and is consistent with having completely disappeared by $z = 1$. Similarly, the scatter in the ultraviolet colour decreases with redshift, consistent with the gradual disappearance of the blue horizontal branch population (Fig. 3.6). These results imply that only models with a helium rich component, enriched to around 45% (double the cosmological value) can account for the evolution of the ultraviolet flux at all redshifts.

Quentin Salome is working on the so-called AGN feedback. The energy released by the central AGN is thought to influence the evolution of the host galaxy, by quenching star formation. To do so, he will focus on the molecular gas as the main reservoir for star formation. In Metsähovi, he will study star formation in Narrow-Line Seyfert 1 galaxies. The recent nuclear activity in these sources is a key step in our understanding of the global effect of AGN feedback in galaxy evolution.

3.2.2 Stellar and Galactic Astrophysics

The double-peaked Type Ic supernova 2019cad

SN 2019cad is a peculiar Type Ic supernova (SN Ic) discovered by the Zwicky Transient Facility (ZTF) on 2019 March 17, which shows unprecedented observational properties. On one hand, its optical photometry reveals a double-peaked light curve with a relatively faint initial peak that fades

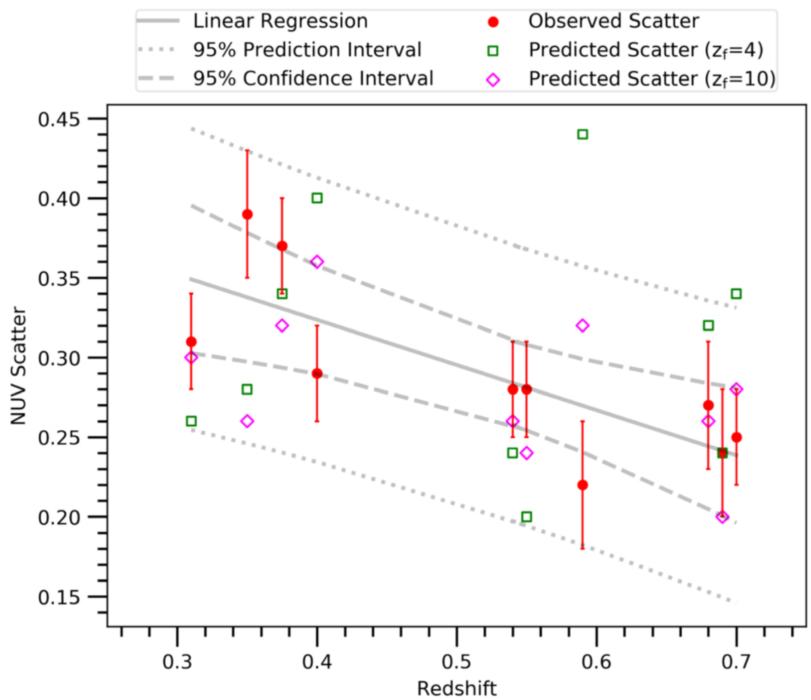


Figure 3.6: We also estimate the intrinsic scatter that should be observed if the entire scatter in the optical colour-magnitude relations is due to to age effects (for two different formation epochs: $z = 4$ (green squares) and $z = 10$ (pink diamonds) and a linear fit with confidence intervals to the data

in two weeks, prior to rapidly rise again to the main light-curve peak. On the other hand, its spectral evolution is also unique, showing a transformation from a normal SN Ic to a peculiar type Ic event. We published a paper on the photometric and spectroscopic evolution of SN 2019cad during the first ∼100 d from the explosion: Gutiérrez et al., 2021 "The double-peaked Type Ic supernova 2019cad: another SN 2005bf-like object", MNRAS, 504, 4907.

In this paper, we characterise the evolution of this object with the aim of understanding its peculiar photometric behaviour. By comparing the bolometric light curve to hydrodynamical models, we find that SN 2019cad cannot be reproduced by the canonical explosion picture (collapse of a massive star) and additional mechanisms are required to understand its light curve. Our results suggest that SN 2019cad is consistent with a progenitor with a pre-SN mass of 11 $M_{\odot}$, and an explosion energy of 3.5×10^{51} erg. The light-curve morphology can be reproduced either by a double-peaked 56Ni distribution with an external component of 0.041 $M_{\odot}$, and an internal component of 0.3 $M_{\odot}$ (Fig. 3.7) or a double-peaked 56Ni distribution plus magnetar model ($P \sim 11$ ms and $B \sim 26 \times 10^{14}$ G; Fig. 3.8). If SN 2019cad were to suffer from significant host reddening (which cannot be ruled out), the 56Ni model would require extreme values, while the magnetar model would still be feasible.

Although there are still many issues in our understanding of these peculiar objects, their analyses are promising and let us explore multiple alternatives to better understand the explosion mechanisms and nature of their progenitors.

Cataclysmic Variables

Dr **Hakala** has been participating in various projects related to the studies of short period binary stars. He has continued working with the University of Athens team on contact binaries (W UMa systems) leading to two refereed papers discussing the evolutionary status of these binary stars. He has also been active in studying various aspects of magnetic white dwarfs in binary system. Together with colleagues from University of Warwick (UK) he launched a survey for fast spinning magnetic white dwarfs in cataclysmic variables. This has been allocated 6 nights of observing time on NOT and 4 nights on NTT. He has also carried out observing programmes on NOT to study the magnetic fields of white dwarfs in pre-cataclysmic variables, which are binary systems where a magnetic white dwarf is only accreting stellar wind from the companion star. In Fig. 3.9 we show a resulting cyclotron emission map on the surface of one magnetic white dwarf accreting matter via stellar wind from the donor star. The bright regions mark the footprints of the magnetic fields lines, along which the matter is accreted (analoguously to the aurora on earth). The detection and measuremant of magnetic field strengths in these systems is vital for our understanding of both binary star evolution and the formation mechanism of the white dwarf magnetic fields. The paper will be submitted in 02/2022.

In addition to these, Dr **Hakala** has been involved in NOT and VLT-FORS2 study of fast rotating late type stars that show photometric variability, but no other signs of stellar activity like flaring. These stars are puzzling and we have used VLT-FORS2 spectropolarimetry to detect/measure magnetic fields of these stars and also spectra from the NOT to study the possible binarity of these systems. These studies provide important clues on the origin of magnetic activity in the very lowest mass stars.

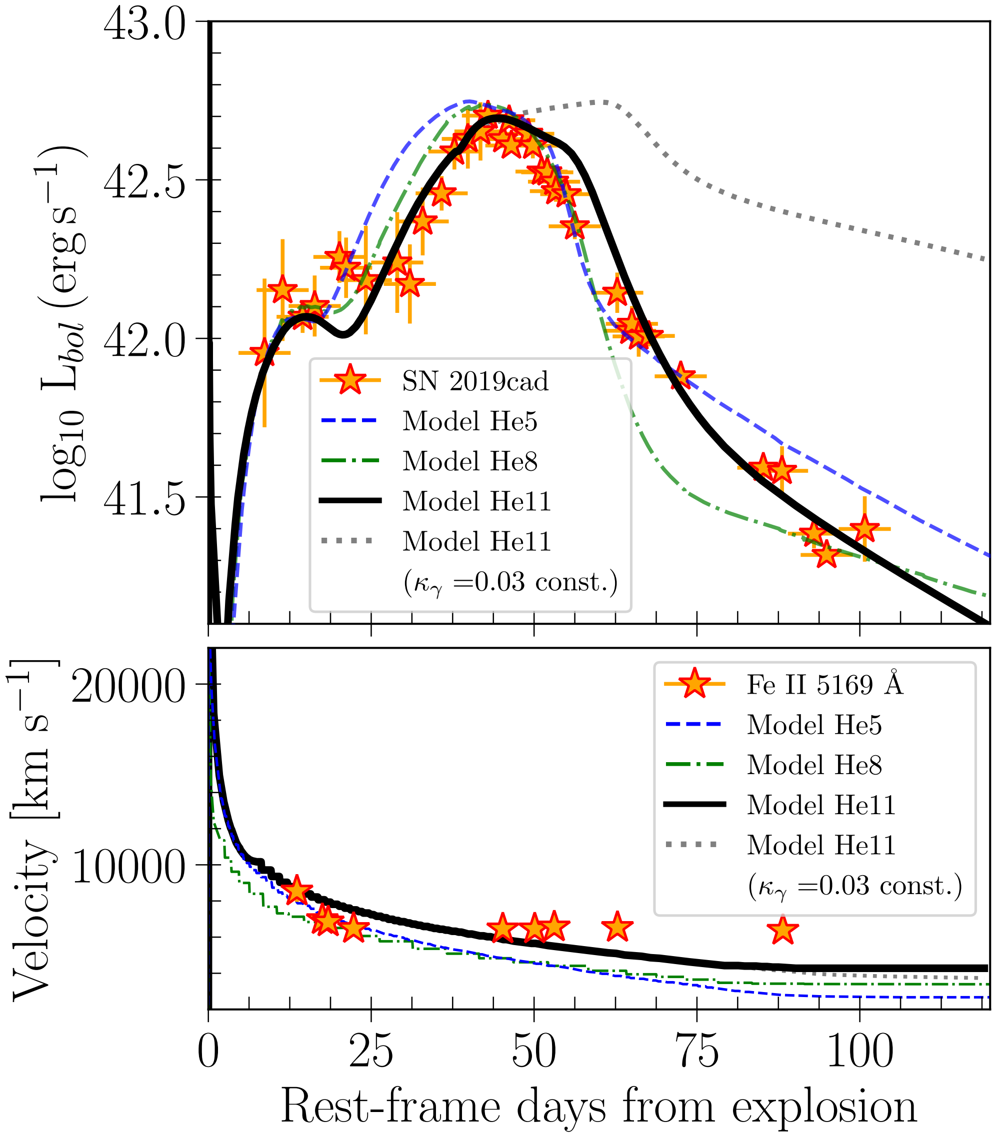


Figure 3.7: Top panel: Comparison between our preferred double-peaked 56Ni model (black solid line) and the SN observations (orange stars). For this model, we use a progenitor with a pre-SN mass of 11 $M_\odot$ (He11), corresponding to a zero-age main sequence mass of 30 $M_\odot$, an explosion energy of 3.5×10^{51} erg, and ejected mass of 9.5 $M_\odot$. For comparison, we also include the double 56Ni distribution models for lower pre-SN masses: 5 (He5; in blue dashed line) and 8 (He8; green dash–dotted line). In all three cases, an enhancement of the gamma-ray leakage is assumed at around the date of L-main peak. Models with lower mass produces an earlier main peak and overestimate the rise time luminosity. The He11 model assuming a constant $\kappa\gamma = 0.03$ (dotted grey line) is also presented as reference. Bottom panel: Evolution of the He11 (black solid line), He5 (in blue dashed line), and He8 (green dash–dotted) line photospheric velocity compared with the Fe II velocity of SN 2019cad.

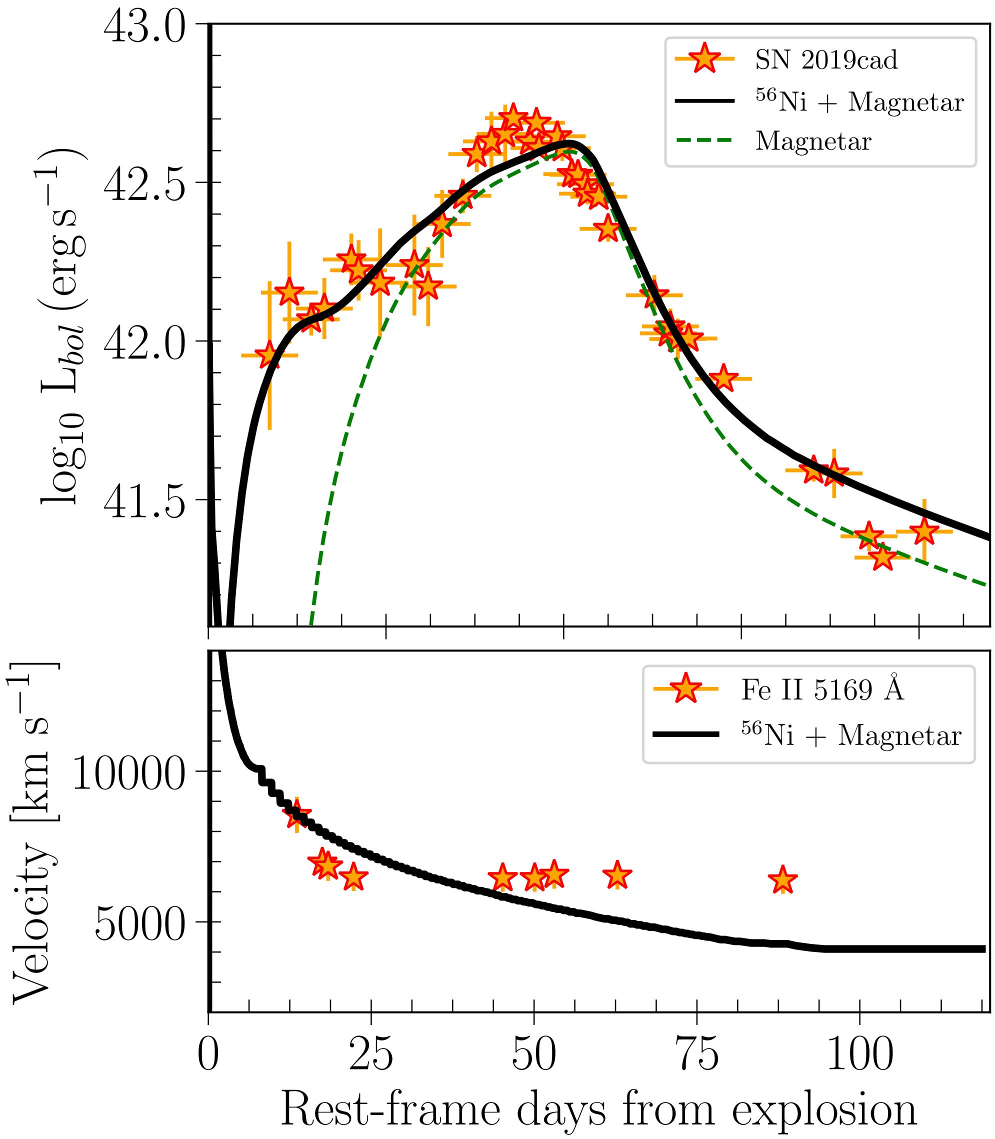


Figure 3.8: Top panel: The magnetar plus nickel model for a progenitor mass of 11 $M_{\odot}$ compared with the light curve of SN 2019cad. For the first maximum, an outer 56Ni mass of 0.041 $M_{\odot}$ is assumed. The second, main peak was modelled with an inner mass of 56Ni 0.05 Msun and a magnetar with an initial period P = 11 ms and a magnetic field of $B = 26 \times 10^{14}$ G (dashed line). The calculated light curve with both 56Ni components and the magnetar is shown in black solid line. Bottom panel: Evolution of the magnetar plus nickel model photospheric velocity compared with the Fe II velocity of SN 2019cad.

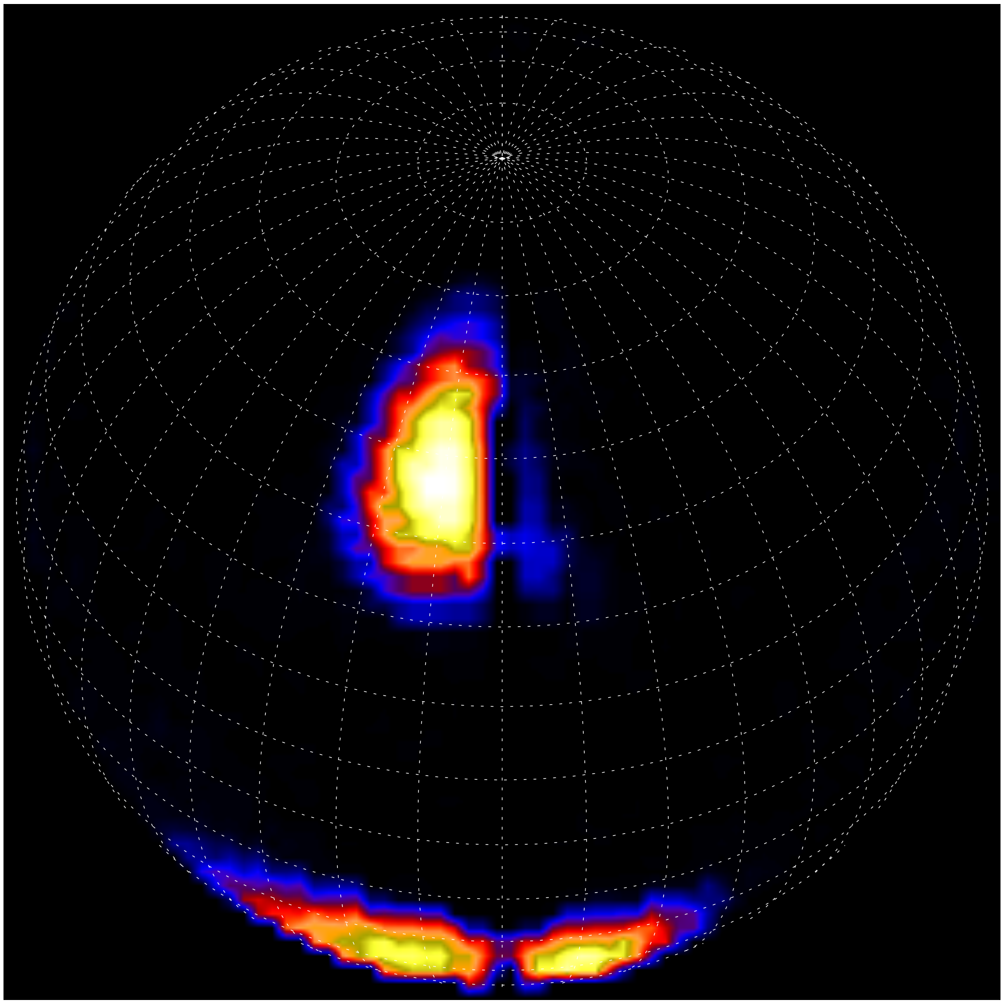


Figure 3.9: Cyclotron emission map on the surface of one magnetic white dwarf accreting matter via stellar wind from the donor star. The bright regions mark the footprints of the magnetic fields lines, along which the matter is accreted.

Studying the stellar wind-jet interactions in the microquasar Cygnus X-3

Cyg X-3 is a unique high-mass X-ray binary in our Galaxy hosting a Wolf-Rayet star with a strong stellar wind and likely a black hole orbiting each other in a short 4.8-hour period. Cyg X-3 is known for massive outbursts that emit throughout the electromagnetic spectrum from radio to gamma-rays and produce major radio flaring episodes during which the source is the most radio-luminous object in our Galaxy. A likely explanation for the enhanced brightness is an efficient energy dissipation of the jet kinetic energy in the surrounding stellar wind (Koljonen et al. 2018). This interaction of the jet and the wind can produce detectable changes in the radio flux densities along the binary orbit.

Karri Koljonen et al. studied the possible radio orbital modulation during radio flaring periods in 1983, 1985, 1994, 1995, 2002, 2016, and 2017 using radio data from Metsähovi Radio Observatory, Medicina Radio Observatory, Very Large Array, Very Large Baseline Array, and Ryle Telescope (Egron et al. 2021). They found radio flux modulation with maxima corresponding either to the orbital phase 0 (i.e. compact object behind the companion) or to the orbital phase 0.5 (i.e. compact object in front of the companion) during a so-called hypersoft accretion state when the wind density is speculated to be higher in the vicinity of the jet (Koljonen et al. 2018). The former supports a scenario of free-free absorption in the stellar wind of the companion (Zdziarski et al. 2018), while the latter can indicate a bent jet due to the strong stellar wind pressure (Dubus et al. 2010). Clearly, additional radio interferometric observations targeting different accretion states would be needed to further resolve the emission geometry in the system.

In another study, **Karri Koljonen** et al. studied the effect of the strong X-ray irradiation produced by the accretion disk around the compact object on the stellar wind launching of the Wolf-Rayet companion (Vilhu et al. 2021). They modelled the supersonic part of the stellar wind by computing the line force locally in the wind considering the radiation fields from both the companion and the accretion disk in several accretion states observed from the system. Based on this study, they showed that the line force is most affected by the extreme ultraviolet photons in a way that if the flux in this wavelength region is high, the line force in the wind is weak, and consequently, the wind velocity is low. This in turn affects the wind accretion rate onto the accretion disk, the luminosity of the accretion disk, and therefore the irradiating extreme ultraviolet flux creating a feedback mechanism. Assuming a moderate wind clumping and a low-mass compact object (2-3 solar masses) the observed luminosities of the different accretion states can be produced by this mechanism.

4. Instrument Development

Son of X-Shooter (SOXS) calibration unit completed

Son of X-Shooter (SOXS) calibration unit completed

The SOXS instrument is in the construction phase. In 2021, the construction of the calibration unit (CU) of SOXS, Finland's contribution funded through FINCA FIRI grant, was completed in the SOXS lab at Quantum building, University of Turku.The work was led by Academy Fellow Hanindyo Kuncarayakti (Department of Physics and Astronomy, Univ. Turku). SOXS CU incorporates commercially available parts and custom-made components, some are manufactured by University of Turku's Protopaja workshop. The SOXS CU has undergone tests and final verification before being shipped to the SOXS consortium headquarter in Italy late 2021, for integration with the SOXS instrument.

MICADO: the only first-light ELT instrument for some time

Participation in the much larger scale ELT instrument projects is necessary for the Finnish community to strengthen its position in front-line astronomical research. These instruments are being built by international consortia between institutes in ESO member states. It is paramount to get involved in a first-light ELT instrument, as it represents a unique opportunity for the Finnish

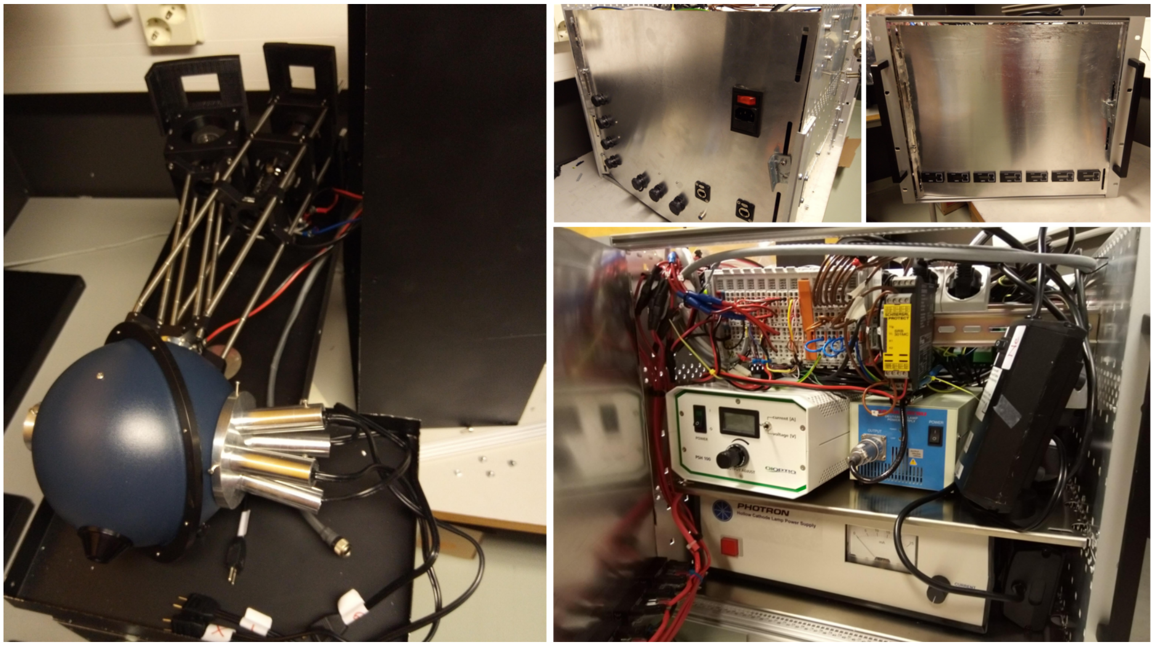


Figure 4.1: (Left) The Calibration Box with top cover removed, showing the integrating sphere and lamps. (Right) The CBX electronics subrack, outside view (top 2 panels), and inside view (bottom panel), showing the lamp power supplies and Beckhoff modules..

community to get access to ELT data from the start. For this purpose, we are full members in and have used the FIRI funding to participate in the MICADO consortium, including in-kind contribution led by UTU. MICADO, the adaptive optics (AO) -assisted diffraction-limited near-infrared imager and long-slit spectrograph, is progressing successfully and will probably be the only first-light ELT instrument ready to start operations in 2027 when the ELT will be completed. MICADO has much better sensitivity and spatial resolution than any current facility, and addresses key science topics, such as the dynamics of dense stellar systems, black holes in galaxies, the star formation history of galaxies through resolved stellar populations, the formation and evolution of galaxies in the early universe, planets and planet formation, and the solar system. The primary science cases for MICADO are an excellent match with science interests in all FINCA universities.

MICADO's has already passed three of its four Final Design Reviews (FDR) with ESO, with the final FDR4 in 2022. There is going to be about 10% cost increase of MICADO, due to increased cost of material and manufacturing.

A group led by Academy Researcher Hanin Kuncarayakti (Dept. Physics and Astronomy, Univ. Turku), together with Jani Achren from Incident Angle company and FINCA postdoc Steve Williams, participate in the PSF-Reconstruction Working Group of MICADO, within the non-AO effects Work Package. Activities include simulating the MICADO optics and PSF as affected by turbulence and aberrations, and re-writing the INAF simulation code from IDL to Python.

The MICADO instrument was recently described in the article Davies et al. (2021), The Messenger, 182, 17-21. (including **J. Kotilainen** as the FINCA co-author).

Figure 4.2: The logos of the participating institutes of the MICADO consortium

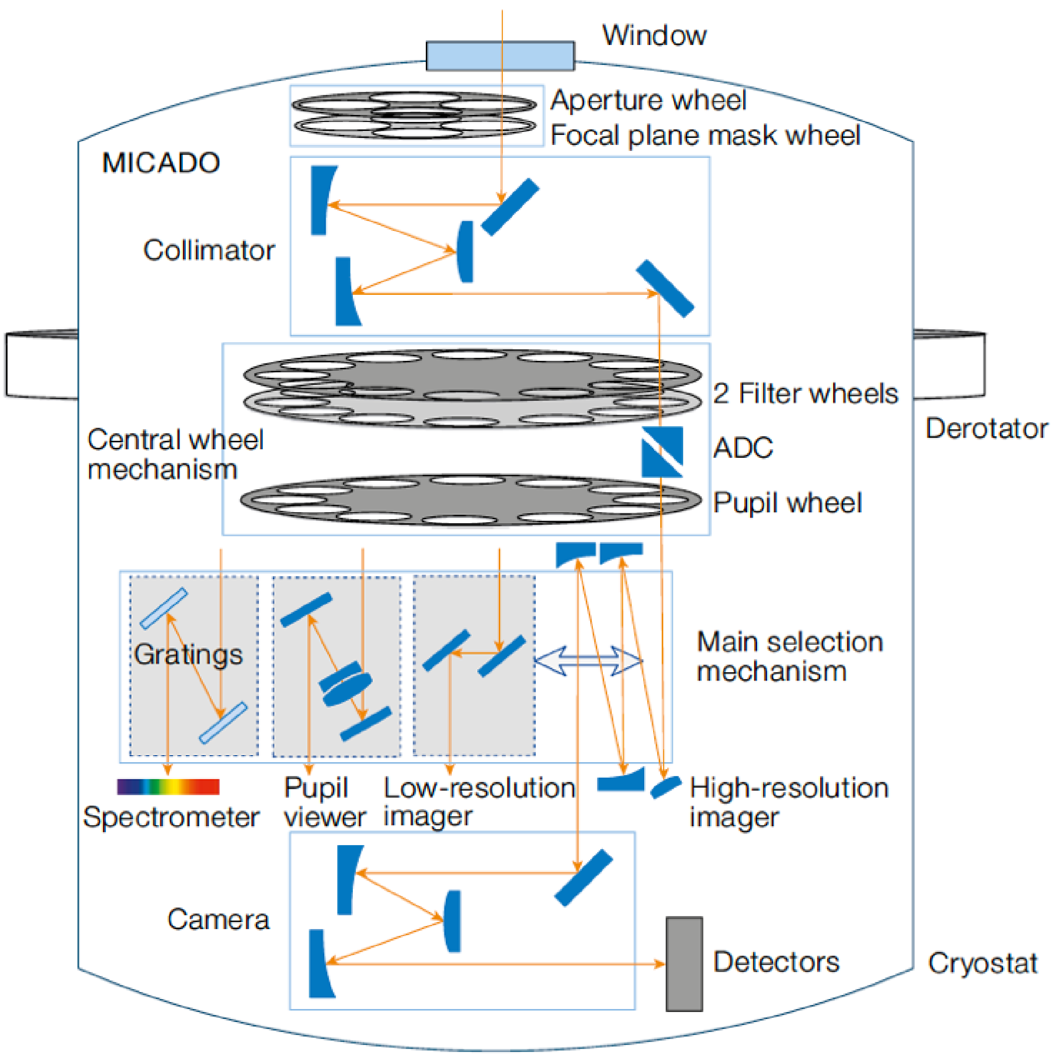
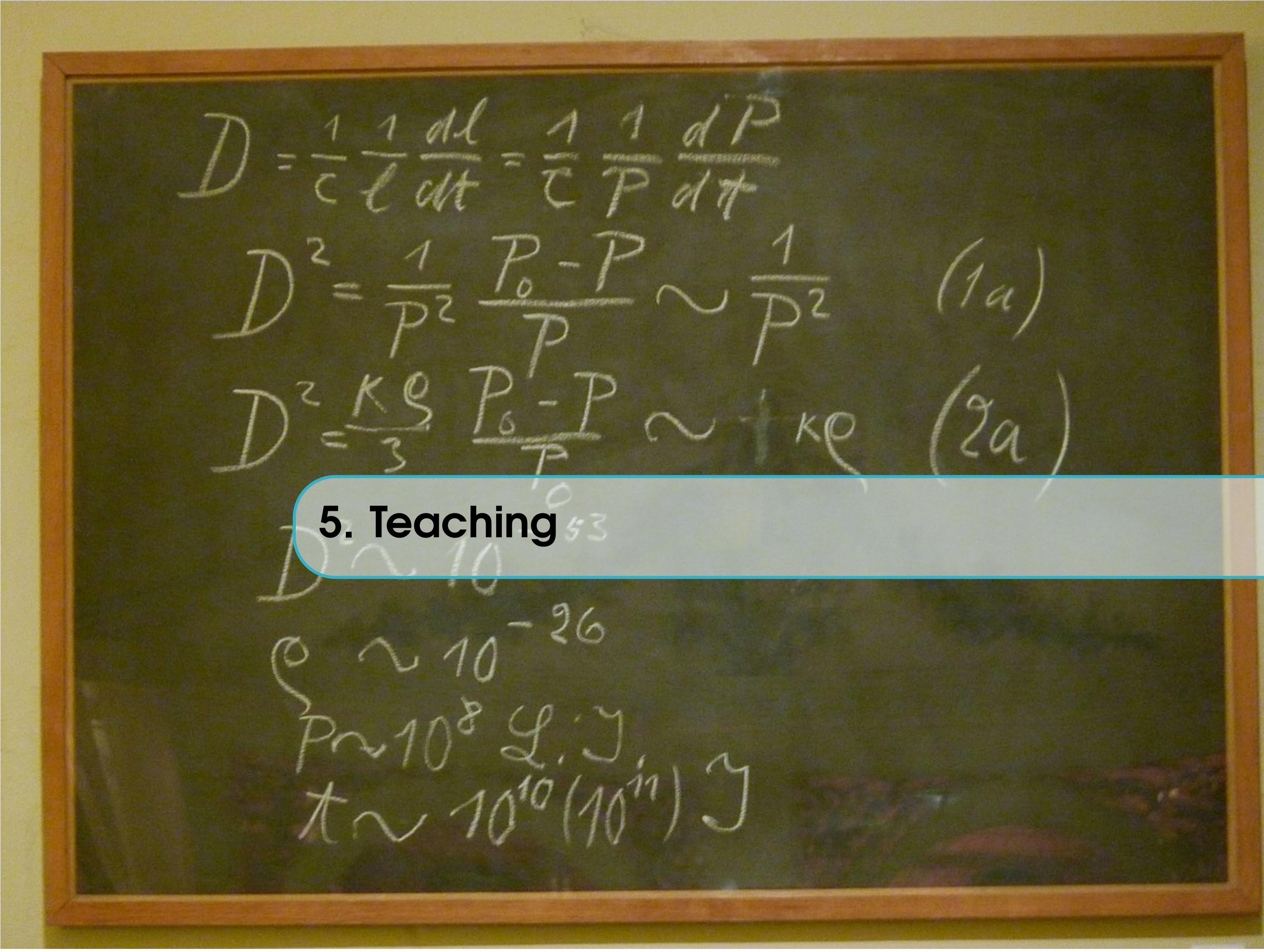


Figure 4.3: Schematic view of the MICADO design concept, illustrating how the cold optics and mechanisms are assigned to separate modules that can be tested separately and then integrated together in the cryostat.

Hardware at Metsähovi Radio Telescope

As part of hardware development, **Derek McKay** is working on the prototyping and evaluation of components that will contribute to a new fully-digital, high bandwidth backend for the Metsähovi Radio Telescope. The new system will record and correlate radio signals from two linear polarisations, which is imperative for advancing studies of large-scale magnetic field structure and energy dissipation in blazar jets. The hardware has now been set up at the observatory and evaluation and prototyping work is now in progress. Additionally, as part of this work, commissioning of the Metsähovi Compact Array 5-metre antenna has been carried out. This small parabolic antenna will be used for testing the new backend system.



5. Teaching

5.1 Lectured courses (in whole or in part)

Basic level - in Finnish

Teacher	Course	Credits
Jenni Jormanainen (assistant)	The Big Bang for the Studies	4
Talvikki Hovatta (co-lecturer)	Introductory Astronomy (Radio)	5
Elina Lindfors (co-lecturer)	Maailmankaikkeuden ja maapallon luonnon kehitys alkuräjähdyksestä nykyhetkeen	5

Intermediate level - in Finnish or English

Advanced level - in English

Roberto De Propris (co-lecturer)	Galaxies and Cosmology	6	Turku
Talvikki Hovatta (co-lecturer)	Radio Astronomy and Interferometry	5	Turku
K. Koljonen	Space Instrumentation	5	Aalto
D. McKay	Space Debris	6	Aalto
Elina Lindfors (co-lecturer)	Virtual OPTICON Archival School using ESO and ALMA data		

5.2 Completed theses

MSc theses

Joonas Tarvainen, Kvasaarien joukkoympäristot (in Finnish; Group environments of quasars), supervisor: Jari Kotilainen

PhD theses

Andreas Kvammen, UiT - The Arctic University of Norway, *Auroral Image Processing Techniques - Machine Learning Classification adnd Multi-Viewpoint Analysis*, co-supervisor: Derek McKay

6. Other research activities

Memberships in conference SOC/LOC and other committees

T. Hovatta	Finland's representative in the ESO Scientific Technical Committee
	Member / Chair (Oct 2021) of the European Science Advisory Committee (ESO/ALMA)
	Member of the European VLBI Network Programme Committee
	Member of the CTA Consortium
E. Lindfors	Science coordinator of the CTA Consortium
	Member of the Time Allocation Committee of the MAGIC Collaboration
	Member of the Collaboration Board of the MAGIC Collaboration
	Opticon and Radionet Package on "Optical and IR schools" member of the board
D. McKay	Secretay of the Finnish Astronomical Society

Conference presentations

J. Jormanainen	Extragalactic jets on all scales - launching, propagation, termination - June 2021, virtual - “Confronting observations of VHE gamma-ray blazar flares with reconnection models”
	37th International Cosmic Ray Conference - July 2021, virtual - “Confronting observations of VHE gamma-ray blazar flares with reconnection models”
	Tuorla-Tartu meeting - October 2021 - Confronting observations of VHE gamma-ray blazar flares with reconnection models
T. Hovatta	Looking at the Polarized Universe: Past, Present and Future, May 24-26, virtual conference, oral presentation: Optical polarization in the kpc-scale jet of 3C273
T. Hovatta	Extragalactic jets on all scales - launching, propagation and termination, Jun 14-18, virtual conference, invited talk: Blazar magnetic fields from launch to termination
T. Hovatta	Tuorla-Tartu meeting 2021: Interaction of the cosmic matter, Oct 6-8, Turku, oral presentation: Association of IceCube neutrinos with radio jets of active galactic nuclei
E. Lindfors	"Observations of Active Galactic Nuclei with current and future gamma-ray observatories" (invited talk), 43rd COSPAR general assembly (online)
	"Association of IceCube neutrinos with radio sources observed at Owens Valley and Metsähovi Radio Observatories" (contributed talk) 43rd COSPAR general assembly (online)
	"Extragalactic Science with CTA" Astronomical Society of India (online)
	"Association of IceCube neutrinos with radio sources observed at Owens Valley and Metsähovi Radio Observatories" (contributed talk) Jets2021 (online)
D. McKay	“Pajala Fireball” EGU General Assembly 2021, 19-30 April (Vienna and online)

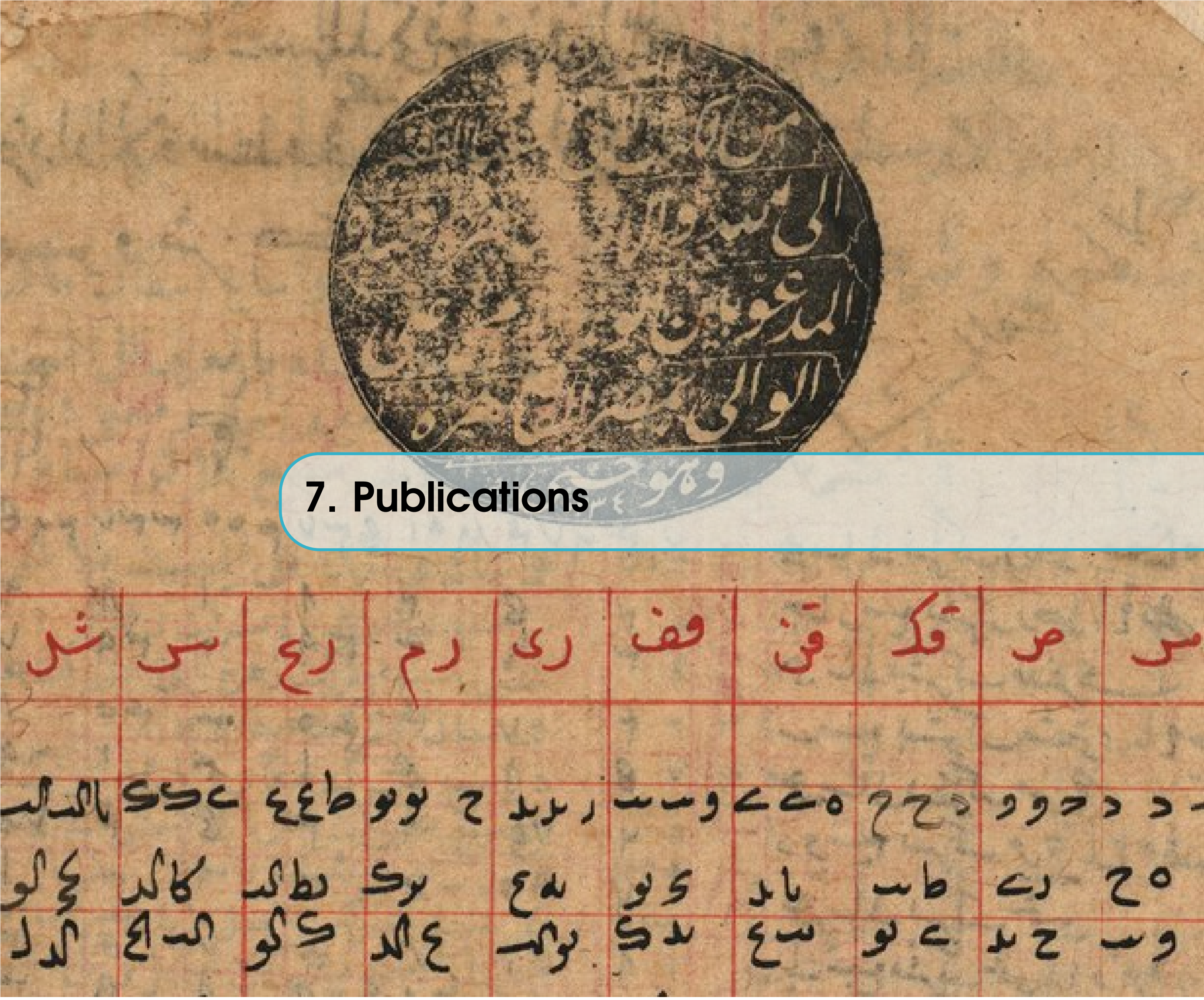
Other talks

T. Hovatta,	Magnetic fields in relativistic jets, Max Planck Institute for Radio Astronomy, 12 November 2021
E. Lindfors	"Multi-messenger emission from relativistic jets launched by supermassive black holes" University of Amsterdam, October 2021, in person
D. McKay	"Lessons Learned from Machine Learning" FINCA Seminar, 12 April 2021
D. McKay	"Mapping the Free Electrons in Our Atmosphere" FINCA Seminar, 25 October 2021

Research Visits

Hosted visitors

Stefano Ciroi, University of Padova, Italy – Host: M. Berton
Serena Loporchio, INFN Bari, Italy – Host: E. Lindfors



7. Publications

Refereed publications by FINCA staff 2021:

01. Abdalla, H. et al. (including **Berton, Hovatta, Lindfors**) *Sensitivity of the Cherenkov Telescope Array for probing cosmology and fundamental physics with gamma-ray propagation*, 2021, JCAP, 2, A48

02. Abdalla, H. et al. (including **Fallah Ramazani, Lindfors, Neustroev, Nilsson**) *H.E.S.S. and MAGIC observations of a sudden cessation of a very-high-energy γ-ray flare in PKS 1510089 in May 2016*, 2021, A&A, 648, A23

03. Acciari. V. et al. (including **Berton, Fallah Ramazani, Jormanainen, Hovatta, Lindfors, Nilsson**) *VHE gamma-ray detection of FSRQ QSO B1420+326 and modeling of its enhanced broadband state in 2020* , 2021, A&A, 647, A163

04. Acciari. V. et al. (including **Fallah Ramazani, Jormanainen, Lindfors, Nilsson**) *MAGIC Observations of the Nearby Short Gamma-Ray Burst GRB 160821B* , 2021, ApJ, 908, A90

05. Acciari. V. et al. (including **Fallah Ramazani, Jormanainen, Lindfors, Nilsson**) *MAGIC Observations of the Nearby Short Gamma-Ray Burst GRB 160821B* , 2021, ApJ, 908, A90

06. Acciari. V. et al. (including **Fallah Ramazani, Jormanainen, Lindfors, Neustroev, Nilsson**) *Multiwavelength variability and correlation studies of Mrk 421 during historically low X-ray and γ-ray activity in 2015-2016*, 2021, MNRAS, 504, 1472

07. Acciari. V. et al. (including **Fallah Ramazani, Jormanainen, Lindfors, Nilsson**) *First detection of VHE gamma-ray emission from TXS 1515-273, study of its X-ray variability and spectral energy distribution* , 2021, MNRAS, 507, 1528

08. Acciari. V. et al. (including **Fallah Ramazani, Jormanainen, Lindfors, Nilsson**) *Investigation of the correlation patterns and the Compton dominance variability of Mrk 421 in 2017*, A&A, 655, A89

09. Acciari. V. et al. (including **Fallah Ramazani, Jormanainen, Lindfors, Nilsson**) *Search for Very High-energy Emission from the Millisecond Pulsar PSR J0218+4232*, ApJ, 922, A251

10. Acharyya. A. et al. (including **Hovatta, Lindfors**) *Sensitivity of the Cherenkov Telescope Array to a dark matter signal from the Galactic centre*, 2021, JCAP, 1, A57

11. Adams, C. B. et al. (including **Fallah Ramazani, Jormanainen, Lindfors, Nilsson**) *Observation of the Gamma-Ray Binary HESS J0632+057 with the H.E.S.S., MAGIC, and VERITAS Telescopes*, 2021, ApJ, 923, A241

12. Ajello, M. et al. (including **Liodakis**) *Gamma Rays from Fast Black-hole Winds*, 2021, ApJ, 921, A144

13. Ajello, M. et al. (including **Liodakis**) *Fermi Large Area Telescope Performance after 10 Years of Operations*, 2021, ApJS, 256, A12

14. Algaba, J. C. et al. (including **Fallah Ramazani, Jormanainen, Lindfors, Nilsson**) *Broadband Multi-wavelength Properties of M87 during the 2017 Event Horizon Telescope Campaign*, 2021, ApJ, 911, L11

15. Ali, S., **De Propris, R.**, Chung, C., Phillipps, S., Bremer, M. *Evolution of the Ultraviolet Upturn at 0.3 < z < 1: Exploring Helium-rich Stellar Populations*, 2021, ApJ, 923, A12

16. Alvarez-Hernandez, A. et al. (including **Hakala**) *The intermediate polar cataclysmic variable GK Persei 120 years after the nova explosion: a first dynamical mass study*, MNRAS, 507, 5805

17. Baldini, L. et al. (including **Liodakis**) *Catalog of Long-term Transient Sources in the First 10 yr of Fermi-LAT Data*, 2021, ApJS, 256, A13

18. **Berton, M.** et al. (including **Kotilainen**) *Hunting for the nature of the enigmatic narrow-line Seyfert 1 galaxy PKS 2004-447*, 2021, A&A, 654, A125

19. Blinov, D. et al. (including **Hovatta, Liodakis**) *RoboPol: AGN polarimetric monitoring data*, 2021, MNRAS, 501, 3715

20. Casadio, C. et al. (including **Hovatta**) *SMILE: Search for MIlli-LEnses*, 2021, MNRAS, 507, L6

21. Dainotti, M. G. et al. (including **Liodakis**) *Predicting the Redshift of γ-Ray-loud AGNs Using Supervised Machine Learning*, 2021, ApJ, 920, A118

22. **De Propris, R.** et al. *Brightest cluster galaxies: the centre can(not?) hold*, 2021, MNRAS, 500, 310

23. Dey L. et al. (including **Valtonen**) *Explaining temporal variations in the jet PA of the blazar OJ 287 using its BBH central engine model*, 2021, MNRAS, 503, 4400

24. Egron, E. et al. (including **Koljonen**) *Investigating the Mini and Giant Radio Flare Episodes of Cygnus X-3*, 2021, ApJ, 906, A10

25. Fiore, A. et al. (including **Berton**) *SN 2017gci: a nearby Type I Superluminous Supernova with a bumpy tail*, 2021, MNRAS, 502, 2120

26. Gazeas, K. D. et al. (including **Hakala**) *CoBiToM project - I. Contact binaries towards merging*, 2021, MNRAS, 502, 2879

27. Ghaffari, Z. et al. (including **De Propris**) *Clustering of red and blue galaxies around high-redshift 3C radio sources as seen by the Hubble Space Telescope*, 2021, A&A, 653, A44

28. Goddi, C. et al. (including **Valtonen**) *Polarimetric Properties of Event Horizon Telescope Targets from ALMA*, 2021, ApJ, 910, L14

29. Goldoni, P. et al. (including **Lindfors**) *Optical spectroscopy of blazars for the Cherenkov Telescope Array*, 2021, A&A, 650, A106

30. Grayling, M. et al. (including **Gutierrez**) *Understanding the extreme luminosity of DES14X2fna*, 2021, MNRAS, 505, 3950

31. **Gutierrez, C.** et al. *The double-peaked Type Ic supernova 2019cad: another SN 2005bf-like object*, 2021, MNRAS, 504, 4907

32. Hiramatsu, D. et al. (including **Gutierrez**) *Luminous Type II Short-Plateau Supernovae 2006Y, 2006ai, and 2016egz: A Transitional Class from Stripped Massive Red Supergiants*, 2021, ApJ, 913, A55

33. Homan, D. C. et al. (including **Hovatta**) *MOJAVE. XIX. Brightness Temperatures and Intrinsic Properties of Blazar Jets*, 2021, ApJ, 923, A67

34. **Hovatta, T.** et al. (including **Lindfors, Liodakis**) *Association of IceCube neutrinos with radio sources observed at Owens Valley and Metsähovi Radio Observatories*, 2021, A&A, 650, A83

35. Inserra, C. et al. (including **Gutierrez**) *The first Hubble diagram and cosmological constraints using superluminous supernovae*, 2021, MNRAS, 504, 2535

36. Kallunki, J., **McKay, D.**, Tornikoski, M. *First Type III Solar radio bursts of Solar cycle 25*, 2021, Solar Physics, 296, 57

37. Kankare, E. et al. (including **Berton, Kotilainen**) *Core-collapse supernova subtypes in luminous infrared galaxies*, 2021, A&A, 649, A134

38. Kiehlmann, S. et al. (including **Hovatta, Liodakis**) *The time-dependent distribution of optical polarization angle changes in blazars*, 2021, MNRAS, 507, 225

39. Kipper, R., Taam, A., Tempel, E., **De Propris, R.**, Ganeshaiah Veena, P. *The role of stochastic and smooth processes in regulating galaxy quenching*, 2021, A&A, 647, A32

40. Kipper, R., Tenjes, P., Tempel, E., **De Propris, R.** *Non-equilibrium in the solar neighbourhood using dynamical modelling with Gaia DR2*, 2021, MNRAS, 506, 5559

41. **Koljonen, K. I. I.** & **Hovatta, T.** *ALMA/NICER observations of GRS 1915+105 indicate a return to a hard state*, 2021, A&A, 647, A173

42. Komossa, S. et al. (including **Valtonen**) *Project MOMO: Multiwavelength Observations and Modeling of OJ 287*, 2021, Universe, 7, 261

43. Komossa, S. et al. (including **Valtonen**) *X-ray spectral components of the blazar and binary black hole candidate OJ 287 (2005-2020)*, 2021, MNRAS, 504, 5575

44. Liodakis, I. et al. (including **Hovatta**) *Identifying changing jets through their radio variability*, 2021, A&A, 654, A159

45. Medler, K. et al. (including **Gutierrez**) *SN 2020cpg: an energetic link between Type IIb and Ib supernovae*, 2021, MNRAS, 506, 1832

46. Nwaokoro, E. et al. (including **De Propris** *GAMA/XXL: X-ray point sources in low-luminosity galaxies in the GAMA G02/XXL-N field*, MNRAS, 502, 3101

47. Parrag, E. et al. (including **Gutierrez**) *SN 2019hcc: a Type II supernova displaying early O II lines*, 2021, MNRAS, 506, 4819

48. Pelisoli, I.. et al. (including **Hakala**) *Optical detection of the rapidly spinning white dwarf in V1460 Her*, 2021, MNRAS, 507, 6132

49. Perley, D. A. et al. (including **Gutierrez**) *Real-time discovery of AT2020xnd: a fast, luminous ultraviolet transient with minimal radioactive ejecta*, 2021, ApJ, 907, A61

50. Prentice, S. J. et al. (including **Gutierrez**) *Transitional events in the spectrophotometric regime between stripped envelope and superluminous supernovae*, 2021, MNRAS, 508, 4342

51. Ramsey, G., **Hakala, P.**, Wood, M. A. *Detection of an energetic flare from the M5V secondary star in the Polar MQ Dra*, 2021, MNRAS, 504, 4072

52. Rakshit, S., Stalin, C. S., **Kotilainen, J.**, Shin, J. *High-redshift Narrow-line Seyfert 1 Galaxies: A Candidate Sample*, 2021, ApJS, 253, A28

53. Rakshit, S., et al. (including **Kotilainen, J.**) *TXS 1206 + 549: a new γ-ray-detected narrow-line Seyfert 1 galaxy at redshift 1.34?*, 2021, MNRAS, 504, L22

54. Readhead, A. C. S. et al. (including **Hovatta, Liodakis**) *The Relativistic Jet Orientation and Host Galaxy of the Peculiar Blazar PKS 1413+135*, 2021, ApJ, 907, A61

55. Stone, M. B. et al. (including **Kotilainen**) *Low-redshift quasars in the SDSS Stripe 82 - II. Associated companion galaxies and signature of star formation*, 2021, MNRAS, 501, 419

56. **Valtonen, M.** et al. *Promise of Persistent Multi-Messenger Astronomy with the Blazar OJ 287*, 2021, Galaxies, 10, 1

57. Vilhu, O., Kallman, T. R., **Koljonen, K. I. I.**, Hannikainen, D. C. *Wind suppression by X-rays in Cygnus X-3*, 2021, A&A, 649, A176

58. Vincenzi, M. et al. (including **Gutierrez**) *The Dark Energy Survey supernova programme: modelling selection efficiency and observed core-collapse supernova contamination*, 2021, MNRAS, 506, 2819