Project summary

Towards direct imaging of forming planetary systems with the angular resolution of a 200m telescope (OTKA grant 102014)

International collaboration between
MTA Research Centre for Astronomy and Earth Sciences
Konkoly Thege Miklós Astronomical Institute
and
Leiden Observatory, Leiden University, the Netherlands

Motivation and overview

A large fraction of observing time with cutting edge optical-infrared instruments is offered for the community on a competitive basis. However, the teams, institutes who built the instruments have a natural advantage in these competitions. And for example, after the commissioning of a new instrument at the European Southern Observatory (ESO), which is probably the most important optical-infrared observatory nowadays, the instrument building consortia are rewarded with Guaranteed Time for observations. Given the complexity and the cost of the next generation ESO instruments, i.e., the European Extremly Large Telescope (E-ELT), it is likely that even larger fraction of the observing time will be controled by smaller groups. In the recent years, Hungarian teams have used world-class telescopes and instruments and achieved siginficant results. In a scenario where the role of application is decreasing, the current success rate can not be mantained ï therefore getting involved in instrument development in international consortia will become necessary.

In the field of optical-infrared astronomy it already has been started. A Hungarian team participated in the work related to science software of two missions of the European Space Agency, i.e., the Infrared Space Observatory and the Herschel Space Observatory. In 2004 Konkoly Observatory started a collaboration with the Max Planck Institute for Astronomy (Heidelberg, Germany), and contributed to the science cases and science software of the ESO Very Large Telescope Inerferometer (VLTI) instrument MATISSE. MATISSE is the second generation mid-infrared instrument for the VLTI in Chile. Starting from 2016, MATISSE will produce high angular resolution milliarcsecond-scale infrared images of the close environment of compact objects, e.g., the forming planetary systems of young analogs of our Sun. In 2010 the opportunity arose to join instrument hardware and software development. We proposed a joint collaboration between Leiden Observatory and Konkoly Observatory to work on the development of MATISSE. We aimed at increasing the ability of the two institutions to fully exploit the scientific potential of MATISSE.

By participating in the engineering works, we wanted to achieve two primary goals at the end. First, to get involved in MATISSE Guaranteed Time Observation (GTO) programs. Second, to get involved in further instrument development projects, which can lead to further scientific collaborations. By the end of 2014, Konkoly Observatory has its own share from MATISSE GTO and is involed in a number of MATISSE GTO projects and other instrument developments.

The report is structured as follows. 1. Overview of MATISSE, focusing on the study of young stellar objects (YSOs); description of 2. preparatory science projects; 3. image reconstruction study; 4. software development; 5. hardware development; and 6. summary of results, conclusions.

1. MATISSE at the Very Large Telescope Interferometer

One of the ultimate goals of modern-day astronomy is to reveal the secret how our planetary system and in particular the Earth was born. In the case of Sun-like (low-mass) stars, the circumstellar accretion disks govern the star formation as the dust and gas of the parent molecular cloud is accreted onto the star through the disk. As a by-product of this process, planets are formed from the same material in the disks. Therefore planet and star formation can not be detached. The structure of the circumstellar disk and dynamical processes in it define the architecture of the future planetary system, while the composition of its dust determines the composition of terrestrial planets. Investigations of circumstellar disks around low-mass young stars provide inputs for further theoretical studies of planet formation. Given the typical distance of the objects and the typical sizes of the disks, - 150-400 pc and 100 AU, respectively, - the structure (i.e. density and temperature distribution) of the disk can only be determined by model fitting to the spectral energy distribution of the object.

Observations of the planet forming regions (size of a few AU) require high angular resolution imaging instruments. Even at the distance of the closest star forming regions, it corresponds to milli-arcsecond resolution. This level is beyond the capabilities of the current top (10m-class) telescopes. Such resolution can only be achived by telescopes with diameters of 100-200m at infrared wavelengths. Currently the largest telescopes planned for this and the next decade will be 30-40m class instruments. Stellar interferometry offers the possibility to achive the required angular resolution.

The VLTI consists of four 8.2m and four 1.8m telescopes, which can form a telescope-array with a diameter up to 200m. Although the current VLTI instruments provide spatial information on these scales, those data can only interpreted via model-fitting. The image reconstruction potential of the VLTI is still limited. However, one of the next generation VLTI instruments under development, i.e. MATISSE, will be able to routinely create milli-arcsecond resolution images in the 3-20 εm mid-infrared regime. MATISSE stands for Multi-AperTure Interferometric and SpectroScopic Experiment, the Consortium is led by Observatoire de la Cote dôAzur (Nice). The major partners in the consortium are: NOVA Netherlands Research School for Astronomy (Leiden), Max Planck Institute for Astronomy (Heidelberg), Max Planck Institute for Radioastronomy (Bonn). MATISSE is in last phase of development now, and will be tested in Europe and Chile soon. The instrument design was finalized in 2012, which was followed by the fabrication of the instrument parts, assembly and integration of the instrument (2012-14).

MATISSE will answer fundamental questions for low- and intermediate-mass YSOs. The images of a few milli-arcsecond resolution produced by MATISSE will show the surface brightness distribution of the circumstellar disks without the need of modeling. *What is the status of disk clearing?* The inner 0.1 - 1.0 AU region of the circumstellar disk is thought to be dust free because of the radiation of the central illuminating source. Based on MATISSE images, one can determine the size of the cleared region and investigate its relation to the dust sublimation radius, which depends on the composition of the dust. *Is the inner disk structure* *modified by early stages of planet formation? Is there indirect or even direct evidence for the presence of planets?* MATISSE observations and image reconstruction will allow us to find inhomogenities in the circumstellar structure. Such inhomogenities can be considered as signatures of ongoing planet formation or the presence of a planet itself. As an inhomogenity in the disk starts to grow and accretes more and more material, an increase of the surface brightness should be observable in the mid-infrared. A gap in the disk, which is expected to be opened by planet(s) at later stages, should also be revealed by MATISSE.

2. Science with MIDI

All preparatory studies for future MATISSE observations consist of analysis of VLTI/MIDI data. MIDI, the precursor of MATISSE at the VLTI, is a two-element infrared stellar interferometer, operated in the 8-13 εm spectral band until early 2015. In studies of protoplanetary disks MIDI observations provided information about 1. the structure of the circumstellar disks around young stellar objects, 2. the spatial distribution of the dust species in the disk. Although image reconstruction is not possible, MIDI data consist some limited spatial information, i.e., the spectra of the whole system and the inner disk regions.

2.1 We studied the circumstellar structure of highly variable, eruptive low-mass YSOs. It is hypothesized that all low-mass YSOs undergo eruptive phases during their early evolution. These eruptions are thought to be caused by highly increased mass accretion from the disk onto the star, and therefore play an important role in the early evolution of Sun-like stars, of their circumstellar disks (structure, dust composition), and in the formation of their planetary systems. The outburst of V1647 Ori between 2003 and 2006 offered a rare opportunity to investigate such an accretion event. We investigated the temporal evolution of the inner circumstellar structure of V1647 Ori, the region where Earth-like planets could be born. We modeled interferometric, spectroscopic and photometric data of five epochs. For the modeling we calculated radiative transfer models with the MC3D code (developed by S. Wolf). We found that 1. the disk and the envelope are similar to those of non-eruptive YSOs, 2. the accretion rate varied during the outburst, and 3. the inner radii of the disk and envelope changed. These findings are among the first direct evidences of dynamical processes revealed on such small scales derived with stellar interferometry. These results became part of the basis for variability studies with MATISSE. (Article: Mosoni et al. 2013, A&A, 552, A62)

2.2 We also study the eruptive object V883 Ori. We collected MIDI, Keck, Spitzer and other data. As for V1647 Ori, we attempted radiative transfer modeling, with the RADMC code (developed by C. P. Dullemond). The modeling process was supervised by A. Juhász in Leiden. This object has not been very well studied so far, no system parameters have been derived. In order to have robust results, we computed several thousand models. We have started the first runs in 2013. Until now we could exlude the possibility that the system is dominated by the radiation of the disk. Mass accretion in the disk does not have to be considered in the calculations, has no effect on the model results. Different disk+halo system configurations are still tested. (Article: Gabányi et al., in prep.)

2.3 We also participate in the MIDI Guaranteed Time programs (project led by Max Planck Institute for Astronomy, Heidelberg). We started to work on the data of 6 low-mass YSOs. The most advanced study is that of a young close binary, AK Sco. Our radiative transfer modeling of the data (with RADMC) revealed that the system consists of a circumbinary disk and a small dust halo. Although the object "looks like" an ordinary YSO, some gas lines are

missing in the spectrum. Until now we could not resolve this contradiction. (Article: Gabányi et al. 2013, Protostars and Planets VI Conf., Heidelberg, 2013 July)
We investigate the structure of the innermost region of three circumstellar disks around pre-main sequence stars HD 142666, AS 205 N, and AS 205 S. We determine the inner radii of the dust disks and, in particular, search for transition objects where dust has been depleted and inner disk gaps have formed at radii of a few tenths of AU up to several AU. We performed interferometric observations with IOTA, AMBER, and MIDI in the infrared wavelength ranges 1.6-2.5 mum and 8-13 mum with projected baseline lengths between 25 m and 102 m. The data analysis was based on radiative transfer simulations in 3D models of YSOs to reproduce the spectral energy distribution and the interferometric visibilities simultaneously. Accretion effects and disk gaps could be considered in the modeling approach. Based on these observations, a disk gap could be found for the source HD 142666 that classifies it as transition object. The classification of AS 205 as a system of classical T Tauri stars could be confirmed using the canonical model approach, i.e., there are no hints of disk gaps in our observations. (Article: Schegerer et al., 2013, A&A, 505, 103)

Besides these targets there are more than 50 low-mass YSOs observed with MIDI over the last decade. The MIDI Science Team agreed that we should make a homogeneous analysis of data and results for the whole sample. Since radiative transfer modeling of individual objects turned out to be slow and inefficient in many cases, our team decided to apply a different approach in the future. A similar study is in an advanced state for the intermediate-mass YSOs (Menu et al., in prep.). They considered simple disk structure for all objects: 1. a two-layer geometrically flat disk with power-law temperature distribution, 2. with simple dust composition. Their results look nice. We have started to apply their method for our sample. Although the work will be finished well after the closing date of our grant, I wanted to mention it, because I believe it will be the resolution on the difficulties we had faced.

2.4 We also have initiated observing programs investigating structure of YSOs. One program on intermediate-mass YSOs. Circumstellar structure can show direct evidence of planet formation. In the transitional phase between primordial protoplanetary disks and debris disks dust depleted inner holes, gaps are expected to form. While sub-mm observations could indeed resolve these cavities in several cases, recent high contrast coronographic near-infrared images of the same sources did not show a break in the surface brightness distribution at the cavity wall. These results suggest that a size-sorting mechanism operates at the cavity wall, that decouples millimeter and micron sized grains, observed at sub-mm and near-infrared scattered light, respectively. The existence of such size-sorting mechanism has very important consequences for planet formation. Data reduction is in progress. (PI: Gabányi).

Another MIDI program was initiated to study variability of five selected intermediate-mass YSOs. ESO The project aims at monitoring the targets on weekly basis. The goal of the program is twofold. 1. Since the targets are well-studied, the mechanisms behind the variations might be constrained by the obtained data. 2. The data will be the basis for one of the MATISSE GTO programs (see below). Data reduction is in progress. (PIs: Grellmann, University of Cologne, & P. Ábrahám)

2.5 One particular low-mass YSO, DG Tau, shows highly variable silicate feature. Our MIDI observations, aiming at determining the origin of the varying emission were carried out during the winters of 2011/2012, 2012/2013 and 2013/2014. The prominent silicate feature disappeared by the time of our observations. Weak silicate emission and absorption are seen in the spectra of the outer and inner disk spectra, respectively. This finding suggests selfabsorption. The origin of the variations can not be studied here. However, the strong silicate emission seen earlier might be linked to the outflow activity of the object. It was not expected, because of the different spatial scales of the two regions. Our observations were done in a "quiet" period. Although evidence of strong outflow activity was found again in Spring 2013, mid-infrared spectra from winter 2013/2014 did not show the silicate feature. In the absence of strong silicate feature, we could not carry out the planned analysis of the silicate composition. (Mosoni et al. 2013, Protostars and Planets VI Conf.)

3. Image reconstruction tests

We planned to execute image reconstruction tests to study the effect of the variation of different system parameters during the observations. For the MATISSE software studies the proposed image reconstruction tests were not required. The first tests were carried out for two cases. 1. The disk structure is asymmetric due to a planet embryo. 2. The asymmetric structure is caused by disc wind. In both cases 3 nights of observations were simulated to investigate whether the changes are observable. We used the MIRA and MACIM codes for image reconstruction (Cotton et al. 2008, SPIE). We found that except in the cases of highly inclined disks (i=70 degree), the image reconstruction is doable, however the structure in the image is more likely reflects the limited telescope configurations and not the variations. Preliminary results shows that 5-7 nights of observations are needed for such a project. The results were presented at the VLTI community days, 2014.01.13-16., A. Juhász, M. Benisty, L. Mosoni, C. Dullemond, Infrared variability of protoplanetary disks, http://vlti-pionier.sciencesconf.org/

The second tests were made for the preparations of a MATISSE GTO program. Konkoly Observatory initiated a program to study the prototype eruptive variable YSO, FU Ori. In the tests, 3 nights of observing time was considered. That is the Hungarian time budget available for this project. Similarly to the other project, the tests showed that observing time of 5 nights is required as a minimum for image reconstruction. More detailed tests will be carried out in the next 6-12 months.

4. MATISSE instrument software development

To obtain first hand information about the technical capabilities of the instrument, we participated in the development of the instrument software of MATISSE.

According to the rules of ESO, the design of new instruments are reviewed several times before manufacturing and integration starts. The Final Design Review (FDR) of MATISSE took place in April 2012. One of our contribution for the FDR was part of the Instrument Software Design, in particular the design of the near real-time system of MATISSE. This system controls partly the instrument during observations. After initiating different observing sequences (target acquisition or fringe search/track), the obtained data are investigated. Selected part of the information is displayed for the observer. Based on these displays, the observer can continue the observations in different ways: start the next step, refine the setup of instrument elements, make corrections or abort the observations. In order to build a working system, we had to understand the current VLTI environment and define the steps of the different modes of MATISSE observations. Later we described the displayed information and the options to be offered for the observer. Our work was presented to ESO as part of the

FDR documentation, int he Instrument Software Design Description and the Template Manual documents.

Although we started the development of the near real-time system, it will be mostly done by the PI team in Nice because of managment/organisational reasons. The graphical interfaces of the observation control are still development. The first one (that of the target acquisition) was completed by our team in 2013. It allows the operator to check whether the four images of the target are on the right places on the detector, and if needed, make the necessary corrections. The control panels for the interferometric observations are developed in Nice.

We have started to work on the data reduction software prototype (IDL/C++). Besides the ESO standard data reduction pipeline, the consortium needs a more flexible, easily changeable software for testing and commissioning of the instrument. The plan is that we will upgrade the current MIDI data reduction software for MATISSE. A MATISSE data simulator was dveloped in Leiden for data reduction and image reconstruction tests to define the first MATISSE GTO science programs.

The upgrade of the current VLTI/MIDI real time data analysis systems was not carried out. Although the decommissioning of the instrument will take place only early 2015, ESO announced it first already in 2013.

5. MATISSE hardware development (and spinoff projects)

We participated in the development of the hardware of the VLTI/MATISSE instrument. The hardware of MATISSE is built by excellent European laboratories. The cold optics system, the last unit of MATISSE which guides the light beams onto the detectors, was built by the NOVA Optical/Infrared Lab in the Netherlands. Our mechanical engineer worked on the design of the cold optics system of MATISSE at the NOVA-ASTRON Optical/Infrared Lab in the Netherlands in the first year. In particular, he participated in the design of the MATISSE Wheel Box (WHB), Camera Box (CAB) and Re-Imager Box (RIB), three sub-assemblies of the MATISSE Cold Optics Box (COB). Since MATISSE is a mid-infrared interferometer, the entire COB operates in vacuum and at approx. 40°K. All the optics have to be placed very precisely (on micrometer-scales). In three separate wheels more than a dozen optical components (filters, and dispersive elements) are located in the WHB. He designed the housings of optics in precision mechanics at cryogenic temperatures. He also worked on the housing of the CAB lenses. Deploying Finite Element Analysis (FEA), the deformation of lenses caused by the clamping force holding them in position were calculated. These lenses also have special mounts to compensate for the differences in the coefficient of thermal expansion between their own material and the aluminium housing. Also by utilising FEA, the eigenfrequencies of the RIB to avoid resonance in the structure were calculated. He also gained hands-on experience in handling (cleaning and assembling) delicate mechanisms during the integration of MATISSE sub-assemblies. 1. Assembled the four shutters of the COB in a clean room. 2. Made thermal tests of a camera interface in a cryostat cooling down the part to 19°K.

Thermal analysis of the MATISSE Cold Optics Box was carried out in Budapest in the second year. The heat of a motor might introduce mechanical deformations to the system and therefore affect the performance of the instrument. Applying Finite Element Method we are now able to confidently calculate the temperature distribution in MATISSE. Heat generation, conduction, convection and radiation can be taken into account and the performance of the instrument can be predicted. The analysis revealed no show-stoppers.

During the Summer 2013 Konkoly Workshop finalized the design and organized the production of the so-called Technical Camera (MTC), which is used during the Integration and Testing phase. The MTC is a simple but accurate instrument having two lenses and a simple mechanism which makes one of the lenses removable from the light beam. It was the first project where Konkoly played a key role in the development of an instrument part, organized its production (the part was manufactured by a Hungarian company) and shipped it to the foreign partner.

Our engineer designed an appropriate Transportation Equipment for the delicate COBs. These are used to keep the instrument clean and prevent damage during road or air transportation. The equipment is to be used three times until MATISSE arrives at Chile in 2015. After integration and testing the COBs are transported from The Netherlands to Germany, then from Germany to France and at last from France to Chile. During these shipments the delicate optical components of the COBs have to be protected from vibration, shocks and physical contamination such as dust, moisture and other particles. The COB is mounted inside a special aluminum frame that is placed on shock isolators. The whole assembly is mounted on a clean plastic pallet and is enclosed in a wooden crate.

For the last year of our project, the integration and testing of the COB was planned. The test measurements provided by the Dutch partners were partly analysed in Budapest. We could take advantage of our involvement and connections built in the MATISSE consortium. A young researcher from Konkoly Observatory, who worked on an FP7/Space project (called CESAR, testing electronics in cryogenic environment), could spend months in Heidelberg and worked on the testing of the integrated cryogenic and electronic systems.

The Hungarian participation in the development and integration of the cold optics of MATISSE is considered as a learning curve. In 2011 we hoped that it will lead to further collaborations in other cutting edge instrumentation. At the moment there are two such projects.

FAME: Freeform Active Mirror Experiment (FP7 OPTICON Work Package 5)

The aim of this FP7 project is to develope novel deformable mirrors with high-quality free-form surfaces and long-term stability in order to reduce the number of optical element in instruments like that of the E-ELT. We contributed to the redesign of the existing prototypes, using FEA techniques and an interferometer to measure the shape of the mirror surfaces. Our engineer developed a very promising method to predict deformations of a real mirror using finite element models. Zernike polynomials were considered to compare the real (measured) and computer-calculated shapes. Very good fits were achieved, thus our model is accurate. Therefore the development process became faster. Now the optical design of the project demonstrator is frozen; the final product is set to be presented in 2016 during the SPIE conference. Konkoly Observatory became a beneficiary of the OPTICON FP7 grant by the end of 2014 (providing approx. 30000 EUR over the coming years).

WEAVE: wide-field multi-object spectrograph for the William Herschel Telescope

Following the work done in the MATISSE and FAME projects, Konkoly Observatory was invited to join the WEAVE team that is developing and building a new multi-object spectrograph for the William Herschel Telescope on La Palma, Spain. WEAVE will start operations in 2017. Together with the Isaac Newton Group of Telescopes (ING) people in Konkoly Workshop work on development of the Bench Spectrograph and the Prime Focus Corrector assembly (e.g., design of the mounts of 1.2m lenses). Negotiations have started about Hungarian partnership in WEAVE. As a reward for the hardware design contribution, the team of Maria Lugaro (MTA CSFK CSI, Momentum Group leader 2014-2019) can join the Science Team and will have access to the data.

6. Summary of results, conclusion

One of the major goals of our program was that after being involved in the development of MATISSE software, our institute will be able to use MATISSE with competence. By knowing the operation of the instrument and the data reduction, one can plan more efficiently observing proposals for the Open Time beyond and after the observing time granted for the MATISSE Consortium. On the other hand, contribution to hardware building might turn out to be a very good investment in terms of reward, since it is always considered seriously. The collaboration with the Dutch partners was considered so successful, that a Memorandum of Understanding was signed between NOVA and MTA CSFK in Summer 2013. It allows Hungarian astronomers to participate in guaranteed time scientific projects of MATISSE. Besides that Hungarian astronomers can freely join all Dutch led programs, Konkoly Observatory got its own share from the MATISSE Guaranteed Time. This is approximately 2% of the total guaranteed observing time. The projects we are involved are the following (Hungarian time contribution noted):

1. Imaging of FU Ori (PI: P. Ábrahám, Hungarian CoIs: Á. Kóspál; *Hungarian observing time: 18 hours*)
2. Study of YSO disk variability (PI: S. Wolf, Hungarian CoIs: P. Ábrahám, Á. Kóspál; *Hungarian observing time: 6 hours*)
3. Study of transitional disk structure (PI: R. van Boekel; Hungarian CoIs: K. Gabányi)
4. Hot material in transitional disks (PI: C. Dominik; Hungarian CoIs: Zs. Regály)
5. Massive planets in disks (Dominik, Hungarian CoIs: Zs. Regály)
6. Transient dust in warm debris disks (Olofsson, Hungarian CoIs: A. Moór)
7. Gas (CO) in gaps (PI: Hogerheijde, Hungarian CoIs: Zs. Regály, P. Ábrahám, Á. Kóspál)
8. Study of binary Cepheids (PI: Nardetto, Hungarian CoIs: L. Szabados)
9. Study of AGB stars (PIs: Chiavassa & Hron, Hungarian CoIs: M. Lugaro; *Hungarian obsevring time: 6 hours*)

MATISSE is built by an international collaboration, thus participating in the work of the consortium grants a number of strategic advantages at the level of the Observatory: we learned in details how large projects work, how to participate in the work of international/multi-institute work packages, and how such a project should be led. We also built professional connections all accross Europe. Since MATISSE will be an ESO instrument, thus contribution to its developement is aligned with the general efforts and vision of the Hungarian astronomy to join ESO within a reasonable timescale. Similarly to the case of Konkoly Infrared Space Astronomy Group (KISAG, led by Péter Ábrahám), we also conclude that the investment of resources into technical contributions to cutting edge instrumentation turned out to be a successful strategy at international level.

Appendix: References for hardware development projects

http://spie.org/profile/viewer.aspx?name=Attila.Jask%u00f3-9861

MATISSE

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FAME

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Design and development of a freeform active mirror for an astronomy application
Author(s): Zalpha Challita; Tibor Agócs; Emmanuel Hugot; Attila Jaskó; Gabby Kroes; William Taylor; Chris Miller; Hermine Schnetler; Lars Venema; László Mosoni; David Le Mignant; Marc Ferrari; Jean-Gabriel Cuby

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WEAVE

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Jaskó, Jan Kragt, Dirk Lesman, Christopher J. Mottram, Stuart D. Bates, Francis James H. Gribbin, Luis F. Rodríguez-Ramos, Jose M. Delgado Hernandez, Carlos Martin, Diego Cano Infantes, Ramón Navarro, Michael J. Irwin, James R. Lewis, Eduardo Gonzalez-Solares, Neil O'Mahony, Andrea Bianco, Christina Zurita, Rik ter Horst, Emilio Molinari, Marcello Lodi, Jose Guerra, Antonella Vallenari, Andrea Baruffolo, "Project overview and update on WEAVE: the next generation wide-field spectroscopy facility for the William Herschel Telescope", in Ground-based and Airborne Instrumentation for Astronomy V, Suzanne K. Ramsay; Ian S. McLean; Hideki Takami, Editors, Proceedings of SPIE Vol. 9147 (SPIE, Bellingham, WA 2014), 91470L.

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