MATISSE
Multi-AperTure Mid-InfraRed SpectroScopic Experiment

Bruno Lopez et al.
AfterTwelve/APreS-MIDI model experiment, testing a possible optical interface with the current 2 beam MIDI instrument
AfterTwelve/APrēS-MIDI model experiment, testing a possible optical interface with the current 2 beam MIDI instrument.
Towards the Imaging in the mid-IR domain

Young star flared disk

Clumpy dust torus of AGN at different inclinations

Red giant atmosphere

Red giant envelope with bright rim and dust clumps
Towards the Opening of New Spectral Windows

Present MIDI Instrument
Towards the Opening of New Spectral Windows

MATISSE Instrument
Objectives: to better understand the inner regions of dust disks and the conditions under which the planets form and evolve.

Formation and evolution of the planetary systems

Earth - 7 mas
Jupiter - 36 mas
Neptune - 215 mas
Protoplanetary disk evolution: Mass versus Age
T Tauri sources, Herbig Sources and the required sensitivity

<table>
<thead>
<tr>
<th>Instrument</th>
<th>T Tauri stars</th>
<th>Herbig stars</th>
<th>Debris disks</th>
<th>Massive YSOs</th>
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Low set of observed T Tauri sources versus Herbig type sources (From MATISSE Science Analysis Report, Issue 1).
T Tauri sources, Herbig Sources and the required sensitivity

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<tr>
<th>Instrument</th>
<th>T Tauri stars</th>
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How to test / analyse the disk evolution?
How to study protoplanetary disk composition?
How to search for disk / forming planets (embryos, gaps, waves)?

From Leinert et al. 2004
How to test / analyse the disk evolution?

How to study protoplanetary disk composition?

How to search for disk / forming planets (embryos, gaps, waves)?

From Leinert et al. 2004

From Dullemond and Monnier 2010
How to test / analyse the disk evolution?
How to study protoplanetary disk composition?
How to search for disk / forming planets (embryos, gaps, waves)?
Highlights: L & M band ~ 2.9 – 5.0 mm
• New dust species: e.g., H₂O ice broad band feature (2.8 – 4.0 μm)
• Polycyclic Aromatic Hydrocarbons (PAHs): 3.3 μm, 3.4 μm;
• Nano-diamonds: 3.52 μm
• Transition from dust scattering to dust thermal reemission as the source of spatially extended emission
• CO fundamental transition series (4.6 – 4.78 μm)
• CO ice features 4.6 – 4.7 μm
• Recombination lines, e.g., Pfβ at 4.65 μm

N Band ~ 7.5 – 13.5 μm
• Spectral features to be investigated with MATISSE will be very similar to those studied with MIDI: Silicates, Olivine, Forsterite, SiC.
Example of dust mineralogy effects

van Boekel et al. 2004, Nature, 432, 479
Example of dust mineralogy effects

Different scenarii:
- Disk inclination ($\Delta i = 10^\circ$)
- Inner rim ($\Delta r_{in} = 1$ UA)
- Size of dust grains ($\Delta a_{grain} = 1$ $\mu$m)
- Dust composition: silicate + crystalline material

van Boekel et al. 2004, Nature, 432, 479
Example of dust mineralogy effects

Different scenarii:

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How to test/analyse the disk evolution?
How to study protoplanetary disk composition?
How to search for disk/forming planets (embryos, gaps, waves)?

YSO plus planet
(see PDR report)

SNR of squared visibilities = 20

3x4 ATs

uv coverage: vis² (162); bispectrum (108)

original

error 4.64%

IRS

error 4.64%

BBM
Performances answering the science objectives

Science objectives

Spécifications

Performance analysis

VLTI characteristics, performances, contraints & environnement
Instrumental concept study

✓ Best concept in term of performance (SNR on coherent flux)
  • Co-axial or multi-axial / Pairwise or global combination
  • Taking into account the instrument feasibility

✓ Strategy to reduce the effect of the thermal background
  • Use of OPD modulation, spatial filtering, photometric channel, chopping

✓ Strategy to optimize the calibrated visibility accuracy
  • Spatial filtering without fiber
  • Contrast stability vs flux loss taking into account VLTI AO performances

✓ Strategy to optimize the phase accuracy
  • Beam commutation

✓ Study of the parasitic light effects
  • Effect of parasitic fringes (“Fizeau”, “Perot-Fabry”, “Young”) on instrumental performance
MATISSE concept

Beam commutation
Spectral separation
OPD modulation
Delay lines
Spatial filter

Anamorphic optics
L band
N band

Beam configuration
3D 9D 6D

3D 9D 6D

Anamorphic optics
Filters
Polarizers
Dispersive elements
Camera optics

I(u)

Thermal background
Photometry
Coherent flux
MATISSE concept

- Beam commutation
- Spectral separation
- OPD modulation
- Delay lines
- Spatial filter

Beam configuration
- 3D
- 9D
- 6D

Photometry Units
- Interferometry/photometry splitter
- Anamorphic optics
- Filters
- Polarizers
- Dispersive elements
- Camera optics

3D, 9D, 6D

I(u)

Thermal background + photometry for each beam

Thermal background + Coherent flux
MATISSE in the VLTI focal lab

Cold Optics

Warm Optics
A list of Challenges

- Concept & Optical Design
- Cryocooling
- Detectors: Hawaii 2RG & Aquarius
- Adjustment motors
- Data flow
- Data Reduction Software & Image Reconstruction
- Integration, Alignment and Tests
- VLTI Infrastructure Requirements
MATISSE FUNCTIONS

- **VLTI**
- **ADAPTIVE OPTICS**
- **TIP/TILT CORRECTION**
- **PUPIL MONITORING**
- **FRINGE TRACKING**

**MATISSE**

- **BEAM COMMUTATION**
- **BEAM ANAMORPHISM (1)**
- **SPECTRAL SEPARATION**

**L band**

**N band**

**ARTIFICIAL SOURCES**

- **OPD MODULATION**
- **CO-ALIGNMENT**
- **CO-PHASING**

**BEAM SELECTION**

**SPATIAL FILTERING**

**PHOT/INTERF SPLITTING**

**INTERFEROMETRY**

- **BEAM CONFIGURATION**
- **BEAM ANAMORPHISM (2)**
- **SPECTRAL FILTERING**
- **POLARIZATION SELECTION**
- **SPECTRAL DISPERSION**
- **BEAM COMBINATION**

**PHOTOMETRY**

- **DETECTION**
MATISSE FUNCTIONS

VLTI

ADAPTIVE OPTICS
TIP/TILT CORRECTION
PUPIL MONITORING
FRINGE TRACKING

MATISSE

BEAM COMMUTATION
BEAM ANAMORPHISM (1)
SPECTRAL SEPARATION

L band
N band

ARTIFICIAL SOURCES

OPD MODULATION
CO-ALIGNMENT
CO-PHASING

BEAM SELECTION

SPATIAL FILTERING
PHOT/INTERF SPLITTING

Interferometry

BEAM CONFIGURATION
BEAM ANAMORPHISM (2)
SPECTRAL FILTERING
POLARIZATION SELECTION
SPECTRAL DISPERSION
BEAM COMBINATION

Photometry

PHOTOMETRY

DETECTION
MATISSE FUNCTIONS

VLTI → MATISSE

ADAPTIVE OPTICS
TIP/TILT CORRECTION
PUPIL MONITORING
FRINGE TRACKING

BEAM COMMUTATION
ARTIFICIAL SOURCES
BEAM ANAMORPHISM (1)
CO-ALIGNMENT
CO-PHASING

SPATIAL FILTERING
BEAM SELECTION
SPECTRAL SEPARATION
OPD MODULATION
L band
N band

BEAM CONFIGURATION
BEAM ANAMORPHISM (2)
SPECTRAL FILTERING
CO-PHASING

SPATIAL FILTERING
POLARIZATION SELECTION
SPECTRAL DISPERSION
PHOT/INTERF SPLITTING

BEAM COMBINATION
DETECTION

Interferometry
Photometry
## Performances

### Sensitivity:

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<tr>
<th>Limiting Magnitude</th>
<th>L band</th>
<th>N band</th>
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<tbody>
<tr>
<td>UT</td>
<td>6.6 (0.65Jy)</td>
<td>8.35 (0.13Jy)</td>
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<td>AT</td>
<td>4.1 (6.5Jy)</td>
<td>5.85 (1.3Jy)</td>
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### Calibrated visibility: Tech. Spec. ≤ 7.5% (goal ≤ 2.5%) with UTs, 20 Jy

<table>
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<th>Visibility accuracy</th>
<th>L band</th>
<th>N band</th>
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<td>Blind mode</td>
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</table>

### Closure Phase: Tech. Spec. ≤ 40mrad (goal ≤ 1mrad) with UTs, 20 Jy

<table>
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<th>Closure phase</th>
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<th>N band</th>
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<td></td>
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Participants and Partner Institutes


MATISSE Consortium: B. Lopez¹, P. Antonelli¹, S. Wolf⁶, W. Jaffe³, R. Petrov¹, S. Lagarde¹, P. Berio¹, R. Navarro⁴, F. Bettonvil⁴, U. Graser², U. Beckman⁵, G. Weigelt⁶, F. Vakili¹, T. Henning², J.C. Augereau⁹, C. Bailet¹, J. Behrend⁵, Y. Bresson¹, O. Chesneau¹, J.M. Clausse¹, C. Connot⁵, K. Demyk⁵, W.C. Danchi⁷, M. Dugué¹, Y. Fantei¹, E. Elswijk⁴, H. Hanenburg⁴, K.H. Hofmann⁵, M. Heininger⁵, R. t. Horst⁴, J. Hron⁷, J. Kragt⁴, J. Tromp⁴, T. Agocs⁴, G. Kroes⁴, W. Laun², Ch. Leinert², A. Matter¹, Ph. Mathias, K. Meisenheimer², J.L. Menut⁵, F. Millour¹, U. Neumann², E. Nussbaum⁵, L. Mosoni, S. Ottogalli¹, T. Ratzka, S. Robbe-Dubois¹, F. Rigal⁴, A. Roussel¹, D. Schertl⁵, B. Stecklum, E. Thiebaut, M. Vannier¹, L. Venema⁴, K. Wagner², M. Meillen², T. Kroener², N. Mauclert¹, Paul Girard¹, G. M. Lagarde¹.

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2- Max Planck Institut für Astronomie, Heidelberg, Germany,
3- Leiden Observatory, the Netherlands,
4- ASTRON, Dwingeloo, the Netherlands,
5- Max Planck Institut für Radioastronomie, Bonn, Germany,
6- ITAP, Kiel University, Germany,
7- Vienna University Austria.
Requirements on the VLTI Infrastructure

• Fringe Tracker and record of the residuals
  – Full L&M medium and high spectral resolution reading
  – Sensitivity
  – Accuracy

• Tip Tilt correction, Pupil monitoring, residuals
  – Baseline lengths & u coverage
  – Sensitivity
  – Accuracy

• Adaptive Optics on ATs
  – Fringe Tracker
  – Sensitivity

• Hybrid mode coupling ATs-UTs
  – Sensitivity & uv coverage

• Simultaneous observations MATISSE-GRAVITY
Some details on the schedule

- Progress Meeting coupled an informal review about the warm optics: June 2011
- O & C FDR: September 2011
- Instrument FDR: March 2012
- Provisional acceptance of the sub-systems
- PAE: June 2015
- PAC: March 2017
Science Programs and their key Issues

Primary Science Cases

**Star and Planet Formation**

1. Low-mass Star and Planet Formation
   - (a) Complex disk structures on large (~ 100 AU) and small scale (~ 1 AU);
     Transitional objects: Status of inner disk clearing
   - (b) Mineralogy of proto-planetary disks; Evidence for dust grain growth and sedimentation
   - (c) Characteristic structures in disks: Evidence for the presence of giant proto-planets
   - (d) The binary mode of star formation: Circumbinary and circumstellar disks;
     Disk alignment and early evolution of binary systems
   - (e) Nature of outbursting YSOs: Structure of young accretion disks

2. Late stage of planet formation – Debris disks:
   - (a) The outcome of planetesimal collisions and exo-comets evaporation:
     Dust grain properties and disk geometry
   - (b) Complex spatial disk structure – direct indicators for the presence of planets
   - (c) Characterization of Darwin/TPF targets

3. Massive Star Formation
   - (a) Spatial distribution of the gas (carbon monoxide and hydrogen) and dust (silicates/graphite and CO ice) in the typically complex and distant high-mass star-forming regions
   - (b) Link between low and high-mass star formation?
     Search and characterization of accretion disks around young massive (proto)stars

**Active Galactic Nuclei**

Hydro-dynamical models of the central gas and dust distribution in AGN show a dense inner disk (supported by angular momentum) and an outer filamentary structure – the torus.

1. Can we establish the existence of the dense inner disks? Are the disks present in both Seyfert 1 and 2 galaxies?

2. Can we find direct evidence that tori are clumpy or filamentary structures?

Outflow phenomena (supersonic winds, jets) are connected with most kinds of AGN activity

3. To which extend is the torus structure regulated by the outflows?

4. What fraction of the dust emission from within the inner few parsecs of an AGN is emitted by the torus and what by dust entrained in the outflows?
Importance of the Fringe Tracking for MATISSE

- Full L&M medium and high spectral resolution reading
- Sensitivity
- Accuracy
In the ‘MATISSE Performance Analysis Report’

**L band**

![Graph showing Performance on Visibility and Differential Phase for L band](image)

**N band**

![Graph showing Performance on Visibility and Differential Phase for N band](image)
In the ‘MATISSE Performance Analysis Report’

- L band
  - Performance on Visibility: L band, 0.2 Jy, UT, SiPhot
  - Performance on Differential Phase: L band, 0.2 Jy, UT, SiPhot

- N band
  - Performance on Visibility: N band, 20 Jy, UT, SiPhot
  - Performance on Differential Phase: N band, 20 Jy, UT, SiPhot
In ‘Complement to the Science Case document’ of Phase A
A list of AGNs with reference stars

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<th>$L_{AGN_{core}}$</th>
<th>$H_{star}$</th>
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</tbody>
</table>

$K = 10$ off-axis FT
$K = 12$ on axis FT
Importance of the Fringe Tracking, bonus

- Full L&M medium and high spectral resolution reading
- Sensitivity
- Accuracy

- Doubling the MATISSE spectral resolution: example, $R_{\text{max}}$ in L could go from 100 to 1500
- Simultaneous observations MATISSE + GRAVITY
- Possible implementation of a Fourier Transform Spectrometer for high spectral resolution $> 50000$
MATISSE Requirements to the VLTI

In relation with the Fringe Tracking:

- **Number of telescopes**: 4 telescopes

- **Sensitivity**: $K>10$ (Goal: $K>12$, extragalactic program)

- **Tracking accuracy**: 180nm RMS (over 1mn)

- **Chopping compatibility**: Current values in ICD OK
  
  (30ms for fringe reacquisition and 10ms for closing FT loop)

- **Sensing processing**: FT signal part of MATISSE data for offline processing
Contractual Documents

• Agreement
• Technical Specifications
• Memorandum of Understanding
• Statement of Work
• Management Plan

INSU, Jean-Marie Hameury, NOVA, Wilfried Boland, MPIA, Thomas Henning, MPIfR, Gerd Weigelt, OCA, Farrokh Vakili.
From Table 4 of the Science Analysis Report.
MATISSE atteint ses objectifs scientifiques

<table>
<thead>
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<th></th>
<th>Coherent Flux Sensitivity</th>
<th>Visibility Accuracy</th>
<th>Closure Phase Accuracy</th>
<th>Differential Phase Accuracy</th>
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<tr>
<td>Protoplanetary disks (number of available sources)</td>
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<td>Protoplanetary disks (signatures in visibility and closure phase)</td>
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<td>Protoplanetary disks (model fitting approach)</td>
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<td>Protoplanetary disk (image reconstruction approach)</td>
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<td>Asteroids</td>
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<tr>
<td>Extra solar planets</td>
<td>Yes in L and N</td>
<td></td>
<td></td>
<td>Challenging as an exploratory goal</td>
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From Table 5 of the Science Analysis Report.
## Number of sources per object class

<table>
<thead>
<tr>
<th>Science Case</th>
<th>L&amp;M band ATs/UTs</th>
<th>N band ATs/UTs</th>
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<tbody>
<tr>
<td>Star and Planet Formation</td>
<td></td>
<td></td>
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<tr>
<td>- Low-mass Stars and Planet Formation</td>
<td>~100 / &gt;100 (^a)</td>
<td>~100 / &gt;100 (^b)</td>
</tr>
<tr>
<td>- Young low-mass Binary Stars</td>
<td>&gt;25 / &gt;60</td>
<td>&gt;15 / &gt;30</td>
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<tr>
<td>- FU Orionis Stars</td>
<td>6 / 9</td>
<td>5 / 13</td>
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<tr>
<td>- Debris Disks</td>
<td>250 / 320</td>
<td>70 / 180</td>
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<tr>
<td>- Massive Star Formation</td>
<td>~50 (^c) / ~50</td>
<td>~50 (^c) / ~60</td>
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<tr>
<td>Active Galactic Nuclei</td>
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<td>0 / 17</td>
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<tr>
<td>Evolved Stars</td>
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<tr>
<td>- Low-mass stars (^d) a) O</td>
<td>~30 / 30</td>
<td>~90 / 90</td>
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<tr>
<td>- R CrB</td>
<td>3 / 10</td>
<td>3 / 10</td>
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<tr>
<td>- PNs</td>
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<td>3 / 10</td>
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<tr>
<td>- Cepheids</td>
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<td>6 / 6</td>
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<tr>
<td>- High-mass stars: a) B[e] stars</td>
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<td>15 / 3</td>
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<td>- b) WR stars</td>
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<td>10 / 15</td>
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<td>- c) LBV stars</td>
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<td>- d) Be stars</td>
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<td>~10(^3) / ~6×10(^3)</td>
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<td>Extrasolar Planets</td>
<td>3 / 25</td>
<td>0 / 1</td>
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<td>Galactic Center</td>
<td>0 / 1</td>
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