Science case for 1 mas spectro-imaging in the near-infrared

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ABSTRACT

We present the work developed within the science team of the Very Large Telescope Interferometer Spectro-Imager (VSI) during the Phase A studies. VSI aims at delivering $\sim$ 1 milliarcsecond resolution data cubes in the near-infrared, with several spectral resolutions up to 12 000, by combining up to 8 VLTI telescopes. In the design of an instrument, the science case plays a central role by supporting the instrument construction decision, defining the top-level requirements and balancing design options. The overall science philosophy of VSI was that of a general user instrument serving a broad community. The science team addressed themes which included several areas of astrophysics and illustrated specific modes of operation of the instrument: a) YSO disks and winds; b) Multiplicity of young stars; c) Exoplanets; d) Debris disks; e) Stellar surface imaging; f) The environments of evolved stars; g) AGN tori; h) AGN's Broad Line Region; i) Supermassive black-holes; and j) Microlensing. The main conclusions can be summarized as follows: a) The accessible targets and related science are extremely sensitive to the instrument limiting magnitude; the instrument should be optimized for sensitivity and have its own fringe tracker. b) Most of the science cases are readily achievable with on-axis fringe tracking, off-axis fringe tracking enabling extra science. c) In most targets (YSOs, evolved stars and AGNs), the interpretation and analysis of circumstellar/nuclear dust morphology requires direct access to the gas via spectral resolved studies of emission lines, requiring at least a spectral resolution of 2 500. d) To routinely deliver images at the required sensitivity, the number of telescopes in determinant, with 6 telescopes being favored. e) The factorial increase in the number of closure phases and visibilities, gained in a single observation, makes massive surveys of parameters and related science for the first time possible. f) High dynamic range imaging and very high dynamic range differential closure phase are possible allowing the study of debris disks and characterization of pegasides. g) Spectro-imaging in the near-infrared is highly complementary to ALMA, adaptive optics and interferometric imaging in the thermal infrared.

Keywords: optical interferometry, imaging, spectroscopy, circumstellar disks, debris disks, exoplanets, winds, jets, active galactic nuclei, microlensing.

1. INTRODUCTION

Astronomy in the next decade will be dominated by the first light of the ALMA array and the construction of the ELT. These two facilities open the discovery space by pushing further the sensitivity in the sub-mm and optical/near-infrared. However, while the km range baselines of ALMA further open the higher angular resolution window in the sub-mm the limited diameter of the ELT directly translates in limited angular resolution. Indeed an ELT will have a factor of four smaller angular resolution than the VLTI. This is a fundamental limitation that cannot be surpassed via signal analysis (e.g. super-resolution deconvolution) as such techniques can also be applied to optical interferometry. The PSF quality of a segmented ELT, remaining to be demonstrated, is a strong limitation of the final image quality as shown by the adaptive optics results versus interferometric imaging experiments at the Keck telescope. The conclusion is that the VLTI does remain competitive in the ELT era by it's superior angular resolution and image fidelity.

The present science cases addresses the unique parameter space of imaging at 1 mas angular resolution in the near-infrared. It was developed in the context of the VLTI second generation instrument VSI – VLTI spectro-imager. This instrument is described in Malbet et al.[1] and Jocou et al.[2]

The article is structured as follows, it starts by presenting the science case bounding box, then it proceeds with specific examples of the science case that illustrate the instrument modes of operation. Namely, imaging of young star disks and winds, high dynamic imaging of debris disks, characterization of exoplanets via high dynamic range parametric closure phase, characterization of supermassive black holes with parametric visibilities and target of opportunity observations of microlensing events. We conclude with the requirements on the instrument, fringe tracking and VLTI infrastructure of the proposed science programme.

2. SCIENCE CASE BOUNDING BOX

VSI is designed to maximize the scientific return of the VLTI investment. The initial instrument bounding box was: general purpose, near-infrared operation, full use of the infrastructure and complementarity to existing/planned instrumentation.

General purpose Optical interferometry is a technique that is still in its early years. VSI will truly be a second-generation instrument. In contrast, extreme adaptive optics instruments like SPHERE are the fifth generation of adaptive optics instruments at ESO. Furthermore, they will exist in parallel with general purpose AO instruments like SINFONI and CRIRES. A second generation general purpose interferometric spectro-imager maximizes the science return by expanding the users community.

Near-infrared The near-infrared provides unique advantages for high angular resolution. The wavelength range is still short enough for high angular resolution, while providing immediate access to emission/absorption lines that probe the gas in a wide variety of conditions and chemical states. The fact that sublimation temperatures of dust peaks occur in the NIR makes this regime extremely interesting for dust studies. The scientific importance of the near-infrared is backed up by the number of VLTI publications.

Full use of existing infrastructure Eight telescopes and six delay lines are currently installed at Paranal. Currently the CHARA interferometer combines six telescopes and the Magdalena Ridge Observatory Interferometer will combine up to ten telescopes. Making full use of the infrastructure is a necessary condition for the VLTI to remain the top optical interferometric facility in the world.

Complementarity VSI, with its imaging capabilities, is highly complementary to both the AO imaging instrumentation available at the VLT but also to ALMA spectro-imaging. The spectral resolutions have considerable overlap with existing VLT instrumentation, which have much coarser angular resolution. VSI probes the inner dust sublimation surface as well as the gas motions, while MATISSE probes the outer colder dust and GRAVITY will obtain high astrometric accuracy.

For the more detailed design of a general purpose instrument, the science group has defined several astrophysical themes that cover a broad range of astrophysics. However some of the themes are special in that they allow testing of special capabilities (high dynamic range, target of opportunity) and feed the instrument design.

- **Imaging:** Young star disks and winds; Evolved stars; Stellar surfaces; AGN torus.
- **High dynamic range imaging:** Debris disks.
- **Parametric visibilities:** Binaries, AGN BLRs and massive black holes.
- **High dynamic range parametric visibilities:** Extrasolar planets.
- **PRIMA operation:** Additional science in AGN Torus, BLR and massive-black holes
- **Target of opportunity + PRIMA:** Microlensing (additional science)

The VSI science team decided to focus, whenever possible, on large key projects. This new mode of operation is allowed by the factorial increase of data points, given the combined number of telescopes. The survey mode allows operations to be considerably simplified, as well as reducing the number of special features of the instrument. During the instrument lifetime 2015–2025 it is expected that the operation of Paranal will evolve into survey/large programme mode.

In the next sections, we elaborate on the following subset of the science cases: a) imaging young stars' disks and winds; b) high dynamic range imaging of debris disks; c) characterization of hot jupiters; d) parametric visibilities of active galactic nuclei broad line regions and supermassive black holes; e) target of opportunity observations of microlensing events. The image reconstruction results developed by the science team are presented in Filho et al.[3,4] the main conclusion being that 6T provides superior image quality than three different 4T telescope combinations.

3. IMAGING YOUNG STAR DISKS AND WINDS

Stars are forming from the collapse and the fragmentation of a molecular cloud. In the earliest infancy, they are surrounded by a complex environment that obscures their emission at optical wavelengths. Then, a few million years into their evolution, they are revealed in the optical, and are seen to consist of the central protostar, a circumstellar accreting disk and an infalling envelope that will eventually disappear. These disks are also thought to play a fundamental role in the formation of planetary systems, and are therefore also called protoplanetary disks. It is therefore of prime interest to investigate the physical properties and evolution of disks around young stars, to understand the processes of star and planet formation.

Disks are composed of gas and dust and the interaction between these and the central star determines the disk structure, physical and chemical properties. The evolution of the solid component of the disks from sub-micron dust particles (typical of ISM) to larger grains, pebbles and eventually planetesimals is the fundamental process that leads to the formation of the rocky cores of planets. The gaseous component of the disk dominates the total mass, the gas dominates the accretion onto the central star, a process that is closely linked with the formation of outflows and jets, and will also form the giant planets once the rocky cores have developed out of the solid component. The chemical evolution of gas in protoplanetary disks is also a key process for the production of complex and pre-biotic molecules.

The presence of such circumstellar disks around young stars was first inferred *indirectly* from the interpretation of their spectral energy distribution and the analysis of the emission line profiles. Then, high angular resolution instruments, such as adaptive optics equipped ground based telescopes, and radio-interferometers at millimeter wavelengths, have directly imaged their disk-shaped structure at large scales, from tens to hundreds of AUs. Due to the distance of the nearest star forming regions, the study of the region of the disks within 10 AU is precluded to single aperture large optical/near-infrared telescopes. This is the region where the rocky planets are confined. This region is relatively warm due to the irradiation from the central star and emits most of the near- and mid-infrared thermal dust emission from the disk. In these regions of the disk, some key gas and small particle tracers are also emitted: the near-infrared hydrogen recombination lines which are believed to be produced by the gas accreting onto the central star and at the base of the jet; the warm CO overtone emission, a likely tracer of the inner gaseous regions of the disk; and several Policyclic Aromatic Hydrocarbons (PAHs) which trace the surface layers of the disk. Probing all these tracers is essential to understand the physical and chemical processes in the inner regions of the disk.

3.1 VSI step forward

A few visibility points are generally not sufficient to properly constrain the dust properties in the inner regions of circumstellar disks.[5] To remove the degeneracies and properly constrain the physical parameters, several measurements with different baseline length, different hour angles and information on the closure phase are required. This implies that with current systems, where it is very time consuming to acquire all these data, it will be very difficult to go beyond the detailed study of a handful of favorable objects. In the context of protoplanetary disks, we have identified three major science programmes that will be carried out with VSI, and are presented in more detail in the following subsections.

3.2 Probing the physical properties of the inner disk

We selected a sample of well known objects from the TTauri and Herbig Ae catalogues; all these are objects with relatively well known properties in terms of age, mass of the central star, binarity, outer disk properties. We propose to perform detailed observations of each of these systems with VSI to derive the properties of the dust and gas in the inner regions of the systems and to relate these properties with the evolutionary status and environment of the central star. The goal is to obtain a timeline for the evolution of the inner regions of circumstellar disks and hopefully constrain the first stages of the planetary formation process.

The dust To obtain a reliable image of the morphology of the dust near-infrared emission is a first essential step that will give important inputs on the physical processes dominating this emission, and that will therefore enable appropriate *physical* models to be developed. The VSI imaging information will shed light on important questions about dust properties such as: is there a single size of grains responsible for most of the emission, is there vertical mixing or on the contrary is dust settling occurring, with bigger grains in the mid plane? Figure 1 shows the consequent disk images as a function of the dust properties. Clearly the dust disk images can probe the dust properties as well as the disk geometry.

The gas Due to the strong radiation field, the dust thermal equilibrium is essentially determined by the star. Therefore the dust cannot be taken as a proxy to probe the gas excitation in the disk. The gas must be probed directly. The geometry of the gas responsible for the emission lines is also completely unknown. Indeed, one of

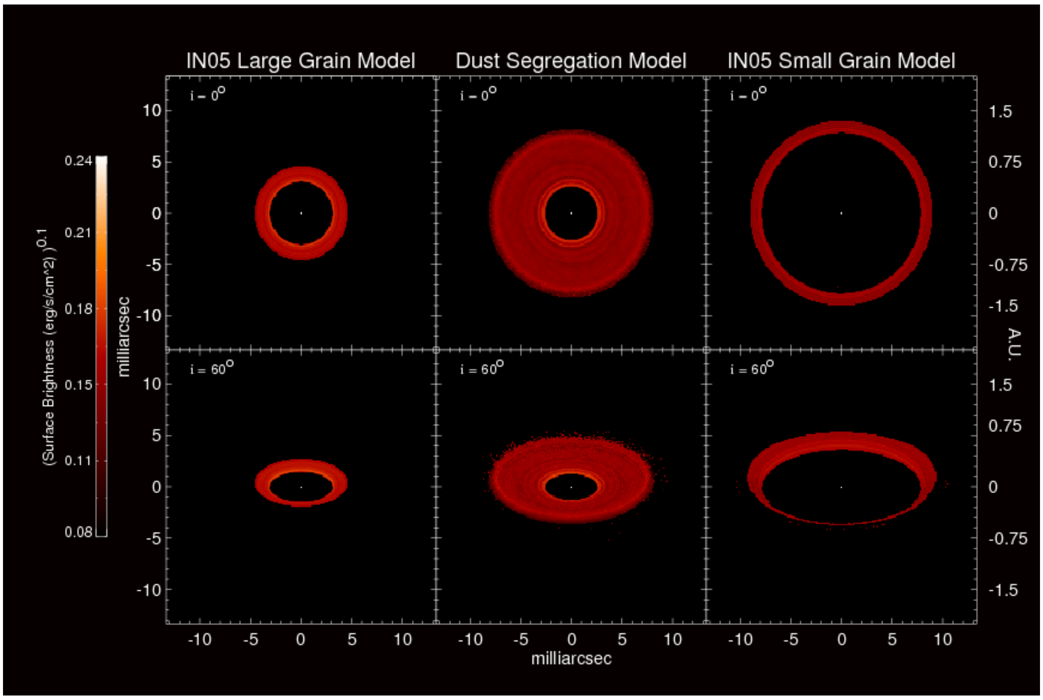

Figure 1. Synthetic 2.2μm images for different rim models.[6] The panels on the left and right are rims computed for 1.2μm (large grain) and 0.1μm (small grain) silicate dust. The center panels are images for the dust segregation model. The star is placed at 150 pc. The star is unresolved at the image scale and is just one bright pixel at the center of the images.

the most surprising AMBER results shows that for some Herbig Ae/Be stars the hydrogen emission has a similar spatial scale as the dust sublimation radius. This emission can either come from the disk wind base or from a disk corona. Some young stars are also known to have CO band-heads that present signatures that are indirectly interpreted as arising in disks. Comparison of images in different CO bandheads will allow direct spatial probing of the gaseous disk conditions.

Presence of a planetary companion The presence of a planetary/sub-stellar companion strongly affects the inner disk geometry. The companion will create a zone of the disk with lower surface density surrounded by two regions of higher density. As the planet migrates inwards and passes through the sublimation rim strong changes take place. The sublimation front might become gas/dust depleted. Extra accretion and time dependent sublimation can take place in the inner zones.

3.3 A disk census in star-forming regions

The purpose of this project is to obtain a large statistical sample of interferometric observations of young stars in given star forming clusters (e.g. Orion, ρ Ophiuchus) in order to investigate the spread of the physical properties of their protoplanetary disks according to the age of the population. A parametric study of dusty and gaseous disk sizes will be correlated with central star properties (e.g., luminosity, age, mass, accretion rate).

3.4 Time dependent phenomena in inner disks

The dynamical timescale of the inner disks is the keplerian period. The VSI angular resolution of 1 mas, translates into a keplerian radius of 0.15 AU at 150 pc. At 0.15 AU the keplerian period is 11.5 days. Therefore the inner regions of the disk evolve on timescales of weeks. The surface of the disk sublimation region, or the inner stellar magnetosphere is supposed to drive the jets observed in young stellar objects and somewhat older low/intermediate mass stars. Current adaptive optics observations show that the flow is already fully accelerated at the diffraction limit of large monolithic telescopes. Therefore the acceleration to speeds of hundreds of km/s take place within the VSI field of view. Multiple ejections are observed in these objects. The dynamical timescales of jets at a spatial scale of 1 mas are of the order of days.

4. HIGH DYNAMIC IMAGING OF DEBRIS DISKS

Debris disks are optically-thin, gas-poor dust disks around main-sequence (MS) stars. Debris disks must be distinguished from protoplanetary disks (denser disks with a high gas content around young T Tau and Herbig Ae/Be stars). In debris disks, gas is only present in the form of stellar winds. The presence of circumstellar dust around stars with ages above $\sim$ 10 Myr is attributed to populations of planetesimals that were neither used to make up planets nor ejected from the system by the time when the nebular gas is dispersed. These leftovers produce dust by mutual collisions and, possibly, comet-type activity. Being continuously replenished by small bodies, the disk can then persist over much of the star's lifetime. Due to its large total cross-section area, dust is much easier to observe than planets, not speaking of planetesimals. On the other hand, distributions of dust respond to the presence of planetary perturbers, reflect distributions of the parent bodies and bear important "memory" of the planetary formation process in the past. Hence debris disks can be used as sensitive tracers of directly invisible planets, as well as small body populations, and should reflect evolutionary stages of planetary systems.

While several hundreds of MS stars have been found so far to possess dust debris, only roughly two tens of debris disks have been resolved at different spectral ranges, from visual to sub-mm. All debris disks resolved so far are structured. Typical are warps, wing asymmetries, offsets, clumpy rings, spirals etc. Many of these features can be attributed to the presence of invisible planets that create various inhomogeneities by gravitational perturbations they exert either on dust grains directly or on populations of dust parent bodies of cometary and asteroidal type.[7]

In our Solar system, the inner planetary region is immersed with small dust grains, forming the zodiacal cloud. While the extension and mass of dust in the outer Kuiper Belt region should by far supersede those of the zodiacal cloud, its low optical depth has prevented it from being observed so far. The situation with other stars is completely reverse. Cold dust emission has been found for hundreds of stars, strongly suggesting the existence of extrasolar Kuiper belts. Mid- to far-infrared instruments (Spitzer, and soon Herschel) are revolutionising the field, allowing analysis of outer disks at a statistical level. However, information on zodiacal clouds, i.e., on dust in the inner, planetary region of the extrasolar systems is extremely scarce.

4.1 VSI step forward

VSI aims, for the first time, at imaging exo-zodiacal clouds. At present, there is hardly any information on systems' architecture in the planetary region. Only very recently, hot dust has been unambiguously resolved for the first time around Vega using high-precision near-infrared interferometry at the CHARA Array.[8] Similar results have also recently been obtained on the old cool dwarf τ Cet[9] and on the A0 dwarf ζ Aql. The structures expected in the inner disks must reflect internal processes, directly related to planet(s) and populations of small bodies. Most notably, observable structures can be produced by planets, even of very low mass. This is exemplified by the asymmetric resonant ring of asteroidal dust around the Earth orbit identified in IRAS and COBE/DIRBE data. Since detecting substructure with VSI seems feasible, this might offer a unique chance to infer the presence of terrestrial planets.

Analysis of spatial distribution of brightness would shed light onto location and total masses of small bodies, for instance to identify large asteroid belts. Such information would be of immense value, allowing one, for example, to get some insight into planetary migration in the past. For systems with ages $\lesssim$ 100 Myr, another global objective would be to seek dust traces of terrestrial planet formation via intensive collisions of embryos. At a smaller scale, phenomena such as dust clouds associated with possible trojan asteroids or dust wakes related to major asteroid families, similar to IRAS dust bands in the solar system might be observable — at least for some of the systems with particularly massive or active asteroidal belts. Further, the multi-colour information provided by VSI will allow grain composition and size distribution, as well as density profiles to be unambiguously constrained. Moreover it might be possible to assess salient features in the near-infrared spectrum of the inner disks that are associated with the ices released by outgassing comets.

We suggest VSI observations of inner debris disks in two basic modes: a) a large-scale survey of an extended list of targets; and b) a close-up, detailed study for a limited set of most interesting objects.

4.2 A survey of nearby Vega-type stars

We will study samples of nearby main-sequence stars and of young stellar clusters to detect potential near-infrared counterparts to the Kuiper-belt-like disks detected in the mid- and far-infrared. The main goal is to perform a large survey to detect the presence of close-in dust down to a meaningful density level and derive statistics for this phenomenon. The detection principle will be the same as in the case of a two-telescope interferometer, i.e., based on the deficit of visibility created at short baselines by the resolved circumstellar emission.[8] By combining short and long baselines simultaneously, VSI will allow a simultaneous measurement of the stellar photosphere and of the circumstellar emission, thereby greatly reducing the time needed to fully characterize the star-disk system. In practice, one set of 15 visibilities and 10 closure phases obtained with a well-chosen six-telescope configuration will be enough to derive the flux ratio between the disk and the star in one of the VSI photometric bands. Based on the data gathered during our survey, we will specifically study:

- the occurrence rate as a function of various stellar parameters. These mainly include age and spectral type, but also metallicity. Further parameters could be added to the list. One could investigate, for example, correlation with stellar rotation, which is closely related to the angular momentum budget of planetary systems;
- possible correlation with the presence of cold excesses described above. Statistical information on excesses across the spectrum — from near-infrared (VSI) to sub-mm (SCUBA/SCUBA2) would allow one to better constrain the overall spatial distribution of dust material in the systems;
- possible correlation with the known (radial velocity) giant planets, as done for outer disks.

Further, the survey results can be connected to dynamical models to assess the prevalence of late heavy bombardment (LHB) -like events around “young” main-sequence stars.

4.3 Detailed study of selected Vega-type stars

Beyond the statistical approach developed in the previous section, which only gives limited information on the morphology of individual debris disks, we intend to carry out the detailed study of a few selected targets showing specific features to improve our understanding of the physical and dynamical processes at play in the inner planetary systems. Among the debris disk stars that deserve particular attention are the so-called transition objects, which are in the transition from viscous protostellar accretion disks to planetary systems. Studying such objects with VSI will allow us to assess the presence of small amounts of first and/or second generation dust in the innermost regions of these systems which are generally assumed to be depleted by disk dispersal and planet formation mechanisms. Besides transition objects, VSI will also focus on a few “classical” debris disks which show particular features. An example of such systems is HD 69830 (already listed among the survey targets owing to its magnitude), which is known to harbor three Neptune-like planets in close orbit as well as a warm ($\sim 400\,\mathrm{K}$) dust belt detected with Spitzer. This dust belt furthermore shows strong silicate features in its infrared spectrum. Resolving this dust belt with VSI would allow us to locate it with precision, which is not possible with spectro-photometric data, and thereby study the gravitational influence of the three planets on the shape of the belt.

In order to test the feasibility of detecting salient asymmetric features we have generated a solar-like zodiacal disk around this star see Figure 2. In Filho et al.[3] it is shown that VSI is able to reconstruct such high dynamic range images.

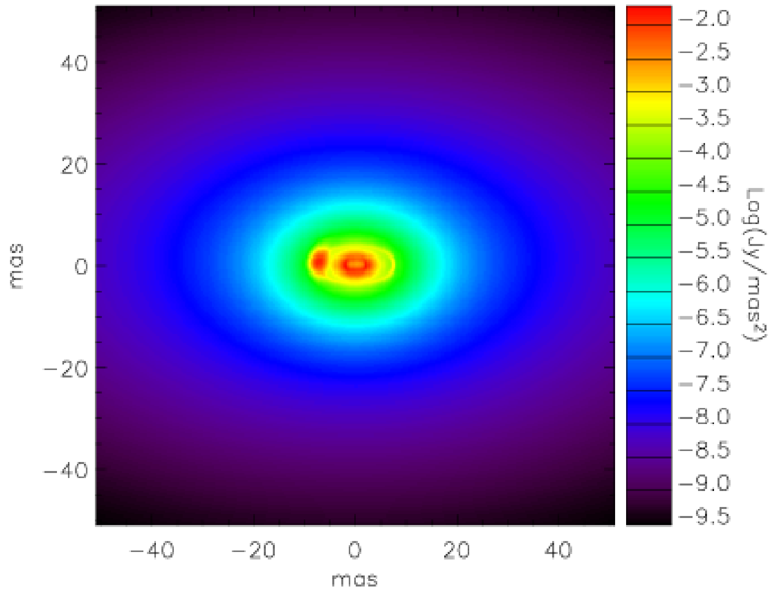

Figure 2. Synthetic image of a putative exozodiacal disk around 58 Eri. The ZODIPIC package has been used to produce this image, using a steeper density power law than in the Solar System. We have used the ring and blob associated to Earth orbit to simulate the outburst of a large comet, by enhancing these two components by factors of 10^5 and 10^6 respectively, and translating them to 0.1 AU instead of 1 AU in the Solar System. The central star has been removed in this illustration to improve the dynamics in the colours. The actual brightness of the star is about 15 Jy in K band.

5. CHARACTERIZATION OF EXOPLANETS

The VLT Spectro-Imager (VSI) will open the near-infrared window on the observations of hot Jupiters. With a low to moderate spectral resolution and with its contrast performance, VSI will provide albedo, temperature and chemical composition of more than a dozen hot jupiters. Such a breakthrough will shift the physical properties of exoplanets to the statistical stage and literally enable the so called comparative exoplanetolgy. The high dynamic range parametric visibility mode application to the characterization of hot Jupiters is presented in Renard et al.[10]

6. PARAMETRIC VISIBILITIES OF SUPERMASSIVE BLACK-HOLES

Active Galactic Nuclei (hereafter AGN) are galactic nuclei powered by non-stellar energy production. In order to explain their high luminosity output (up to $L \sim 10^{14} L_\odot$) and their non-thermal spectral energy distribution, the powering mechanism of AGNs is commonly believed to be accretion onto a supermassive black hole (hereafter BH) with mass in the $10^6 - 10^{10} M_\odot$ range. The most powerfull AGN are also characterized by a strong cosmological evolution: their activity peaked at $z \sim 1{-}2$ where the density of high luminosity quasars sources ($L > 10^{12}\ L_\odot$), was a factor ~ 100 larger than in the local universe. By combining the BH accretion paradigm with the observed cosmological evolution, we expect that most (if not all) nuclei of luminous galaxies host a BH, relic of the past activity. During the past few years BHs have been detected and their masses measured in ~ 40 galaxy nuclei, both normal and active. The BH mass (hereafter $M_{\rm BH}$) is closely related with the mass or luminosity of the host spheroid ($L_{\rm sph}$) and with the velocity dispersion of the stars (σ).[11] These facts indicates that the formation of a massive BH is an essential ingredient in the process of galaxy formation and that there is a tight relation between host galaxy and AGN activity.

By far, the best evidence for a BH in a galactic nucleus is given by center of our own Galaxy where it must have a mass of $M_{\rm dark} \simeq 3 \times 10^6 M_\odot$. The second best case for a supermassive BH is given by NGC 4258 with a dark mass of $\simeq 4 \times 10^7 M_\odot$. For the other galaxies, BH masses are usually measured from the kinematics of circumnuclear gas or stars. It is not possible to measure the velocities of single "test particles" like the stars

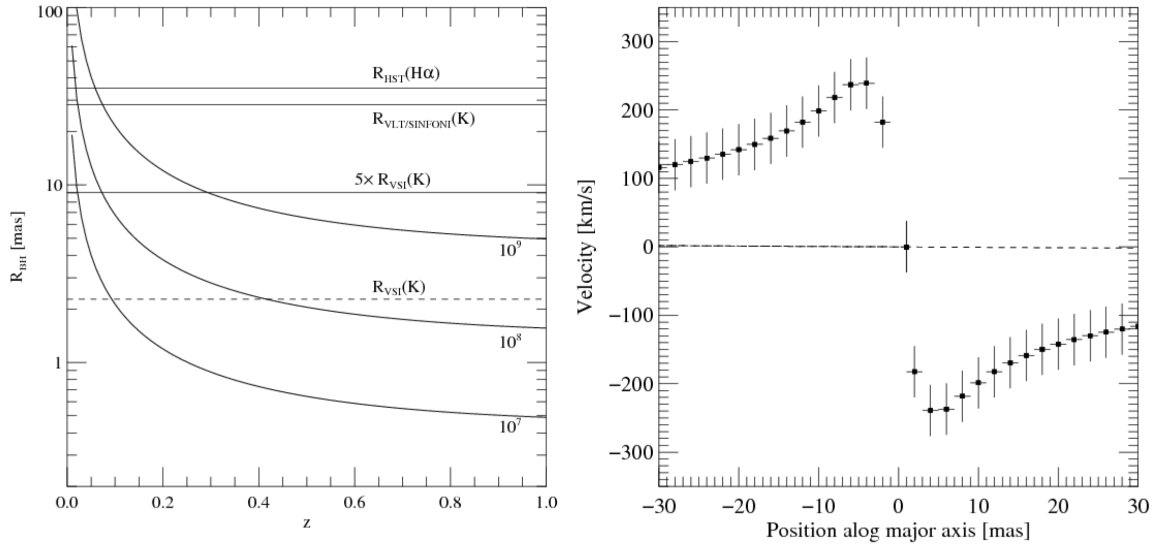

Figure 3. Left: Observed radius of the BH sphere of influence [mas] as a function of redshift and BH mass (10^7, 10^8, 10^9). $R_{VSI}(K)$ denotes half of the spatial resolution of VSI for a maximum baseline of 100 m at 2.2 μm. $R_{HST}(H\alpha)$ and $R_{VLT/SINFONI}(K)$ denote half of the spatial resolution of HST/STIS at Hα and VLT/SINFONI with AO correction in K (full diffraction limited resolution). Right: Expected rotation curve along the major axis of a rotating gas disk in the nucleus of NGC 1365 for a disk inclination of $i = 30$ deg a BH mass of $M_{\rm BH} \simeq 4 \times 10^7 M_\odot$ and a distance of $D \simeq 22$ Mpc. The emission lines are absent within the inner 2.5 mas but velocity points are present due to PSF effects.

in the galactic center or maser gas clouds in NGC 4258. The worse spatial resolution available only allows us to measure average kinematical parameters of large volumes whose projected sizes onto the plane of the sky are set by the spatial resolution of the observations. Clearly, the evidence for a BH in all cases other than the Galactic Center and NGC 4258 is much weaker due to the worse spatial resolution of the observations. In more details, to detect a BH one must resolve the radius of the BH sphere of influence, i.e. the radius within which the gravitational potential is dominated by the BH mass. The apparent size on the plane of the sky if the galaxy is at a distance $D = 20$ Mpc becomes

$$\theta_{\rm BH} = 0.1'' \left(\frac{M_{\rm BH}}{10^7 M_\odot}\right) \left(\frac{\sigma_\star}{100{\rm km/s}}\right)^{-2} \left(\frac{D}{10{\rm Mpc}}\right)^{-1} \tag{1}$$

where $\sigma_\star$ is the velocity dispersion of the stars Thus the radius of the BH sphere of influence is usually very small and successful BH detections require very high spatial resolution.

6.1 VSI step forward

In figure 3 we show the dependence of the BH sphere of influence for different values of $M_{\rm BH}$ and for galaxies located at different redshifts. For a given BH mass the stellar velocity dispersion has been estimated by using the $M_{\rm BH} - \sigma$ relation. This figure clearly shows why the number of BH detections is limited to very small distances ($D < 100$ Mpc) and intermediate mass range ($10^7 - 10^9 M_\odot$): the spatial resolutions of HST (in the optical) and VLT (in the near-infrared) do not allow direct BH mass estimates beyond the local universe, even for galaxies for $M_{BH} > 10^8\, M_\odot$. With VSI in the K band it will be possible to reach a spatial resolution of ~ 5 mas in K for a typical baseline of 100 m (this would marginally resolve a BH sphere of influence with radius $5/2 = 2.5$ mas), improving by more than one order of magnitude what is currently available. Even requiring to sample the BH sphere of influence with at least 5 resolution elements would allow to measure $M_{\rm BH} > 10^9 M_\odot$ up to $z \sim 0.3$ with a significant improvement with respect to what is currently possible.

To firmly establish the "BH mass ladder" one has to secure all its steps. We need direct BH mass measurements in Type 1 AGNs with reverberation mapping and/or virial mass estimates. Due to the cosmological evolution of AGNs most Type 1 objects (Seyfert galaxies and Quasars) are at large distances so that only a handful of them could be resolved with available facilities. Therefore it is fundamental to measure BH masses in a sizeable number of Seyfert 1 galaxies and Quasars in order to secure the BH mass ladder. Figure 3 shows that it will be possible to measure BH masses up to z $0.2 - 0.3$ much beyond the local universe. It was shown that even at those relatively low redshift there is a significant evolution of the $M_{\rm BH}$ -galaxy scaling relations. Thus VSI will allow to directly probe the evolution of the $M_{\rm BH} - L,\sigma$ scaling relations.

To summarize, the use of VSI to measure BH masses in galactic nuclei will allow to answer the following questions:

- Are BHs ubiquitous in galaxy nuclei?
- Is it possible to measure $M_{\rm BH}$ at high redshifts, i.e. are virial BH mass estimates reliable?
- When did the relations with the host galaxy begin and how do they evolve with time?

In order to measure BH masses we will study the kinematics of the circumnuclear gas and we will target the H_2 and Brγ emission lines in the K band. The sources which provide the brightest emission associated with a point-like continuum (at the diffraction limit of an 8 m telescope) suitable for fringe tracking and AO correction are Seyfert 1 galaxies and quasars and some Seyfert 2 (see the target list for the obscuring torus case). At the spatial scales probed by VSI, H_2 and Brγ should be emitted by the circumnuclear material constituting the obscuring torus. The output from a typical VSI observation will be a continuum-subtracted data cube at medium spectral resolution (~ 2000) from which it will be possible to measure the morphology and kinematics of emission lines around the central BHs. If the circumnuclear gas motions are dominated by rotation around the central BH it will be possible to measure the BH mass. Assuming that the H_2 or Brγ emission is distributed in the obscuring torus with an emissivity similar to that of the hot dust in the torus model we can derive the kinematics as it can be observed with VSI. In figure 3 (right panel) we plot the expected rotation curve for NGC 1365. The gas disk has an inclination of $i = 30^\circ$ and is absent within 2.5 mas from the BH location (inner torus size). The presence of a nuclear hole in the line emissivity distribution has in general the effect of cancelling the high velocities which are the signatures of the BH. However, the high resolution of VSI still allows us to distinguish from the case where there is no BH (dashed line) in which no rotation is expected. Overall the simulated rotation curves shows that VSI will allow to accurately measure the BH mass in NGC 1365.

In conclusion, these studies will allow to: a) directly measure the BH mass up to a distance which is a factor > 50 larger than possible nowadays; b) test the virial mass estimates, the only possibility to measure BH masses at high redshift.

7. TARGET OF OPPORTUNITY OBSERVATIONS OF MICROLENSING EVENTS

The phenomenon of gravitational lensing, or multiple splitting of the image of a distant source in the gravitational field of an intervening object (a lensing star, galaxy or galaxy cluster), constitutes one of the most spectacular predictions of general relativity. Gravitational lensing has been studied theoretically for many years and has become an observed phenomenon with the discovery of the twin quasar Q0957+561. Many gravitational lensing systems have been discovered since and the subject has grown into a very mature branch of astronomy. The field of gravitational microlensing is of particular interest for the VLTI. This term describes gravitational lensing which can be detected only by measuring the flux variation of a macroimage made of any number of unresolved microimages. An example of such an event occurs when a source star in the Galactic Bulge, or in the LMC, is gravitationally lensed by a star, or possibly by a massive compact object, in our Galaxy.[12] suggested that photometric surveys of very dense stellar fields should reveal, via microlensing effects, dark Massive Compact Halo Objects (MACHOs). Practical realization of this proposal turned out to be possible just a few years later and several microlensing observing programs were conducted (MACHO , EROS, OGLE , and DUO), providing various gravitational microlensing lightcurves in the Local Group. The quantitative interpretation of a classical (cf. Figure 4) observed microlensed lightcurve induced by a single compact lens, resulting in the formation of double lensed images, essentially depends on two physical parameters:

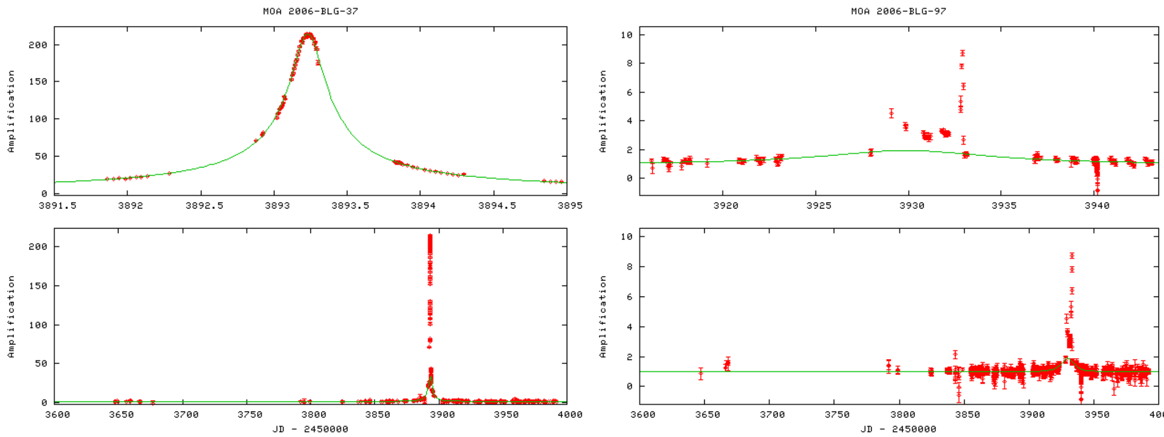

Figure 4. Left: typical observed microlensed lightcurve for which the deflector is a single compact lens. Right: observed microlensed lightcurve for a binary system which could only be resolved using interferometry. Top panels: zooms of the most amplified part of the microlensing event.

- the relative angular velocity of the lens with respect to the source, normalized to the angular Einstein radius (i.e. $\dot{\Theta} = \dot{\theta}/\theta_E$) and
- the minimum angular impact parameter θ_{min} normalized to the angular Einstein radius θ_E (i.e. $u_{min} = \theta_{min}/\theta_E$). Note that the expression of the angular Einstein radius θ_E is: $\theta_E = \sqrt{\frac{4G}{c^2} M \frac{D_{ds}}{D_{od} D_{os}}}$, where M is the mass of the microlens, D_{ds}, D_{od} and D_{os}, represent respectively the 'deflector-source', 'observer-deflector' and 'observer-source' distances. As usual, G and c stand for the gravitational constant and the velocity of light.

There is no way from such observations to estimate the angular Einstein radius θ_E, nor the mass M of the microlens. It is only by adding a priori statistical hypotheses regarding the dynamics of the lensing objects supposed to be stars (cf. their velocity distributions) that the previous teams have been interpreting such observations. These programs have aimed at an indirect estimation of the lens population mass function, the optical depth to gravitational lensing in the Galaxy, and fundamental limits on the possible contribution to the total mass of the galactic halo from the massive, compact, and not directly observable, objects.

7.1 VSI step forward

The splitting power of a compact lens with a mass of several $M_\odot$ located within a few kpc from us is only sufficient to separate the source images by about several milliarcsec (mas), which is not resolvable by even the largest individual optical telescopes. Therefore, no direct detection of multiple lensed images split by several mas has ever been made. However, thanks to interferometric observations with the VLTI, it will become possible to directly measure the value of the angular Einstein radius θ_E.[13] It can easily be shown that for a simple microlensing event induced by a single compact lens with a mass ≥ 0.05 $M_\odot$, VSI-VLTI visibility measurements should directly lead to the values of (i) the angular Einstein radius θ_E, (ii) the relative angular velocity $\dot{\theta}$ of the lens with respect to the source and to the minimum angular impact parameter $\theta_{\rm min}$.

Nevertheless, there are quite a number of observed microlensing lightcurves for which the fits of the observations using classical microlens models show significant departures, specially near the maximum amplification. The reason could be manifold:

- It could be that due to the large amplification, the background source is being resolved and that the source structure is being differentially magnified.
- The lens is more complex than the assumed single compact object.

- The source could as well consist of more than a single object.

All these effects may show up combined altogether and lead to a visibility curve that significantly departs from the classical one for the case of a single compact lens and source.

Because of the possibly great complexity of microlensing effects and their short timescales, it is imperative to perform snapshot imaging of a large number of microlensing events near the lightcurve maxima. The limitations of interferometry for microlensing are linked to the apparent magnitude of the lensed objects, to the short time scale of the event and to the availability of an array with many simultaneous different baselines in order to obtain snapshot images. All these limitations should be overcome thanks to VSI when using up to 6 or more simultaneous baselines. Finally, direct imaging of microlensed images with VSI as a function of time (at least two well chosen epochs) will allow to solve independently for the lens mass M, the relative transverse velocity and the minimum impact parameter, provided the source and the lens distances are known. Independent and subsequent observations of the lens and of the source should enable one to determine their distances based upon their spectral type identifications.

VSI/VLTI snapshot imaging will reveal for the first time the proof of existence of microlensing in terms of the detection of multiple images with mas angular separations. Of particular interest will be those microlensing events corresponding to several caustic crossings and the chance to resolve for the first time the multiple (3, 5...) micro-lensed images predicted by the theory. This will enable to determine the mass of the lensing star and of its companion (binary, planet…).

In conclusion, interferometry will allow us, in conjunction with ongoing microlensing prompt alerts, to follow the microlenses in real time, to spatially resolve them, to measure their image separations, and essentially to change the whole phenomenological framework of quantitative study of these events.

7.2 Target of opportunity survey

Since our aim is to characterize at best a flux limited sample of microlensing candidates without using any a priori model (cf. the single compact lens model) and given the short time scale of such events (cf. several hours during a caustic crossing), we propose to obtain direct snapshot images of all those events with mas angular resolutions. Simulations of caustic crossing cases indicate that a minimum of 6 simultaneous baselines are mandatory to perform such a program. VSI/VLTI with a 6 beam combiner will provide such an ideal facility.

The interferometer will receive alerts from photometric survey programmes when a sufficiently bright microlensing event of interestingly long duration (several weeks or more) begins or when a caustic crossing is foreseen in the following days or weeks.

For single assumed events, the interferometer could take one snapshot image near the lightcurve maximum and depending on the obtained results, one could decide whether a second epoch observation is mandatory or not. If only two lensed images are detected, no more observations should be taken.

8. CONCLUSIONS

The science cases described above put the following requirements on the instrument design and on the VLTI infrastructure.

8.1 Spectroscopic requirements

- The lowest resolution should be defined by sensitivity considerations as the exact value is not critical for the science case. However, the lowest resolution should not be less than 20–30.
- The intermediate spectral resolution is set to 1500–2500.
- The high spectral resolution is set to 12000.
- At a lower scientific priority than the above, a mode with spectral resolution of 5000 is recommended.

- On average the spectral position of each pixel should be determined with an error no less than 0.20 of the pixel wavelength width. Methods allowing a higher precision should be implemented if found accessible by the system group.
- The lowest boundary of accessible instrument wavelengths should be ≤ 1.08 μm.
- The accessible J band in intermediate spectral resolution should have at least 1.08 μm as its lower limit.
- The K band accessible to the instrument should range from 1.95 μm to 2.37 μm; ideally up to 2.40 μm.
- During an observing night, the spectral band (J, H or K) in the science channel can remain fixed.

8.2 Fringe tracker requirements

- A fringe tracker is required for the science case.
- The fringe tracker design should be driven by sensitivity*.
- The fringe tracker can operate at a different band than the science channel, except for the K band. A mode where part of the K band light is used to fringe track and part to do science should be available.
- Interesting additional science would be allowed if the the fringe tracker could fringe track on one of PRIMA's dual beams, the other being reserved for the science channel.

8.3 Imaging requirements

- Telescope positions should remain fixed during the night.
- An imaging mode where three different combinations of four telescopes (3×4T) are available within a time-span of weeks, is required.
- An imaging mode where the simultaneous combination of six telescopes (6T) is available in a single night provides superior image reconstruction than (3×4T).

8.4 Requirements on the infrastructure

Fringe tracker The fringe tracker drives the limiting magnitude of the instrument and therefore the available science space. We have therefore included the fringe tracker in the instrument and no external fringe tracker is required.

AO for ATs AO in the ATs would push the J/H limiting magnitude of the instrument (and K under bad seeing). Additional science in the winds of young stars and evolved stars would be allowed.

PRIMA The star separator system and the differential delay lines of the PRIMA facility would allow additional faint science for VSI in the fields of AGNs and young stars. It would allow the VSI fringe tracker to track using a nearby star and the VSI science channel would image the science object.

Delay lines Currently the VLTI has installed 6 delay lines. Unconstrained operation of the delay lines, in contrast to the current situation where only 4 lines can be used, will allow 6T operation. The 6T operation will allow superior image reconstruction and new unique science such as the temporal evolution of young stars and novae. It will also allow increased speed and the viability of some of the parametric surveys.

Telescopes The possibility of the combination of UTs and ATs should be verified.

*Corcione et al.[14] find that the limiting magnitude of the fringe tracker is $m_K = 10.5$.

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