VITRUV - Science Cases

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Summary. VITRUV is a second generation spectro-imager for the PRIMA enabled Very Large Telescope Interferometer. By combining simultaneously up to 8 telescopes VITRUV makes the VLTI up to 6 times more efficient. This operational gain allows two novel scientific methodologies: 1) massive surveys of sizes; 2) routine interferometric imaging. The science cases presented concentrate on the qualitatively new routine interferometric imaging methodology. The science cases are not exhaustive but complementary to the PRIMA reference mission. The focus is on: a) the close environment of young stars probing for the initial conditions of planet formation and disk evolution; b) the surfaces of stars tackling dynamos, activity, pulsation, mass-loss and evolution; c) revealing the origin of the extraordinary morphologies of Planetary Nebulae and related stars; d) studying the accretion-ejection structures of stellar black-holes (microquasars) in our galaxy; e) unveiling the different interacting components (torus, jets, BLRs) of Active Galactic Nuclei; and f) probing the environment of nearby supermassive black-holes and relativistic effects in the Galactic Center black-hole.

1 Introduction

The idea behind VITRUV is that by combining simultaneously 4 to 8 telescopes the VLTI becomes 2 to 6 times more efficient than by using non-simultaneously these same telescopes. Therefore an immediate operational gain is achieved and two scientific methodologies become possible: 1) massive surveys of sizes; 2) routine interferometric imaging. The science cases presented here are essentially centered on routine interferometric imaging as this is the novel VLTI capability made possible by VITRUV.

1.1 Imaging with the VLTI

With the full operation of the AMBER instrument and 3 movable ATs the Paranal Observatory will have the same interferometric imaging capabilities of the Plateau de Bure Observatory at it's dawn. The VLTI and PdBI have similar baselines (Fig. 1), but because the VLTI operates at a wavelength up to 1000 times shorter than the PdBI its angular resolution will be up to 1000 times sharper.

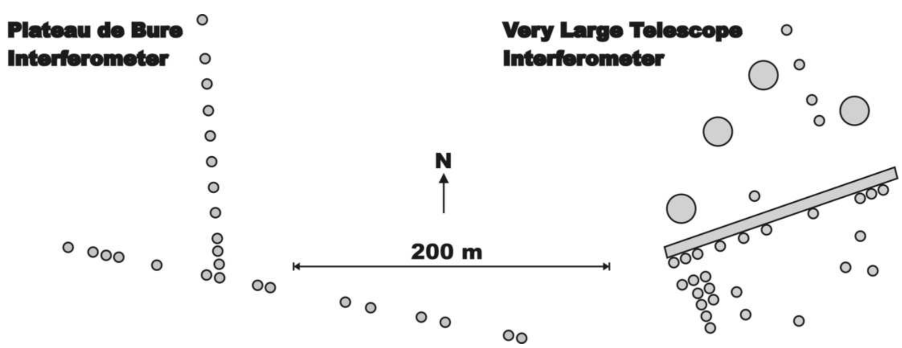

Fig. 1. The Plateau de Bure Interferometer (PdBI) and Very Large Telescope Interferometer (VLTI) have similar baselines. Because the VLTI operates at $\sim 1\mu$m and the PdBI at ~ 1 mm the angular resolution of the VLTI is ~ 1 milliarcsec and of the PdBI ~ 1 arcsec.

In interferometry, imaging is achieved by inverting a sufficiently large number of complex visibilities. These can be obtained by triangular combinations of telescopes. A sufficiently large number of complex visibilities, typically six different antenna triangles, were used by the PdBI together with a significant integration in hour angle. As the hour angle changes, the triangular projection in the sky rotates. For a given triangle, many more (8-16) complex visibilities are available for large (-4 h to 4 h) hour angle variations. Imaging with 3 telescopes is therefore time consuming. One image requires a complete night for each of the 6 triangles, i.e., six nights are required to image one object. This was common practice at the PdBI in its early days – a typical example is given by Guilloteau et al.(1992).

The conclusion to draw from the PdBI experience is that interferometric imaging of compact sources with a quality similar to the PdBI with AMBER and the ATs is possible but it will be expensive in terms of telescope time and an operational burden.

1.2 The VITRUV instrument

VITRUV is a general purpose spectro-imager for the PRIMA enabled VLTI. The instrument is described in detail in these proceedings by Malbet et al. (2005) In the following sections we concentrate in a few key areas where VITRUV spectro-imaging will make a significant step forward. These areas are not exhaustive and should be seen as complementary to the PRIMA reference mission document.

VITRUV being a spectro-imager has three modes with spectral resolutions of 100, 1000 and 10000. These modes are essentially dictated by the science cases: low resolution for continuum imaging, intermediate resolution for line emission imaging and high resolution for stellar surface imaging and line emission kinematics. The spectral coverage is centered on JHK with possibilities of extending it to visible (R+I) and L bands. The visible region allows higher angular resolution and access to scientifically interesting lines such as Hα and the Calcium triplet. The L band extension allow polycyclic aromatic hydrocarbons (PAHs) and nanodiamonds science.

2 The formation of stars and planets

Accretion and outflow are the distinctive simultaneous signatures of star formation. However even for the best studied case of **low mass stars** **(**$M \lesssim 2M_\odot$**)** the physical mechanism by which matter is accreted and ejected remains unknown. The angular scales responsible for the bulk of the observed SED emission (specially in the optical-NIR) and the angular scales where the outflow activity originates are smaller than those probed by adaptive optics on 8m class telescopes – any progress is only possible by directly imaging the optical/NIR emission lines and continuum at $1'''$ resolution.

Only recently was the existence of Keplerian gas disks in **intermediate mass stars** **(**$2M_\odot \lesssim M \lesssim 8M_\odot$**)** demonstrated with mm interferometric imaging (Mannings & Sargent, 1997). NIR-interferometric observations have shown (e.g. Millan-Gabet et al., 2001) that the bulk of the NIR emission comes not from a disk but from from a puffed-up inner wall located at the dust sublimation radius. This completely different disk geometry from their lower mass analogs underlines how imaging information is critical for the SED understanding.

High mass stars **(**$M \gtrsim 8M_\odot$**)** have a very strong radiation field that photoionizes the surrounding and also has a dynamical effect via radiation pressure. Powerful mass ejection also takes place. Only around ten disk-like structures have been detected so far and it is not clear if some of them are actually unstable infalling material rather than Keplerian disks. Recently 2MASS counterparts have been found around a sample of massive protostellar candidates (Kumar et al. 2005), opening the exciting possibility of studying the close environment of these objects with NIR-interferometry.

2.1 The structure of inner disks of young stars

The morphology of the dusty close environment of pre-main-sequence stars will be studied by VITRUV, particularly the following interconnected aspects:
a) What are the effects of the central radiation field in the environment structure – exact shape of the sublimation surface/rim and inner cavity?
b) How does the morphology correlates with dust properties?
c) Are there orbiting companions opening cavities in the central disk region? What are consequences on companion formation and migration scenarios?
d) Is the environment shaped by central source winds and outflows? Are these winds dusty?
e) How does the structure of the inner disk affects the initial conditions for planet formation?
f) What is the distribution and morphology of PAHs and nanodiamonds in the inner regions of disks?
Time dependent morphology At Taurus the Earth orbit is located at 7 mas. For the first time a systematic study of the orbital evolution of the dusty environment will be feasible and compared to hydrocode simulations.
Evolutionary aspects By comparing objects at different evolutionary stages the timescales for the morphological evolution and dissipation can be addressed. With AMBER a considerable advance in PMS stellar evolution models is expected and more precise timing of the central stars will be available by 2010.
Central source mass The stellar mass will affect the central radiation field and the dusty environment via sublimation/heating and pressure.

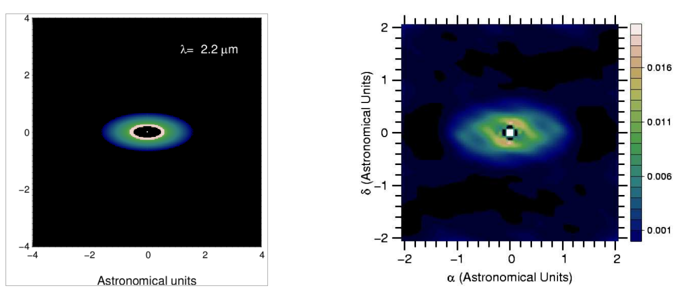

Fig. 2. Left: puffed-up inner wall model (star removed). Right: reconstructed image Thiébaut & Tatulli (including central star). The ring is 15 times fainter than the central star.

2.2 The launching of jets and winds

The morphology of the emission lines in close environment of young stars will be studied, particularly the following interconnected aspects:

a) Where does the jet originates, in the disk, star, or disk-star interaction region?
b) What is the mechanism responsible for maintaining the ionization in the outer launching regions as required by MHD models?
c) How is the strong magnetic field required for the jet launching at the wind base made compatible with the equipartition regime required by the magneto-rotational instability?
d) Energetically the magnetic engine is a way to tap gravitational accretion power from the disk into the jet. How can this made compatible with the SED modeling that taps the same energy in the form of viscous dissipation?
e) What is the relation between the observed dust morphology and the jets/winds?
f) What are the chemical, ionization, thermal, kinematic and morphological properties (collimation, wiggling) of jets at their launching region?
g) What is the exact contribution of accretion and winds to the observed infrared hydrogen lines emission profile?
Time dependent morphology Is wind and jet launching an intrinsically time dependent phenomenon (related to some instability) or what the time variability is simply a consequence of variable accretion in a otherwise stationary engine? Are there orbital effects in the ejection?
Evolutionary aspects How do the jet and winds properties (in particular collimation and excitation) evolve in time and correlate with disk accretion?
Central source mass How does the central jet engine evolves with the central mass, in particular what are the effects of different: 1) radiation fields; 2) stellar magnetic fields; 3) disk structures.
Radiative transfer Two breakthroughs are expected: a) 2D and 3D radiative transfer will be required to analyze the observations; b) clumpiness is expected as the ejection process is unstable – this stochastic density along the line of sight will radically alter the radiative transfer.

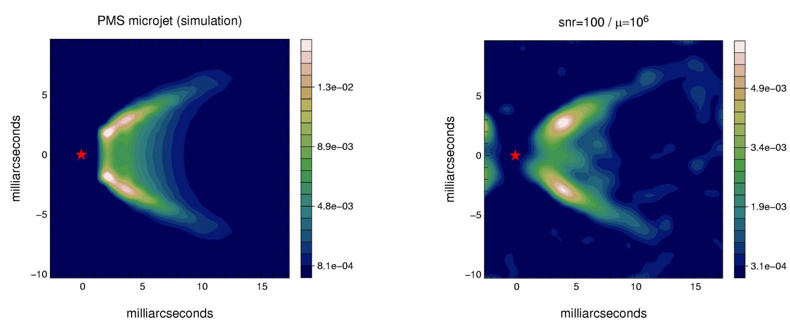

Fig. 3. Paβ emission from the inner region of a MHD disk wind, (left) and reconstructed image by Thiébaut et al (right). The star contribution, which is on average has a surface brightness 100 times the jet has been removed.

3 Imaging stellar surfaces

VITRUV, as an imaging device, open the possibility to study various surface properties as vertical and horizontal temperature profiles, abundance inhomogeneities and detect their variability. These key observations will address stellar activity processes, mass-loss events, magneto-hydrodynamic mechanisms, and stellar evolution.

3.1 Photospheric convection and activity of late type stars

Dynamos The variable magnetic field that causes stellar activity is generated by a process that we call the dynamo, in which the kinetic energy in convection and large-scale circulations is converted into magnetic energy. Ab initio, comprehensive modeling of stellar dynamos is at present impossible; instead modelers are forced to introduce multiple simplifications and approximations into their models, without knowing whether these are warranted, or what side effects may be introduced by them. Consequently, the diversity of results from currently existing models critically requires observational guidance on, for example, how the field-emergence patterns change over periods of years to decades. Repeated imaging of stellar chromospheric emission patterns over multiple years with VITRUV will provide the essential observational knowledge on which of these patterns actually occur on other stars, and how they depend on fundamental stellar parameters as well as rotation rate.
Spots on magnetically active stars Energy of late type stars is mainly carried outwards by convection whose study is critical in modeling the inner structure as well as the atmosphere of these objects. VITRUV imaging of the turbulent eddies of such stars together with classical interferometric measurements of their size and luminosity (or temperature) will allow a better understanding of stellar convection. Late type stars might exhibit asymmetric and even highly fragmented mass-loss events, which are believed to be linked to stellar surface parameters such as limb-darkening, effective temperature or surface features.

Pulsating Miras

Surface temperature and chemical inhomogeneity VITRUV will test chemically inhomogeneous mass-loss in the AGB phase. Of further interest is the suggested existence of magnetic cool spots produced by a relatively weak large-scale asymmetric magnetic field amplified by turbulent dynamo on the surface of Miras as the cause of aspherical mass distribution.
Polarization aspects Narrow-band photo-polarimetry and spectro-polarimetric observations demonstrated that the polarization magnitude varies through the molecular bands of Miras and post-AGB stars (e.g. Trammell et al. 1994). Such an affect may be due to changes in albedo with optical depth in the

extended atmosphere. When spatial information is available the interpretation of polarization data is much more strongly constrained. Interferometric polarization measurements of late-type giant stars with VITRUV will provide new insights into their atmospheric structure and the geometry of their circumstellar material, and the chemical and physical properties of the dust in the photosphere and the winds, constraining theories of mass-loss from red giant stars and hydrodynamical models of planetary nebulae formation.

3.2 Abundance and magnetic field of Ap stars

Chemically Peculiar A and B stars (CP stars) exhibit strong chemical abundance inhomogeneities of one or more chemical elements, such as helium, silicon, chromium, strontium, or europium, and a large-scale organization of their magnetic field that produces a typical signature in circularly-polarized spectra. CP stars represent a major class of the known magnetic stars in the solar neighborhood and constitute ideal targets for studying how magnetic fields affect other physical processes occurring in stellar atmospheres. VITRUV simultaneously mapping of abundance distributions and magnetic fields will tackle the fundamental question of the origin of the magnetic field in CP stars (Moss, 2001). Both the fossil and the core-dynamo theories have difficulty in explaining all the observed magnetic characteristics. These same maps will allow to better understand the key role of magnetism in a) atmosphere structuration; b) ion migration across the stellar surface and; c) chemical stratification.

4 Evolved stars

4.1 The shaping of the outflows from evolved stars

In the last twenty years, the extraordinary geometry of young and evolved PNe and related objects (like for instance nebulae around symbiotic stars) has been revealed by ground-based and HST observations. These observations gave a strong impulse to theorists, and a plethora of theoretical explanations has been proposed. However, none of them could be fully tested, as in most cases even HST cannot resolve the spatial scale at which collimation occurs.

The most popular models to explain the onset of asymmetry in the outflows involve: a) strong interactions between (anisotropic) AGB and post-AGB winds producing wind-heated and wind-blown expanding bubbles (Balick & Frank 2002); b) collimation by several processes (like accretion disk winds interacting with the stellar winds) in close and wide interacting binaries; c) magneto-hydrodynamical (MHD) shaping – this latter scenario is also possibly related to enhanced rotation and magnetic fields due to binary interactions.

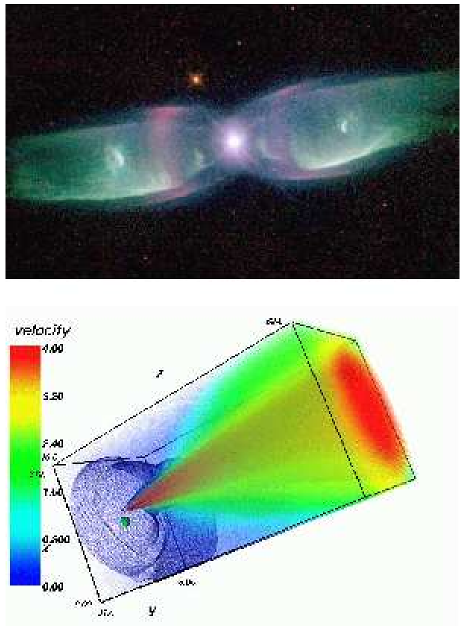

Fig. 4. Top: HST image of the bipolar nebula M 2-9. The long side of the f.o.v is about 30000 AU. Bottom: the hydrodynamical simulation by Garcia-Arredondo & Frank (2004) using an accreting interacting symbiotic-like binary with P=20 yr. The model box includes only the innermost 320×160×160 AU.

Resolving the collimation region In many of these objects, VITRUV will allow us to see directly the collimation region and follow in real-time its dynamical evolution, revealing which one(s) of the models above is correct. Figure. 4, top, presents the image of the highly collimated nebula M 2-9 (d=640 pc), obtained with the HST. At the bottom, on a 100 times smaller scale it is instead shown the hydrodynamical simulation by Garcia-Arredondo & Frank (2004), where the cell size of of 0.5 AU and FoV matches those of VITRUV at the distance of M 2-9. At such resolution, the 10 AU offset of the jet origin (produced by the unresolved hot companion and its accretion disk) with respect to the primary star, the corkscrew matter distribution around the stars, and the jet aperture and bending, can be clearly revealed and would unambiguously demonstrate the nature of the binary collimation source. VITRUV will follow in real-time the evolution of the outflows, distinguish among all the proposed scenarios, as each model predicts its own characteristic growth behavior. By measuring the Doppler shifts of lines emitted by the circumstellar nebulae will result in detailed spatio-kinematical maps. Finally, physical conditions in the circumstellar gas will be derived from the emission line spectrum.

The same scientific objectives described above also apply to related objects, like the outflows from symbiotic novae, classical novae , as well as to nebulae around more massive stars, like LBVs.

Expansion parallaxes The ability of resolving the apparent expansion of the nebulae, while measuring at the same time their radial velocities, will also allow us to determine the distance of the nebulae via their expansion parallax. This is one of the most robust methods to determine the distances of these objects which represent the most severe limitation to determine their basic physical properties, like the luminosity, mass, age, and energetics.

Binarity In a number of cases where the central regions are not severely "polluted" by a large amount of gas and dust, VITRUV imaging will be able to detect and resolve the two stellar components in binary systems. This would be another important result, as binarity effects might explain most of (if not all) the deviations from spherical symmetry observed in the outflows from evolved stars. According to the theoretical models two third of all PN central stars are binaries, the great majority of which have orbital periods much larger of 1 AU, resolved by VITRUV. The VITRUV detection rate of binaries is expected to be much higher and sampling a complementary separation space than previous surveys. For objects at intermediate separations, orbital parameters will also be obtained by multi-epoch observations.

4.2 Microquasars (stellar black-holes)

Microquasars (Mirabel & Rodríguez 1994), can be seen as galactic counterparts of the extragalactic quasars, but on a much smaller scale since they are thought to harbor stellar mass black holes ($M \sim 10M_{\odot}$). Radio images of microquasars show either extended structures like in SS433 or very compact ones like in Cyg X-1 at mas scale and, in general, radio emission is interpreted as the presence of compact steady jets or sporadic ejection events also seen in infrared and X-ray bands. Due to their smaller physical size compare to AGNs, their radio emission can be strongly variable and correlated to various X-ray states, which indicates that jet emission is physically linked to the accretion process. Radio observations have also shown pairs of bright radio knots moving at apparent superluminal velocities.

The light curves of microquasars in all wave-band exhibit very complex time behavior connected to the accretion-ejection mechanism. The origin of the infrared emission in microquasars is far from being completely understood. Open questions are: a) What is the dust and jet contribution to the infrared emission of the innermost regions of microquasars? b) How does it connect with the radio jet emission? c) How does it vary with the X-ray spectral states?

Infrared imaging of microquasars at mas scale has never been done up to now. K band images of microquasars at mas resolution will allow to: a) study the jet morphology; b) constrain the different parameter distributions (particle distribution, density, magnetic field) all along the jet; c) constrain

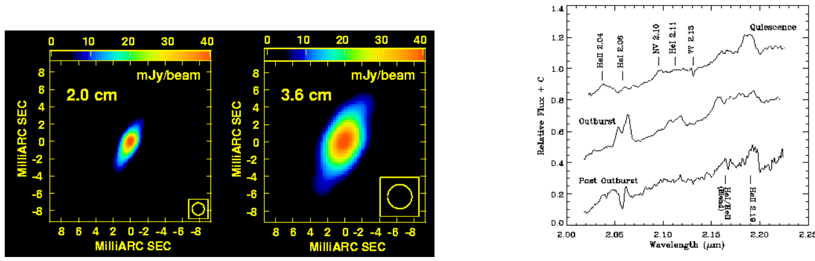

Fig. 5. Left: VLBA images at 2.0 and 3.6 cm on April 2, 2003 showing the compact jet. The convolving beams are 1.4 and 2.8 mas, respectively. 1 mas corresponds to 12 AU at 12 kpc distance. (Fuchs et al. 2003) Right: K-band spectra of Cyg X-3, each displayed with an arbitrary flux offset for clarity. At the top a quiescent spectrum, in the middle a spectrum taken during a very extreme radio/X-ray flaring of the system, at the bottom a "post-outburst." spectrum (Hanson et al. 2000).

accretion-ejection models; d) characterize dust in the inner region of these objects.

5 Active Galactic Nuclei

Active Galactic Nuclei (hereafter AGN) are galactic nuclei powered by non-stellar energy production. Marconi et al. (2001) summarize the expectations from AGN observations with the first generation of VLTI instruments (AMBER and MIDI). Although very important scientific results can be achieved with AMBER and MIDI (e.g., Jaffe et al. 2004), it is clear that without any imaging capability, observations are limited only to the estimate of source sizes. A significant step forward with respect to AMBER and MIDI can only be obtained by providing images of the circumnuclear environment of an AGN at mas resolution (i.e. ∼ sub-pc scales). In the following, we will show the possibilities of the combined use of VITRUV and PRIMA in addressing several open issues on AGNs and supermassive Black Holes.

The dusty torus The dusty torus is a fundamental component of the AGN unified model, but we do not know if it really exists and what is its real morphology. In Fig. 6 we present K-band model images of the torus of NGC 1068 illustrating how VITRUV K band imaging of the nuclear region of an AGN will allow to:
a) confirm/negate the existence of tori;
b) disentangle synchrotron from hot dust emission, i.e. discriminate between torus and jet emission;
c) study the torus morphology and determine its geometrical parameters like the inclination w.r.t. the line of sight;

d) constrain radiative transfer models;
e) study the torus dust composition (using radiative transfer models).

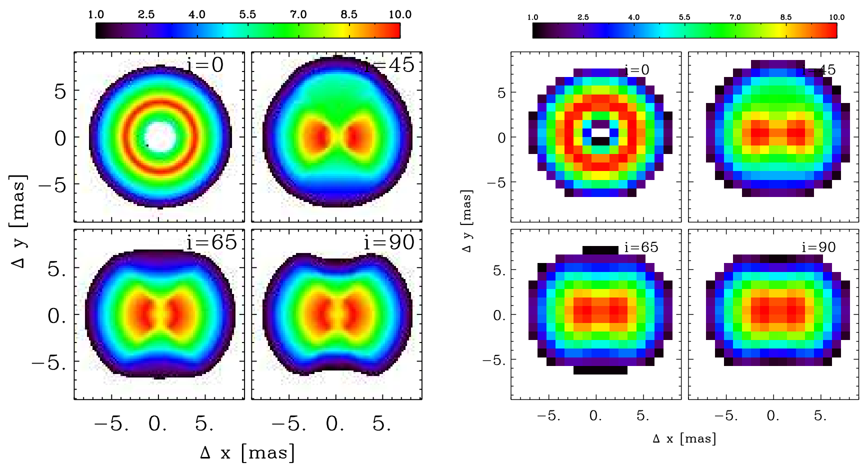

Fig. 6. Left: Model images of the NGC 1068 torus (Granato et al. 2004) seen at different inclinations in the K band. i is the inclination of the torus pole axis with respect to the line of sight (with $i = 0$ the torus is seen face on). Images are in units of 10^{-10} erg s^{-1} cm^{-2} $Å^{-1}$ except for the $i = 0$ image which is in units of 10^{-10} erg s^{-1} cm^{-2} $Å^{-1}$. Right: same images as before but convolved with a PSF with 2 mas FWHM and re-binned to 1 mas pixels.

The Jet Some Active Galactic Nuclei (AGNs) exhibits powerful collimated jets. Although a minority, they are very interesting because, first the ejection phenomenon from a Black Hole environment is very intriguing, and also because jets are sources of high energy processes. We present in Fig. 7 a K-band model images of the jet of 3C 273. It is worth noting that, in the infrared, the synchrotron self absorption becomes important a distance much closer to the central engine than at radio wavelength. We will then have access for the first time to the jet inner regions. Moreover, given the broad-band (radio up to X-rays) jet spectra observed in AGNs, we expect a high energy cut off of the synchrotron emission, which must lie between radio and optical. Its detection is important to better constrain the maximal energy of the emitting particle. VITRUV K band imaging of AGN jets at mas resolution will allow to:
a) study the jet morphology;
b) constrain the different parameter distributions (particle distribution, density, magnetic field) all along the jet;
c) study the acceleration processes that may occur in the jet;
d) constrain accretion-ejection models.

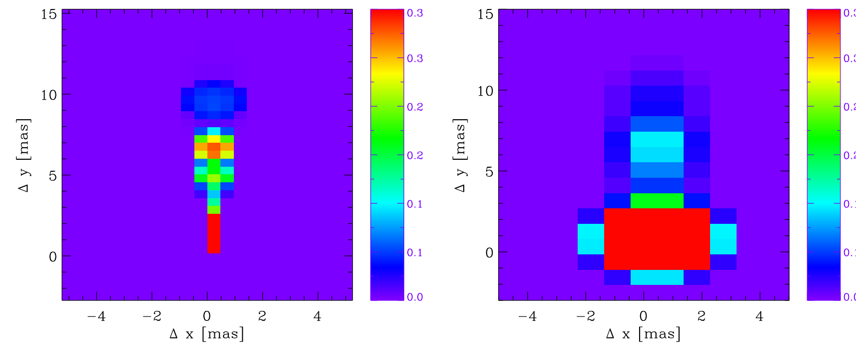

Fig. 7. Left: Model image of the jet of 3C273 in the K band. Image is in units of mJy. This image assumed a conical jet with a simple power law distribution for the particles. The density and magnetic field distributions along the jet axis are tuned to reproduced real VLA radio observations (Mantovani et al. 1999). Right: same model image as before but with a 2 mass spatial resolution and pixels of 1 mas.

The Broad Line Region The BLR is the region where the broad (FWHM> 1000 km/s) permitted lines observed in the spectra of type 1 AGNs originate. The morphology and kinematics of the BLR are still unknown. The spatial resolution of VITRUV is not enough to provide conventional images of the Broad Line Region however by combining medium resolution spectroscopy with accurate phase measurements it will be possible to recover the photocenter position of the BLR in each wavelength (velocity) bin. This will allow to constrain the morphology and kinematics of the BLR it will be possible to:
a) estimate the size of the BLR and establish a secure size-luminosity relation for the BLR which is fundamental for virial mass estimates of BH masses (the only way to measure BH masses at high redshift).
b) constrain geometry and kinematics of the BLR.
c) if BLR is in a rotating disk, the BH mass can be directly measured.

6 Supermassive blackholes

To detect a BH one must resolve the radius of its sphere of influence which, projected on the plane of the sky, is

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

It is clear that in order to probe the BH sphere of influence high spatial resolution is mandatory. Until now, except for the Milky Way and NGC 4258, the best spatial resolution achievable is given by HST, i.e. $\sim 0.1''$.

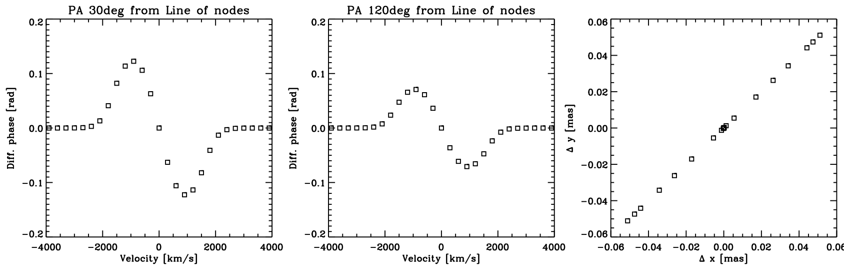

Fig. 8. Observations of the BLR of 3C273 which is assumed to be a gas disk inclined of 30 deg w.r.t. the line of sight and rotating around a $3 \times 10^8\ M_\odot$ BH. In the left and middle panel we show the expected line differential phase per wavelength bin along 2 possible baselines. In the right panel we show the reconstructed positions of the line centroid in each wavelength bin. The line centroids are aligned along the disk line of nodes combining their relative positions with their associated velocity it is possible to directly measure the BH mass.

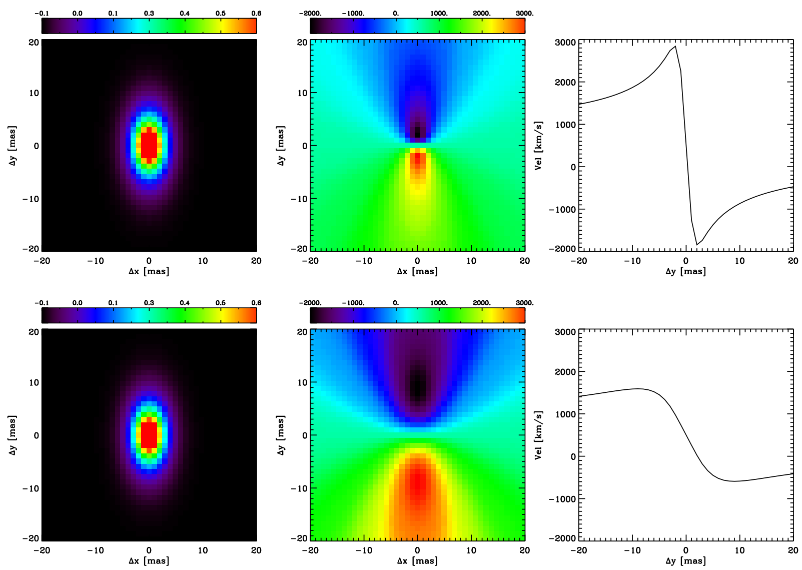

Fig. 9. Left panels: Line images (e.g. Brγ) of the rotating gas disk of Centaurus A which is inclined by 60 deg w.r.t. the line of sight and has the major axis along the y axis. The line images have pixel sizes of 1 mas and spatial resolution of 2 mas. Middle panels: velocity fields of the rotating gas disk with the same pixel size and spatial resolution as before. Left panels: velocity curves along the major axis. Top panels refers to the case of a central supermassive BH of $10^8\ M_\odot$, while bottom panels consider the case of an extended massive dark objects with $10^8\ M_\odot$ mass and core radius of 5 mas. The two cases are clearly distinguishable kinematically.

Galactic Center VITRUV will allow to measure proper motions of stars near the Galactic Center BH with an accuracy better than 1 mas.
a) It will be possible to further constrain the spatial extent of the dark mass concentration (the supposed BH) to exclude even the last possible alternative, the boson star.
b) The knowledge of orbits with such a high accuracy will allow to search for general relativistic effects like the periastron precession.
c) It will be possible to disentangle the flaring IR emission near the BH event horizon from the background emission. Thus it will be possible to obtain accurate light curves and determine the periodicity of the emission which might lead to a measurement of the BH spin.

Extragalactic BHs Combining the imaging and the spectroscopic capabilities at medium resolution (> 1000) it will be possible to obtain data cubes of emission lines around the central BHs. This will allow to study the morphology and kinematics of the ionized gas. From these studies it will be possible to:
a) constrain the size of the massive dark objects in nearby galactic nuclei to exclude plausible alternatives to BHs;
b) directly measure the BH mass up to a distance which is a factor ~ 50 larger than possible nowadays.
c) establish "secure" BH mass vs hot galaxy properties relations.
Fig. 9 clearly show how it is possible to distinguish between the cases of a supermassive BH or of an extended massive dark cluster.

7 Conclusion

In these paper we presented a series of science cases for the VITRUV second generation VLTI instrument concept. The focus was on imaging as this is the novel routine capability enabled by this instrument. VITRUV is a general purpose instrument. The science is not exhaustive but illustrative, and complementary to the PRIMA reference missions (Perrin et al. 2004). The following areas were addressed:
a) the close environment of young stars;
b) activity in the surfaces of stars;
c) the origins of Planetary Nebulae geometries;
d) accretion-ejection structures in micro-quasar;
e) the components (torus, jets, BLRs) of AGNs;
f) the environment of nearby supermassive black-holes;
g) relativistic effects in the Galactic Center black-hole.

These cases together with the dramatic operational gains allowed by VITRUV clearly underline the importance of a general purpose spectro-imager for the second generation VLTI instrument.

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