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37th Liège International Astrophysics Colloquium: conclusions and perspectives

Jointly summarized by

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1 Fundamental stellar parameters

This section is largely based on the presentation by M. Wittkowski (these proceedings).

1.1 Key parameters for stellar physics

Our understanding of the physical processes taking place in the inner regions of stars and also of the evolution of stars is based on some fundamental parameters. Some of these might come easily to one's mind as for instance the mass (M), the luminosity (L) and the radius (R). In addition to that, the (initial) chemical composition and the age of the star may be also of major importance. Sometimes it is useful to replace M, L, and R by other parameters like the effective temperature ($T_{\rm eff}$), the surface gravity (g) and the mean density (ρ). Knowing some of these figures, it is for instance possible to compute a theoretical evolutionary track of a star in a HR-diagram (log L vs. log $T_{\rm eff}$) depending on the mass of the star. Or one can investigate how the chemical composition, i.e. the metallicity, influences the star's track in the HR-diagram as time goes by.

If one restricts oneself to a certain evolutionary stage of a star, some other parameters might become very interesting. These are the (initial) angular momentum (I), the magnetic field (B), the pulsation period (P), the mass loss rate ($\dot{M}$) and also the circumstellar environment. The rotation and the magnetic field of a star can for instance have a non-negligible effect on the evolutionary track within the (L, $T_{\rm eff}$) plane.

1.2 Measuring stellar properties

While the mass and the luminosity of a star are well-defined integrated physical parameters that can in principle be measured, the radius of a star is not well defined. As stars are gaseous spheres they do not have a well defined edge. What can be observed is the intensity profile across the stellar disk (the center-to-limb intensity variation, CLV) which depends on the stellar atmospheric structure[1]. Thus, some parameters are directly accessible and well defined and others have to be derived.

1.2.1 Mass estimates

Binary stars are the main source for measurements of high precision masses: one can distinguish between double-lined astrometric-spectroscopic binaries (giving the radial velocity of both components and the relative orbit), absolute astrometry (yielding the absolute orbits of both stars), and single lined spectroscopic binaries (from which the radial velocity, the relative orbit and the distance can be inferred). Interferometry can surely improve mass estimates as the orbits of the binaries can be measured with higher precision.

Another way of measuring the mass of a star makes use of estimates of the surface gravity and the temperature coming from spectroscopic observations. However, these are indirect mass measurements as models for the stellar atmosphere are required.

1.2.2 Luminosity

The luminosity can be derived from the apparent bolometric flux and a distance estimate, for instance a Hipparcos parallax. In order to improve the measurement of luminosities the other two variables need to be determined more precisely.

1.2.3 Radius estimates

The direct observable is the intensity profile, i.e. the CLV, of the star and not the radius. Very often the angular diameter of a uniform disk is measured and then transformed into a Rosseland angular diameter by using atmospheric models. What is needed here are high-spectral-resolution measurements of the CLV with a few resolution elements across the star.

1.2.4 Chemical composition

At a given evolutionary stage of the star the chemical composition on its surface is directly observable, e.g. by using high-spectral resolution studies. However, if one wants to measure inhomogeneities, for instance caused by magnetic fields, the composition should be determined for several resolution elements across the star. In that respect one future objective might be to discriminate stellar tracks with different chemical compositions at the ZAMS.

1.2.5 Estimates for additional parameters

The magnetic field of a star is directly observable via the line-splitting of the spectrum. For the angular momentum, the surface rotational velocity can be measured by spectroscopic observations. An estimate for the mass loss rate can be derived from outflow velocities and studies of

[1] It should be mentioned that the CLV is a measure for a vertical temperature profile which may be superimposed by a horizontal temperature profile.

the circumstellar material. Monitoring the flux and the (angular) radius yields possible pulsation periods. For some stars (e.g. classical Cepheids, RR Lyrae) the relation between the luminosity and the pulsation period provides the possibility to estimate the distance to the star.

1.3 Possible applications and required precision

There are several purposes for which a solid knowledge of stellar parameters is required. Tests concerning the stellar evolutionary theory and also the stellar atmosphere theory can be carried out in all evolutionary stages of the stars across the HR-diagram. Constraints of precise effects can be found, for instance on the main sequence. Furthermore, improved descriptions of physical phenomena such as convection and magnetic activity can be derived. Finally, different material tables, such as opacity tables, and nuclear reaction rates, can be tested on their consistency. For sure there are more applications that benefit from a precise knowledge of the stellar parameters. However, the few mentioned here give already an idea of the scientific relevance of accurate measurements.

Referring to Andersen (1991), the precision needed for the different parameters varies. For the mass and the radius an accuracy of 1%-2% is required whereas for the luminosity 5%-10% is sufficient. Higher accuracies are not needed as there are other effects limiting the computations (e.g. the metallicity). However, as our understanding of these limiting factors increases a more sophisticated analysis of the stellar parameters becomes necessary again. Thus, it seems worth to carry out specific investigations in parallel determining the precisions needed for constraining the theoretical models.

1.4 Science cases for the next generation of interferometers

Before focusing on a possibly limiting case for the next generation of interferometric facilities, the science cases can be summarized as follows:

> "High accuracy measurements of all fundamental parameters of stars in all evolutionary stages across the Hertzsprung-Russel diagram."

In that respect, special focus might be on the following topics:

- Precise effects on main sequence stars
- Detailed analysis of metal-poor stars
- Detailed analysis of low mass stars (M, L, T)
- Detailed analysis of high mass stars, especially concerning the mass loss on the main sequence
- Mass loss of evolved stars
- Magnetic activity of stars
- Stellar rotation and its evolution
- Improving the descriptions of convection and turbulent mixing

A possible limiting case for future interferometers might be a very low mass star at the bottom of the main sequence. Referring to evolutionary calculations by Chabrier et al. (2000), such a star has the following properties:

- $M \simeq 0.08\,M_\odot$, hence on the limit to a brown dwarf
- Age $\simeq$ 5 Gyr
- $R \simeq 0.1\,R_{sun}$
- Luminosity: $\log(L/L_{sun}) \simeq -3.6$
- $M_V \simeq 19$, $M_K \simeq 11$, $M_M \simeq 10$

If the star is at a distance of 10 pc, these figures result in an angular diameter $\theta = 0.1$ mas and, assuming interferometric measurements at a visibility $V = 1\%$, in apparent correlated magnitudes $m_V \simeq 24$, $m_K \simeq 16$. In order to sample such a star with three to five resolution elements, a total amount of 9 to 30 stations with a maximum baseline of 6 to 10 kilometers is required.

1.5 Specifications and requirements for future interferometers

Based on the assumptions made in the previous section and taking into account general considerations, Table 1 summarizes the specifications for the next generation of interferometric facilities. A future interferometer having these properties will be able to contribute significantly to scientific progress in the field of fundamental stellar parameters.

	Value	**Rationale**
Sensitivity	$m_V \simeq 19$	for low mass stars at 10 pc
	$m_K \simeq 11$	
Observing mode	multi field	simultaneous calibration, star measurement
Baseline	$6 - 10$ km	3-5 resolution elements
Amount of stations	$9 - 30$	3-10 stations along radial direction
		+ 3 stations and Earth rotation for azimuth coverage
Wavelength rage	$0.4 - 10\ \mu$m	comparison of atmospheric models
		coverage of spectral lines
Spectral resolution	> 100000	to constrain surface gravity, metallicity etc.
Field of view	> 1 arcsec	to include circumstellar material

Table 1: Specifications for the next generation of interferometers for science related to fundamental stellar parameters.

In addition to these specifications related to the instruments there are also other possibilities to improve the scientific results. Simultaneous measurements of high-precision bolometric fluxes or the coordination with external facilities to obtain high-precision parallaxes are just two options.

2 Binaries and multiple systems

This section is largely based on the presentation by F. Verbunt (these proceedings).

2.1 Scientific interest

The analysis of the stellar population over the last decades demonstrated that indeed most stars happen to be bound in a binary or multiple system and only a small fraction of stars live on their own. In that respect one should be reminded that there is a huge variety of, for instance, binary systems and that the two components of the systems are not necessarily main sequence stars: pulsars, neutron stars or even black holes can also represent components of bound systems. Thus, their pure abundance and their very distinct characteristics make binary and multiple systems very interesting for scientific research.

2.2 Current research questions

Some of the most interesting questions are related to the formation of the multiple systems as, so far, the initial distributions of the mass ratios and the orbital periods are rather unknown. In addition, the further evolution of binaries and multiple systems needs to be investigated in greater detail. What are the differences in the evolution between multiple systems and single stars? What are the related fundamental parameters? How do multiple systems influence the enrichment and the energetics of the ISM? This list, however, can easily be extended by numerous additional questions. Finally, there are some very interesting individual systems, e.g. systems containing very high density objects (massive neutron stars). What happens if such a component continues to accrete mass from its partner and reaches the mass limit of a neutron star?

Before addressing some of these questions in particular, it is important to understand how these systems can be studied in general.

2.3 Studying binary and multiple systems

In general two different approaches are possible to gain new insights into scientific questions. Either one chooses the theoretical path and tries to make predictions that can then be compared to measurements (or, in the context of astrophysics, observations) or one decides to do experiments and tries to fit those results with theoretical models.

Concerning multiple stellar systems a theoretical approach is not very easy to follow. Although one can start with assumptions for the most important parameters (e.g. mass ratios, the orbital periods, eccentricities of binary orbits) and then evolve the binaries in time and compare the results to observations in order to find the best model that reproduces the stellar population, theoretical methods are rather uncertain. Too few is known about the initial distribution of fundamental parameters, the physics of spiral-in motion lacks understanding and often important figures (e.g. the velocities of neutron stars) are just not well known.

However, also observational methods cannot infer all interesting features of binary systems at once. Via spectroscopy it is possible to derive the radial velocity amplitude of the system and thus the orbital period. Still, the inclination of the orbit is unknown and only in the case of double-lined observations the mass ratio can be inferred. The best option to compute the inclination and the distance of the components is to measure the visual relative orbit. For single-lined binaries it might even be required to measure both visual orbits in order to get access to the mass ratio and the inclination of the orbit. Thus, it becomes clear that in order to gain as much information as possible about binary and multiple systems direct measurements of the orbits are of major importance.

In that respect it is important to point out that so far visual observations lead mainly to the detection of wide and long periodic binaries whereas spectroscopic data reveals close and short periodic systems. The next generation of interferometers, however, might be able to close the gap between these two methods leading to a more complete sample of multiple systems.

2.4 Science cases for the next generation of interferometers

2.4.1 Determining initial conditions

One of the first scientific objectives of the next generation of interferometers might be to find out more about the initial mass function. Today binary properties are quite well known for G and K stars. However, little is known for M dwarfs and also for O, B and A stars. Thus, we lack understanding of the binary properties of the most abundant stars and the most massive ones. Of course this couples directly back to the determination of the initial mass function being surely not unique at this point in time. Table 2 gives some specifications for possible future interferometers yielding new insights into this topic.

	Low mass	**High mass**
Spatial resolution	1 mas	1 mas
K magnitude	K $\simeq$ 12	K $\simeq$ 12
Contrast	ΔK $\simeq$ 8	ΔK $\simeq$ 5

Table 2: Specifications for the next generation of interferometers aiming at improved predictions for the initial mass function.

2.4.2 Increase number and diversity of binary and multiple systems

In order to learn more about the evolution of binary and multiple systems it is important to increase the number of known objects and also their diversity. One goal might be to increase the number of accessible binary systems by a factor of 10. This will require a large amount of observing time and the contrast sensitivity of the instruments will have to be increased. However, by aiming at $\Delta M_V \simeq 10$ or $\Delta M_K \simeq 9$, for instance by means of nulling interferometry, this project is surely feasible. Table 3 shows which orbital periods one can expect to detect if a certain spatial resolution is given. As an additional reference one can assume that a G0V star at 400 pc has a K-magnitude of $K \simeq 11$.

	Resolution	**Distance**	**Orbital period**
Low mass	3 mas	130 pc	100 days
Low mass	1 mas	400 pc	100 days
High mass	3 mas	1 kpc	1 year
High mass	1 mas	3 kpc	1 year
High mass	1 mas	1 kpc	0.2 year

Table 3: With mas-resolution future interferometers will be able to detect a large number of additional binay and multiple systems.

In addition to that, triple and multiple systems will also benefit from highly sensitive mas-resolution interferometers. It is known that multiple systems are very common, as for instance in Praesepe the ratio between single, binary and triple systems scales as $s : b : t = 47 : 30 : 3$.

In certain cases it is possible to derive and resolve the inner orbit of a close binary if the outer orbit of a third component can be resolved. In this context a future target might be to resolve a triple in M67. Typical values for this problem are summarized in Table 4.

	1st star	2nd star	3rd star
Mass (in solar-mass)	2.7	1.7	1.7
V Magnitude	12.3	13.1	12.2
Semimajor axis outer orbit	—	—	5 mas
Semimajor axis inner orbit	—	0.03 mas	—

Table 4: Typical values for a triple system in M67. In specific cases it is possible to resolve the inner orbit by analyzing the larger outer orbit. The requirements for the instrument are equal to those already mentioned in the previous sections.

2.4.3 Compact stars and individual systems

Finally, the next generation of interferometric facilities shall be able to unveil the properties of some very special systems. These systems might be high- and low-mass X-binaries with periods between 1 and 100 days in a distance of some kpc. The visual magnitude ranges between $V = 7$ and $V = 15$ and the contrast in magnitudes between the different components lies between $\Delta V \simeq 1$ and $\Delta V \simeq 5$. Table 5 provides an overview which requirements a future interferometer shall have in order to resolve specific compact systems.

	High mass	Low mass	Carbon stars	Pulsars
Spatial resolution	0.1 mas	0.04 mas	0.1 mas	0.003 mas
K magnitude	K $\simeq$ 7	K $\simeq$ 15	K < 7	K $\simeq$ 20
Contrast	ΔK $\simeq$ 5	ΔK $\simeq$ 1	ΔK $\simeq$ 1	3rd star

Table 5: Some specifications for a future interferometer able to study specific compact objects.

2.4.4 Summary and outlook

¿From the previous sections it becomes clear that the specifications for the next generation of interferometers are quite similar for all science cases mentioned here. However, one should keep in mind that not only these specifications have to be fulfilled but that also large observation campaigns are required in order to gain new scientific insights. It is important to note that for some scientific objectives one might run into a competition with the space mission GAIA to be launched in 2011. Thus, it might be helpful to focus on topics where one can expect fast results. ¿From today's point of view this are the evolution of binaries and the study of special compact systems.

3 Stellar activity and asterosismology

This section is based on the presentation of F. X. Schmider and O. von der Lühe.

The internal structure of stars is not well known. To understand stellar evolution, parameters such as mass, chemical composition, convection or age have to be estimated. But observations only inform us about quantities such as luminosity, effective temperature, chemical composition, distance... Studying stellar oscillations will bring new constraints for stellar evolution models.

Before studying the seismology of stars, astronomers started studying the oscillations of Sun. Heliosismology was born. It reveals a lot of information about the structure of the Sun, like the depth of the convection zone, the rotation profile in latitude and radius, the quantity of helium, the temperature of the core, which governs the nuclear reactions. It helped constrain stellar evolution models. The main excitation mechanisms are of two types: interaction with convection excites a large number of modes, but with limited amplitudes, like in the Sun, and instabilities (kappa-mechanism, for instance) which drives a smaller number of modes with much larger amplitude. This is the case of Cepheids, delta Scuti stars, gamma Dor, and much more. Studying all these type of stars through asteroseismology will allow not only to measure fundamental parameters like age, chemical composition, distance, but also to investigate a lot of physical phenomena, like evolution of angular momentum, atmosphere, convection, diffusion, magnetic fields effects, etc.

3.1 Asterosismologic observations

They are two methods of observations: photometry and spectroscopy. Photometric observations allow to detect periodicity of oscillations but are limited by scintillation on ground. Only stars with large amplitude oscillations could be studied with this technique. Spectroscopy seems to be the best way to study stellar oscillations on solar-type stars by measuring radial velocity for example.

Interferometry with kilometric baselines could allow to study some properties of unresolved stars:

- ***intermediate degree modes (l=3 to 6)***: can be achieved by combining interferometry and spectroscopy, in a principle similar to Doppler imaging (Jankov et al). It allow to investigate more precisely the radial profile of internal structure and rotation of stars, and gives access to helium ionisation zone, for instance.
- ***higher order modes***: direct stellar imaging (see next paragraph) would open a new window in stellar physics. Like on the Sun, high degree modes have larger amplitudes and could be fitted globally. It would be possible to inverse the frequency measurements, and provides a direct measurement of sound speed and rotation at any radius and latitude inside the stars.
- ***stellar convection***: can be studied from velocity fields:
  - in outer convective zones which gives information on luminosity, dynamo effects (poloidal and toroidal fields),...
  - in stellar photosphere which produce Doppler shifts of spectral lines.
- ***radius***: primary parameters of the evolution models, there can be measured with higher precision than luminosity, and are less sensitive to uncertainties on distances.
- ***oblateness***: In case of rapid rotators, frequencies of modes are mainly affected by the geometry of the star. Oblateness as small as 1% has significant effects on oscillations, and should be measured as precisely as possible.

- ***rotation and differential rotation***: Both affect the evolution of stars, through stellar winds, activity, meridian circulation, etc Measurement of differential rotation can provide access to the inclination angle of the rotation axis, an up-to-now unsolved problem in astrophysics (Domiciano et al. 2004).
- ***identification of modes***.

3.2 Requirements for NGOI

Radius and oblateness are obtained by visibilities measurements. High precision measurements are necessary, better than the precision on distance, presently 1% at 10 pcs, but which will be improved by a factor 100 with GAIA, reaching 1% at 1000 pcs. On solar-type stars, this implies the following requirements:

- $B > 1$ km ;
- $\lambda = 0.5\ \mu$m ;
- $M_v = 15$;
- $\sigma_{\mathcal{V}} = 10^{-3}$

In order to avoid calibration problems and to constrain the limb-darkening, it is recommended to have at least three telescopes or more on an aligned base, in redundant configuration. Doing imaging is not a real necessity, so a small number of telescopes could be sufficient.

Rotation measurements and mode identification are based on differential phase measurements within spectral lines. The spectral resolution is necessarily better than the intrinsic line width, but it is generally not useful to have resolution higher than 120000. The precision of such measurements is limited by the number and depth of spectral lines, and by the ratio. Here also a large base is required, but most important is the wavelength range, which should allow measurement as far as possible to the blue. Observations from Earth is complicated because the alternation of nights and days imply appearance of modes which don't exist. A same star has to be studied during long periods, a problem that can be solved by doing multi-sites observations. Until now, no telescope is completely dedicated to asterosismology. Space is a good solution to avoid problems of too short observation times. There are several projects dedicated to asterosismology such as COROT, Kepler, Eddington, etc. COROT will be able to continuously study stars during six months. But ground projects can also give good results. For example, AMBER at VLTI can provide measures of stellar differential rotation and inclination angle if it used with its highest resolution of about 10,000 in K band (Domiciano de Souza et al., 2004). The KEOPS projects in Antarctica, which consists of deployable array of 36 telescopes of 1.5 m diameter, could permit continuous observations of stars because nights last for six months, even if an interferometer can hardly be dedicated to only asterosismology. The spectral coverage needs to range from 2 to 10 μm with an angular resolution of 1 mas at 10 μm. The advantages of this site is that:

- it's very dry,
- the seeing is better than in other good sites such those in Chile,
- the wind is slow,
- the isoplanetic angle is superior to 7" in the visible domain

4 Stellar imaging

This section is based on the presentation by O. von der Lühe and F. X. Schmider.

We have to keep in mind that for doing imagery with interferometers, it is needed to cophase all the apertures of the interferometer. All the existing methods are applied to continuous surface such as monolithic or segmented telescopes (curvature or Shack-Hartmann methods). A method has to be found to cophase long baselines interferometers with diluted apertures.

4.1 Problem of cophasing

The dispersed speckle method can come up to those expectations (Borkowski et al. 2004, accepted). It consists in using three dimensional Fourier transforms to correct piston between sub-apertures. Let us take a simple case of a 3 apertures interferometer. An image given by this interferometer is a honeycomb-like pattern. This method consists in recording such images at several wavelengths, stack them so as to built a cube, for which the third dimension is the wavenumber. This cube has to be corrected from dispersion effects. A three dimensional Fourier transform of it gives an output cube with 6 dots arranged as a tilted hexagon. The heights of these dots give the piston between pairs of sup-apertures. A 6 apertures diluted simulated interferometer, which gives 30 dots in the output cube, need 320 photons per data cube to retrieve piston values.

The diversity phase method developed by ONERA could be an alternative but it was not discussed during this symposium.

4.2 Densification techniques for higher resolution

The first densification technique consists in a multi-element imaging interferometric array, the so-called hypertelescope. It uses pupil densification which consists in increasing the ratio between the sub-aperture diameter and their spacing by optically bringing close together the entrance sub-aperture positions (or increase their diameter), but the geometrical pattern formed by the center of each mirror has to be kept constant. The field of view becomes smaller, and the resulting image consists in a very brilliant peak with secondary peaks less luminous than in a non-densified image because almost all the light is concentrated in the central peak. In the second technique, the densification takes place in the image plane (Vakili et al. 2004) providing an alternative solution where the convolution relation is conserved on a slightly larger field. For example, a same collecting area as OWL and a baseline of 1.5 km, compared to the 100 m of OWL, the resolution becomes 15 times better (Riaud et al. 2004).

Both techniques allow direct imaging for a large number of astrophysical problems, like stellar imaging. It can also be combined with a coronagraph, for search of faint stellar companion or exo-planets.

4.3 Needs for stellar imaging

The requirements for doing stellar imaging are:

- Stars have to be bright ($m_v < 12$).
- Long baseline interferometry with scales from 1 to 100 km are required:
  - 1 km at 1.5 μm for studying large scale structures;

- superior to 10 km at 1.5 μm for studying convection processes.

- A larger number of small telescopes is generally preferable to lower number of larger telescopes.
- Spectral resolution has to be better than 60,000.
- Sensitivity of visibility measures has to be about:
  - 10^{-2} to 10^{-3} for active regions;
  - 10^{-3} to 10^{-4} for convection polarimetric observations.

5 Circumstellar environments

5.1 Young stellar objects

This section is largely based on the presentation by S. Wolf (these proceedings) and on an interesting brainstorming about YSO science with Antarctic Plateau Interferometer, which was held at LAOG.

5.1.1 Star and Planet formation process

The scenario of star formation has been divided, according to different stages of evolution, in four classes, from class 0 to class III (Lada et al. 1987, André 1994). Stars are formed from a cloud of dust and gas where turbulent processes lead dense enough regions to collapse. This produces a flattened disk that is rotating around the central protostar, which is called pre-stellar class 0 core. Generally, at the same time, bipolar outflows from forming star-disk system appear (Bontemps et al. 1996). A significant portion of the left-over dust and gas spirals into the class I protostar adding to its mass. This is known as accretion. The grains which remains in the disks are subject to many forces and frequently collide with each other. Class II objects see their spherical envelope dissipated which makes the central star and the accretion disk observable in the whole spectrum. The last division of this classification corresponds to the moment where the gas reservoir has dissipated and the accretion stops, leading to a class III star with planetesimals and forming planets in a more tenuous disk. This disk results from collisions of planetesimals and may evolve to debris disk.

The most natural explanation for the presence of planets is that the growth from micron-sized dust to planetesimals is extremely efficient (Hueso & Guillot 2003). Possible mechanisms for such an efficient growth are the gravitational instability of the solids themselves (Safronov 1969) or due to turbulence induced by shear (Weidenschilling 1980, Dubrulle et al. 1995), or the collisionnal aggregation of particles (Beckwith et al. 2000). Once planetesimals grow beyond the km-size, runaway growth is thought to drive those which are far enough from the central star to planetary size (Pollack et al. 1996, Hueso & Guillot 2003).

This scenario of planet formation is now currently approved for low and intermediate mass stars but is still to be proven for massive stars.

5.1.2 Current observations status

Observations have allowed to strengthen the dust grain growth scenario in circumstellar disks (e.g. Beckwith & Sargent 1991, Mannings & Emerson 1994, Duchêne et al. 2004, Bergin et al. 2004), to state that the structure of debris disks could be influenced by the interaction with embedded planets (Wahhaj et al. 2003), to image several debris disks, to detect the presence of extrasolar planetary systems, ...

Spatially resolved images (in the optical/near-IR and sub-mm ranges) have allowed, at best, to study circumstellar disks on a global scale. The investigated disks radii range between ten (Malbet et al. 1998, Millan-Gabet et al. 2001, Eisner et al. 2004, Krist et al. 2004) and several hundreds of AU. In order to study the formation of planetary systems in the inner part of the disks, the spatial resolution has still to be increased. Consequently, only long baseline interferometers can provide the required angular resolution.

5.1.3 Challenges for the Future

Structure of the disk region. Concerning small-scale structures in the global disk, there is still a lot to learn about the morphology of the disks, signatures of precursors of planet formation, signatures of planets (gaps, large-scale spiral structures, accretion region around the planet) and interaction of disks in multiple stellar systems.

An accurate study of the inner disk region (at less than a few AU) is required to answer questions related to planet formation such as:

- evolution of the dust phase (size, chemistry),
- evolution of dust and gas distribution in radial and vertical direction,
- signs for planet formation and for already formed planets (local dust concentrations, grain growth, inner clearings).

Interactions between star and disk Concerning that matter, scientific goals concern the interactions of disks in multiple stellar systems, the influence of close stellar binaries, the relative distribution of gas and dust in disks and mainly questions related to star formation such as:

- evolution of the accretion onto the central star,
- structure and geometry of the accreting protostar,
- origin and formation of large-scale outflows,
- origin, formation, collimation and structure of jets,
- influence of magnetic fields (accretion onto the protostar through magnetospheric funnel flows, anchored at the inner disk edge),
- connection between magnetospheric accretion and ejection processes,
- distribution of matter (variability of Herbig Ae/Be stars due to a clumpy distribution of the innermost circumstellar material),
- origin and line emission of winds.

5.1.4 Astrophysical requirements for an NGOI

- *Spatial resolution.* Mainly for answering questions concerning planet formation in the inner region, a spatial resolution of 0.1 to 1 mas is required. Kilometric baselines are required to investigate the interaction zone between accretion, ejection, disk and stellar surface.

- *Wavelength coverage.* Concerning wavelength, the constraint on the interferometer is to cover a range extending from the near-IR to the mid-IR to observe both scattered light and dust re-emission in order to study the geometry, chemical composition and structure of the (inner) disk. An extension to the visible would allow to probe $H\alpha$, emission line region and forbidden emission lines in jets, the most prominent being [OI] 6300 $\mathring{A}$ [SII] 6716, 6731 $\mathring{A}$ and [NII] 6584 $\mathring{A}$ (Dougados 2003).

- *Spectral resolution.* For resolving dust absorption-emission, crystalline and PAH features and taking into account the kinematics involved (e.g. velocity distribution in forbidden line emission in the jets of the order of few hundreds km/s), a spectral resolution between 1000 and 10000 is required.

- *Field of view.* The requirement for field of view is about 10-100 mas for the inner circumstellar disk.

- *Sensitivity.* For the small-scale structure in the outer disk, some difficulties subsist: low fluxes in scattered stellar light (optical to near-IR) and re-emitted radiation (> near-IR) which impose a high sensitivity (1 mJy or less).

- *Contrast.* Concerning contrast, predictions at size scales smaller than 10 AU are hardly possible, hence the necessity to lead preliminary studies with the first and second generation VLTI instruments. Contrasts ranging between 10^{-1} and 10^{-4} are expected in the near-IR depending on the age and geometry of the disk.

- *Temporal resolution.* At the scale of 0.1 AU or less, timescales of evolution are of the order of days or weeks, so a temporal resolution of one day seems to be a good sampling. It should be noticed, concerning temporal coverage, observations at Dome C would allow uninterrupted runs of observations of a few weeks.

- *Imaging capability.* For studying outflows and jets, expected structures like outbursts due to increased accretion rate, larger patterns (e.g. potential spiral structures caused by planets), small-scale structures in the "outer" disk ..., besides visibility measurements, imaging of large regions with a high dynamic range is essential.

- *Polarization.* Polarization provides additional (independent) constraints on dust grain properties (size, alignment).

5.2 Evolved stars

The observation and study of evolved stars such as Mira stars, AGB stars or supergiants has been one of the first significant success of optical interferometry (see for example Scholz 2003). With their large diameters and high luminosities, these stars are easily observed up to a few hundredths of pc with current interferometric facilities and related techniques (such as aperture masking or speckle interferometry). The structure of the dust shells formed around

	Baseline	Goal
Sensitivity	1 mJy	0.1 mJy
# telescopes (uv coverage)	Image reconstruction	$\geq$ 10 (?)
Spatial resolution	1 mas	0.1 mas
Field-of-view	10-100 mas	1 as (multi-field?)
Contrast	10^4	10^6
Wavelength range	1-10 μm	0.5-20 μm
Spectral resolution	1000	10000

Table 6: Summary of the interferometric requirements for studying circumstellar environments.

these evolved stars is now well studied and some features of the process of dust creation such as the motion of successive dust shells have been addressed thanks to recent interferometric measurements (an exhaustive review on this topic has been produced by G. Perrin, 2003). But the formation of dust is still an open issue.

Optical interferometry with state-of-the-art instruments as MIDI and AMBER will significantly improve our understanding of the processes leading to mass loss in evolved stars. In particular, the better spectral coverage and spectral resolution (up to 10000 for AMBER) will allow studying molecules, shocks and dust grains. Imaging, or at least visibility phase measurements, will bring information on the asymmetry of the dust shell (clumps and other structures) and of the star itself (presence of spots). Indeed, the VLTI has the potential to solve most of the current issues concerning evolved stars, but will certainly raise new ones. It is thus difficult to anticipate the needs for a Next Generation Optical Interferometer in the field of evolved star studies. The only obvious requirement is the ability to produce actual images of the environment of evolved stars, or at least obtain a large number of visibility amplitudes and phases on different baselines, in order to detect and characterize possible clumps and structures in the dust shells. Another requirement is the spectral resolution, which should be as high as AMBER's, and a good spectral coverage. An NGOI should allow a systematic study of evolved stars, which will already begin with the VLTI. In conclusion, the study of evolved stars in not a real driver in the context of the design of the next interferometric facility.

6 Extrasolar planets

This section is largely based on the presentation by J. Schneider (these proceedings).

6.1 Current status

Since the first discovery of a hot extrasolar planet orbiting 51 Peg by Mayor and Queloz (1995), about 130 extrasolar planets have been discovered, mainly by means of radial velocity technique. This technique allows characterizing some orbital parameters of the planets such as period, semi-major axis and eccentricity. It also gives a minimum mass for the planet through the product $M_p \sin i$, where the inclination i of the orbit is generally unknown. The current accuracy achieved by state-of-the-art instruments such as HARPS (Rupprecht et al. 2004) is about 0.5 m/s, which allows detecting planet as small as about ten Earth masses. Radial velocity measurements should therefore not allow detecting planets as small as the Earth.

Transits of extrasolar planets in front of their parent star have also been recorded for a few planetary systems through the apparent luminosity decrease of the star. In addition to the period and semi-major axis of the orbit, photometric transits also allow determining the radius of the transiting planet. This is a first step towards physical characterization of exoplanets.

Other techniques such as astrometry and microlensing are also currently being developed and tested. Both have allowed detecting and/or confirming the existence a couple of exoplanets so far. Imaging has also recently allowed to detect a probable young planet.

6.2 Expected advances in exoplanet studies

6.2.1 Near-term future

In the next few years, the techniques cited above will continue to be developed. While the radial velocity technique has probably reached its full potential, photometric transits is a promising method that will allow detecting planets as small as one or a few Earth masses thanks to ultra-precise photometry onboard space missions such as CoRoT (Moutou et al. 2004) or Kepler (Borucki et al. 2003). They will bring the first data about the abundances and the orbital distributions of Uranus-class to terrestrial exoplanets.

Astrometry is also a promising technique for exoplanet census. It will be implemented first in ground-based interferometers with instruments such as PRIMA (Paresce et al. 2002), and then in space missions such as SIM (Marr IV et al. 2002) and GAIA (Sozzetti et al. 2001) within ten years. While GAIA will make a complete census of rather large bodies out to 150-200 pc (typically, Jupiter-sized planets), SIM will be sensible to small planets down to a few Earth masses. Astrometry will provide precise information on the planetary mass (provided that the stellar mass is known) and on its orbital elements.

However, the main breakthrough for the 10 years to come will be the first photon detected and the subsequent spectroscopic study of hot giant extrasolar planets. Current models for hot Jupiters agree that these planets should be gaseous, but diverge on important atmospheric parameters such as the presence and abundance of dust and aerosols, the cloud composition, the thermalization between day and night sides, winds, etc. The spectral analysis of such planets will thus bring major observational constraints for the models. The physical characterization of giant planets will also provide new information on their formation processes and thus new constraints to help validating the possible theories (core accretion vs. disk instability). High precision radial velocity surveys and space missions as CoRoT and/or MOST should pave the way towards this goal. Adaptive optics and interferometry are at the bases of the techniques developed to definitely achieve it, with current European projects such as VLT-PF (ESO proposals by Lagrange et al. and Feldt et al.), GENIE (Gondoin et al. 2004) or Pegase (Léger et al. 2004). These instruments will allow characterizing the near-infrared spectrum of a few tens of hot (or young) giant exoplanets within ten years, but will not yet provide a global census.

6.2.2 Mid- and long-term future

Beyond the objectives already mentioned above, the main objectives for the 10-20 years to come in exoplanet studies are the following (Schneider 2004):

- making the census of planetary systems in our galaxy and characterizing them (orbital as well as physical parameters),
- searching for life in a limited sample of “interesting” planets.

In order to search for the presence of life on terrestrial exoplanets, direct imaging is required, by means of coronagraphy or interferometry (or a combination of both). A critical issue in this quest is the choice of the observation wavelength (visible of mid-infrared). Imaging of exo-systems in the visible is very challenging because of the huge contrast between the reflected light from a terrestrial planet and its parent star: 10^9 to 10^{10}. While the visible regime does not require long baselines (10 m is sufficient to resolve a Sun-Earth system at 50 pc), it demands an extremely precise control of the instrument. Atmospheric turbulence severely degrades the performance of ground-based instruments in the visible regime, and will probably not allow to carry out such a study from the ground. Moreover, bio-signatures in the exo-planet atmosphere (H_2O, O_2, O_3, ...) will be blended with similar spectral bands in the Earth atmosphere. The visible regime will therefore most probably be reserved to space-borne coronagraphs in the 10-20 years to come (e.g. TPF-C – see report "Coronographic Methods for the Detection of Terrestrial Planets" by A. Quirrenbach (ed.), to be published in ESA-SP).

On the other hand, in the mid-infrared, the contrast between a terrestrial planet and its parent star is typically comprised between 10^6 and 10^7. Such a contrast could be manageable for a next-generation interferometric facility, especially in a very good astronomical site as Dome C (Coudé du Foresto 2004). However, the future of terrestrial planet imagery and characterization clearly resides in space, where perturbations are much smaller and thus the specifications on instrumental control somewhat easier to reach.

The long-term future in exoplanet studies is the imagery of the very surface of the planet, searching for continents, oceans, vegetation, etc. Such a goal can only be reached with (space-borne) multi-kilometric optical interferometers. The next generation of optical arrays will pave the way towards such an ambitious goal.

6.2.3 Scientific goals for a next generation interferometer

The first goal for a Next Generation Optical Interferometer (NGOI) should be to routinely detect and characterize Jupiter to Uranus-sized planets in the solar neighborhood, with semi-major axes ranging from a few hundredth of AU to a few AU (or more for young planets). Both the orbital and physical parameters should be studied, as well as the possible presence of rings, satellites, etc. Moreover, the interferometer should be sensible enough to reach the closest stellar forming regions (i.e., about 100 pc), in order to characterize young exoplanets around freshly formed stars.

Besides this first goal, an NGOI should also allow detecting and characterizing planets down to a few Earth masses around the closest stars (within about 10 pc). This requires very precise correction of atmospheric turbulence and instrumental control, which might only be possible in an extraordinary site as Dome C.

6.3 Technical requirements for an NGOI

Two main interferometric modes can be used to characterize exoplanets: direct detection (by means of interferometric nulling or classical visibility/phase measurements) and astrometry.

6.3.1 Direct detection: nulling

The requirement for a nulling interferometer is three-fold: being capable of separating a planet at about 0.1 AU from a star located as far as 100 pc, being sensible enough to detect the planetary photons and, above all, being capable of overcoming huge star-planet contrasts (up to 10^6 for the characterization of a 10 Earth-mass planet at 1 AU of a Sun-like planet). The baseline requirement is straightforward: a **one-kilometer baseline** is required to detect a planet orbiting at 0.1 AU of a star located at 100 pc. A **two-telescope interferometer** should be enough for exoplanet detection, even if three- or four-telescope designs would somewhat improve the detection capabilities for planets very close to their parent stars by achieving a deeper null.

Concerning the telescope size: the larger, the better. A pure photometric computation shows that, working with 10-m class telescopes in a Paranal-type site and assuming a 1% overall throughput, the nulling interferometer would be capable of detecting a warm Uranus-sized planet orbiting at 0.1 AU of a Sun-like star at 15 pc in 1 hour with an SNR of 5, assuming background-limited operation at 3 μm and with a spectral resolution of 100. At Dome C, the same instrument would allow detecting such a planet around a star as far as 40 pc thanks to the lower background emission. An important driver for the telescope size is the detectability of young Jupiters in star-forming regions. In order to characterize a young Jupiter at a temperature of 1000 K orbiting at 1 AU of a Sun-like star at 100 pc, a telescope diameter of 35 m would be required at Paranal (assuming background-limited operation at $\lambda = 3$ μm and $R = 100$ in 1 hour). At Dome C, a 10-m telescope would be enough to do the same job. In order to characterize a large sample of exoplanets, a **telescope size of at least 10 m** is thus required. Working in a **low-background environment** would be very valuable.

Finally, one of the most stringent requirements is the ability to achieve a very deep and stable null to detect an exoplanet as faint as 10^{-6} of its parent star. Instrumental errors have to be controlled with a very high precision: assuming an operating wavelength of 3 μm, optical path delay control at the nanometric level and tip-tilt control at the milli-arcsec level are mandatory. Such performance will be very difficult to meet, even in a good site like Paranal. The actual detection capabilities have to be assessed in light of the expected performance of fringe-tracking and adaptive optics devices. Once again, the gain of building the interferometer at Dome C should be substantial.

6.3.2 Direct detection: other techniques

Besides nulling, other techniques can be used to characterize exoplanets. Visibility and differential phase measurements are two possible techniques. However, these techniques are not expected to be less sensitive to background emission and instrumental effects than the nulling mode, and should thus not lead to relaxed technical requirements.

Advanced methods based on the combination of multi-aperture imaging with various techniques such as densified pupil, coronagraphy, IRAN-type recombination, etc. have also been proposed. These techniques should improve the photometric signal-to-noise ratio in background-limited regime by isolating the planet on a resolution element, and thus allow the use of smaller telescopes. The control of the telescope co-phasing remains a great concern.

In addition, stellar surface imaging of the parent star will provide useful input for planetary physics, e.g. for transiting and/or magnetized planets.

6.3.3 Astrometry

A Jupiter-size planet orbiting at 5 AU of a star at 100 pc produces an astrometric displacement of its parents star of 50 μas. Such a signature will be within reach for the PRIMA instrument at VLTI. In order to detect an Earth-like planet in the habitable zone of a Sun-like star at 10 pc, an astrometric precision of 0.3 μas would be required. The technical feasibility of such a performance from ground is of course questionable, but the fundamental limit indeed comes from stellar physics: some sunspots have areas up to 1% of the area of the Sun and so can cause its apparent center of light to move by as much as 0.5% of its diameter, which means about 5 μas for a Sun at 10 pc. Based on the PRIMA design, let us compute what baseline would be required to reach this fundamental limit. The astrometric error is given by the following relation, in the long-baseline regime (Shao & Colavita 1992):

$$\sigma_\delta \simeq 300 B^{-2/3} \theta t^{-1/2} \tag{1}$$

where B is the baseline, θ the beam separation (i.e., typical field-of-view) and t the integration time. In order to reach a 5 μas accuracy on 10 arcsec field-of-view within one hour, the baseline should be increased to about 1 kilometer. Such a programme does not require very large telescopes: the reference stars typically go down to magnitude K$\simeq$18 for a 10 arcsec field.

	Nulling	Astrometry	Imagery
Telescope size	≥ 10 m	~ 2 m	~ 10 m
Baseline	1 km	1 km	1 km
# telescopes	2 – 4	2 – 4	≥ 10 (?)
Wavelength range	2 – 10 μm	—	2 – 10 μm
Spectral resolution	~ 100	—	~ 100
Field-of-view	~ 100 mas	~ 10 as	~ 100 mas

Table 7: Summary of the interferometric requirements for exoplanet detection and characterization.

7 Extragalactic astrophysics

This section is based on the presentations by D. Fraix-Burnet, A. Marconi, M. Wittkowski and G. Weigelt (these proceedings).

So far, extragalactic astrophysics has not been a predilected science case for interferometry, unfortunately. But the recent results obtained at the VLTI (Jaffe et al. 2004; Wittkowski et al. 2004) and the Keck interferometer (Swain et al., 2003) could definitely change this matter of fact and convince the community of interferometry's great potential to make new and revolutionary science in this field.

7.1 Science case: Galaxies

We will present in this section the science case in extragalactic astrophysics without the pretention to be exhaustive. At the entire Universe scale, the basic ingredients are the galaxies. Our understanding of these complex objects and the way they interact is still very limited and needs new observation capabilities as we will see below.

What are galaxies? A usual definition of a galaxy is an independent group of stars, gas and dust, all of these constituents evolving with time and space. The traditional way of describing galaxies is dictated by old instrumental limitations, that is to say a distant, non-resolved description. The modern way, resolved, is therefore more detailed and is interested in understanding the evolution of these complex objects.

7.1.1 Analyses of features

The easiest and historically first accessible observables in the galaxy studies are the main features they are composed of: bars, dust, gas, star groups,... As our understanding of galaxies progresses, our needs of finer details to further distances increase. The problem is still that galaxies are faint and extended objects, thus not adapted to interferometers in general. The fact is that classical interferometers are still complex instrument with a catastrophic global optical efficiency (about 1%) and by nature with a limited field of view (about 50 mas in K for 8-m telescopes).

7.1.2 Kinematics, chemical composition

It is difficult if not impossible to truly separate the dynamical and the chemical evolutions of galaxies. The imbrication is two-way: the global chemical composition of a galaxy as well as the local distribution of elements depends on the "dynamical mixing" and the dynamical evolution is affected by the global and local chemical interactions. More observations are needed to constrain the models. But, again, at the spectral resolutions needed to carry out this study (R=1000), the signal is much too faint. Interferometry, again, is less adapted than for example ELTs (Extremely Large Telescopes).

7.1.3 Star formation history, stellar characteristics in other galaxies, globular clusters

The star formation rate in different regions of a galaxy gives us indications on its Initial Mass Function. By resolving, characterizing and situating groups of similar stars (clusters) in different galaxies, an NGOI could contribute to the understanding of their formation from the initial clouds.

The aim of the study of stellar characteristics in other galaxies, or "the galactic sociology", is to try to extrapolate the global but precise properties of the whole system from individual characteristics of the stars. The chosen description has to enable us comparing galaxies between them for different morphologies and at different times. It must help understand the formation mechanisms and evolution processes. An NGOI could allow resolving smaller groups of stars (clusters) in other galaxies (100 mas, 15-22 mag).

And, as far as globular clusters are concerned the open questions are: what are their ages, their metallicities?

7.1.4 GRBs, Supernovae, Cepheids, Microlensing

Visible counterparts of GRBs, i.e. the afterglows, are not well understood. Further observations at higher resolutions are needed. The same is true for SN Remnants in other galaxies, to better understand their physics by sampling more objects with same distances. The important question to answer is: are they really good cosmological candles?

As far as Cepheids in other galaxies are concerned, the question is to measure their angular diameters and amplitudes of oscillations in order to deduce their linear diameters. But are they realistic targets? They are so faint (> mag 22 at 200 kpc) and so small (0.001-0.01 mas)!

Microlensing could be interesting to observe with an interferometer but would require a large "survey field of view", which seems, in this respect, out of reach for an interferometer.

7.1.5 Galaxy structures at high redshifts

The structures and morphologies of galaxies change with time. Determining the history and cause of this galaxy structure-redshift relationship, including the origin of modern galaxy morphologies (i.e., ellipticals, disks) is perhaps the missing, and until now overlooked, link in understanding galaxy formation. But the problem is that, even at high redshift, the field of view (FoV) of an NGOI could not be sufficient to characterize the high scale structures (up to 100 mas) of those distant galaxies. Moreover, the integrated magnitude would be out of reach (about 30) ! In an interferometer, there is always a compromise between the FoV and the sensitivity.

7.1.6 Galaxy centers & Active Galactic Nuclei

All the observations undertaken up to now on NGC 1068 with VINCI (Wittkowski et al., 2004) and MIDI (Jaffe et al., 2004) and NGC 4151 with the Keck interferometer (Swain et al., 2003) have clearly proved that next generation long-baseline interferometry will certainly allow us to study nearby galactic centers in more and more detail, but also to extend observations to more and more distant objects up to very old and therefore distant AGN.

Active Galactic Nuclei are galactic nuclei producing non-stellar energy. Non-stellar in terms of luminosities ($L = 10^8 - 10^{13} L\odot$), and in terms of spectra (flat and extending from radio to gamma-rays). Other remarkable characteristics are their high efficiencies of matter-energy conversion (about 0.1), the apparent compactness of the source (less than a few light days), the rapid time variabilities (a few hours) and the presence of relativistic jets.

The most widely accepted model comprises a central black hole in the supermassive (10^6) or hypermassive (10^9) range surrounded by an accretion disk responsible for the radiative energy and matter (outflows) release. Observationnally, the orientation of the AGN with respect to the line of sight accounts for the two main classes, Seyfert 1 (broad emission lines) and Seyfert 2 (narrow lines). The dominating contribution to the Seyfert 1 signal comes from the so-called Broad Lines Region which are small high density gas clouds orbiting around the nucleus (ranging from a few light days to a few light years in the most luminous ones). At larger radii (1-100 pc), the nucleus is surrounded by an obscuring torus of cold gas and dust, main contributor to the Seyfert 2 signal.

The open questions concern:

- The supermassive black holes: do they really exist? Are there intermediate mass BHs? What is the influence of the age of the galaxy on the BH/galaxy interactions?
- The Broad Line Regions: What are BLR geometry and kinematics? What is the origin of the BLRs?
- The Obscuring Torus: does is really exists (crucial test of the unified model)? What is its geometry? What is the dust composition?

7.2 Technical requirements for an NGOI

Two main interferometric modes can be used to characterize galaxies depending on their "activity": the nulling mode that is mandatory in the case of bright AGN (Seyfert I) and the classical visibility/phase measurements for less contrasted objects (Seyfert II for example).

But the principal requirements concern:

1. the sensitivity: should be of about K=22 (R=50), K=20 (R=1000);
2. the uv coverage: full imaging capabilities (the "image reconstruction with aperture synthesis vs. multiplication of the number of telescopes" consensus has to be refined);

	Baseline	Goal
Sensitivity (telescope size)	compromise with FoV	K=22 (R=50), K=19 (R=1000)
# telescopes (uv coverage)	Image reconstruction	≥ 10 (?)
Spatial resolution	1 mas	0.1 mas ($B = 1 - 10$ km)
Field-of-view	1-10 mas	Multi-field approach
Contrast	100	1000
Wavelength range	1-2.5 μm	extension to 10 μm
Spectral resolution	$R = 50$ (low)	$R = 1000 - 2000$ (medium)
Sky coverage	reference star $m_K = 13 - 14$	reference star $m_K = 18 - 19$

Table 8: Summary of the interferometric requirements for extragalactic astrophysics.

3. the spatial resolution: 0.1 mas, requiring kilometric baselines, is mandatory to detail the structure of tori (clumpiness, outflow, cavities) and BLRs;
4. the Field of View: should be greater than 1-10 mas (geometry of tori, composition and kinematics of BLR);
5. the Contrast (nulling): 100 at least (detection of circumnuclei components);
6. the wavelength range: 1-2.5 microns (possibly up to 10 microns);
7. the spectral resolution: ranging from 50 (low) to 1000 (medium) for BLR;
8. sky coverage: depending on the fringe tracking reference star problem (K=18-19 realistic?).

8 Technical summary

8.1 OWL and interferometry

One of the main limitations of Extremely Large Telescopes is the confusion noise. Indeed, with such a large collecting surface, the limiting magnitude is higher than 34 in V band for OWL. In this case, all imperfections in the image contribute to increasing the background. An optimal use of ELTs needs a very good correction with extreme adaptive optics. For example, in the optimistic case of a Strehl ratio of 80%, the detectivity falls by 40% compared to the perfect case. On the other hand, in the case of only 30% Strehl ratio, the loss can reach four magnitudes for a highly crowded field of view. However, even for low source density in the field of view such as Hubble Deep Field or Ultra Deep Field, the confusion noise becomes very important. This can be problematic when the sources are near the Milky Way. Indeed the diffraction residue of foreground stars highly contaminate the signal of observed sources.

The confusion noise in the interferometric scheme is different because interferometers present a low collecting surface compared to ELT and their main limitation is the small size of field of view (High Order Field). This field corresponds to the coherent beam of the sub-apertures and reaches 0.6 arcsec in diameter for a 2-m telescope in the K band. However, it is possible to observe in multiple fields of view on the isoplanetic diameter without crowding effect between the different fields of view (separation greater than 2 λ/d, with d the diameter of the sub-apertures). For all interferometric recombinations (Fizeau, Densified, IRAN), the number of resolution elements is given by the number of sub-apertures and the level of redundancy. This number is about one hundred for 36 apertures, which corresponds to imaging capacity of interferometric scheme for snapshot exposure. The rotation of baseline increases the u,v plan coverage and the number of resolution elements. But for all cases, the system can only image a number of point sources corresponding to the number of resolution elements.

Concerning the R&D and technology readiness, a partnership between the different projects relative to high angular resolution including OWL and interferometry would be profitable. For example, the study of cophasing techniques for the OWL segments could be re-used for long baseline interferometry in direct imaging (Fizeau, Densified, IRAN - Riaud et al. 2004).

8.2 Summary of technical requirements

Topics	**Requirements**	**Goal**
Baseline	1 km	10 km
Spatial resolution	0.1 mas (V band)	0.1 mas (M band)
Field of View	100 mas × 100 mas	2” × 2” (multiple)
Observing mode	multi-field (astrometry)	multi-field (all)
# telescopes / diameter	8/8 m or 36/1.2 m	>10/8 m or >50/1.2 m
Spectral range	$0.4 - 13$ μm	$0.4 - 20$ μm
Spectral resolution	$50 - 1000 - 10000$	higher (> 60000)
V magnitude	$m_V \simeq 17$	$m_V \simeq 20$
K magnitude	$m_K \simeq 10$	$m_K \simeq 13$
Strehl ratio (V/K bands)	15% (V) / 50% (K)	30% (V) / 80% (K)
Dynamic	$> 10^4$	$> 10^6$
Sensitivity for visibility	$\leq 3 \times 10^{-3}$	$\leq 5 \times 10^{-4}$
Sensitivity for detection	$\leq 300\,\mu$Jy @ 10.6 μm	$\leq 30\,\mu$Jy @ 10.6 μm
Instrumentation	imagery, spectroscopy and high contrast imaging	imagery, spectroscopy and high contrast imaging

Table 9: Specifications for the next generation of interferometers: summary

9 Conclusions and perspectives

The European scientific community in optical interferometry occupies the first place in the world: born 30 years ago, it has produced the main concepts, issues the largest scientific production and has created with the VLTI the most powerful, versatile and reliable existing ground based interferometer. The science already carried and published is impressive, and the full VLTI operation will be completed in the next five years. New revolutionary concepts are on the way (integrated optics, single mode fibers, “Carlina-type” telescope) which are already modifying and will modify interferometer designs in the future. Space missions are in preparation, both on the short term with a “formation flying” mission, and on the longer one with the DARWIN mission. European industry has taken the challenge of new systems: optical fibers, interferometric telescopes, delay lines, coronagraphs... Yet, this community, which has been heavily absorbed by the VLTI instruments construction and still is with their operation, is at the moment lacking a prospective vision of its mid-term future, at a time where other astronomical groups have generated ambitious projects (ALMA, the ELT Owl project, the radio Square Kilometer Array). There exists nothing similarly advanced, even on a smaller scale, in European optical interferometry. As an example, the long term ESO program has not received a sufficient attention, and contains at the moment very little regarding the long term prospect for the VLTI itself or a follow-up operation: even the current Long term plan "interferometry chapter" has been essentially produced in ESO internally without a large external contribution of the community. Indeed, the well organized effort to build an European Interferometry Initiative within the EU Opticon network should not be underestimated. Nevertheless, strong collaboration and coordination between the ESO, ESA and EU plans are mandatory for scientific, technical and political reasons: they are very much expected.

We try to summarize below some orientations which seem to emerge from the Liège meeting.

9.1 Scientific objectives

1. Overview. An in-depth review shows that numerous fundamental problems in astrophysics have benefited and will continue to benefit from optical interferometry in the 1-12 μm domain (extension to visible feasible and wished) with spectral resolutions ranging from a few tens to 10^5 in the extreme cases. More specifically: to provide additional observables (diameter, shape, envelopes,) in order to constrain stellar models; to study binary stars over the whole mass range; to image activity on stellar surfaces; to disentangle the complexity of accretion in protostellar and protoplanetary discs, all across the HR diagram; to provide images, structure, spectra of extrasolar planets, especially the hot Jupiters; to give access to the inner part of AGNs, especially the Broad Line Region, the supposed molecular torus and the clumps; to provide images of lensed objects and study galaxy morphology up to z=1-2. While current angular resolution (VLTI or similar baselines) typically provides 1 mas resolution at 1 μm, the aim for the instrument of next generation is to gain an order of magnitude, reaching 0.1 mas. The VLTI observations will adequately explore the lower frequency range and provide a solid basis for this resolution step of 10. This leads to a first conclusion of the Workshop, on the basis of the science objectives: **the next interferometer generation should operate at least from 1 to 12 μm and have kilometric baselines (1 to 10 km at most)**.

2. The most difficult limitation of ground based interferometry is the need for adaptive optics phasing of each pupil and fringe tracking to integrate longer than a few tens of milliseconds. The observation of faint sources requires therefore the use of an adequate reference (m_K brighter than 13-14, basically the same limit for adaptive optics and for fringe tracking), which may or may not be available for a particular observation. Therefore, there are clearly two kinds of programs: the ones observing a sufficiently bright source and/or its immediate neighbourhood, and the ones where a chance coincidence with a close enough reference star will allow the observation: this latter case is typical for most AGNs and galaxies. The hope to push this current m_K limit to magnitudes 18-19, which would entirely change the situation, is quite dim at the moment. **Almost all the above programs, discussed in detail at the Workshop, require adequate fringe tracking reference and will therefore be possible within the current limitations of reference star availability for long integration on faint objects.**

3. Existing interferometers use air or vacuum delay lines with movable mirrors. A kilometric array will have to consider anew the question of delay lines, especially to limit their excessive cost: this requires technological research, exploring several already proposed and/or

tested ideas: suppression of delay lines with moving telescopes (Labeyrie or Angel concepts) or "carlina" type recombination; single mode optical fibers coupling. **Kilometric arrays require dedicated studies of delay lines concepts.**

4. The science programs presented during the Liège Workshop do not uniquely specify the wished telescope diameter: a number of programs (stars, exoplanets) can be done with 2-m class telescopes, while others of high interest (faint stars, galaxies, AGNs, gravitational lensing) require 8-10 m class telescopes. Further discussion is needed either to prioritize the programs, or to conceive a dual interferometer having a mix of large and small apertures (as VLTI or Keck with outriggers). **The wished diameter for the telescopes of the next generation interferometer deserves further discussion.**

5. The imaging philosophy is less clear. Although a larger number of telescopes may always be considered as a better choice than a smaller number, there is no clear cut number which separates a true imager from a less advanced machine. Choosing today 4, or 6, or 27 is not a choice clearly led by scientific motivations. No consensus was achieved at the Workshop on this issue, which exists since the beginning of interferometry, and often is concluded on the basis of a compromise due to the available resources. **Imaging is considered a key capability of the future system, but the extent of imaging requirements and the "imaging strategy" deserves further study and discussion.**

9.2 Strategic aspects

In the context of the current VLTI development, it appears essential for the interferometric community in Europe to express its long range plans for 10-15 years, both for the ground and for space. The Workshop discussion essentially focused on ground-based interferometry.

- The current VLTI long term planning (until 2012) within ESO is minimal, and does not contain an accepted view on the future evolution of interferometry. As stressed at the Workshop, the current tendency in ESO governing bodies may even be to question the pertinence of the current VLTI spending, or even to reduce it.

- It could be argued that no future decision can be envisaged as long as the VLTI science has not produced "breakthrough" results. The need to exploit the VLTI at its full science capability is indeed the top priority of the next decade, but one should keep in mind that discovery does not necessarily follow planning needs! Radio interferometry took a long time to mature and produce exceptional science.

- It is unlikely that a future instrument could be a cheap interferometer, as long as it will have to serve a diversity of goals and users, be a routine machine in an excellent site, working at the standards set by the VLTI. **Any serious project will be a major project.**

- The need is to express a united view of the community. The EII Council certainly is representative. Yet, a new interferometric program is likely to succeed only if it represents a joint effort of ESO and EU, with possibly an ESA support or contribution. It is therefore important that any proposal is elaborated as a joined effort between these three institutions, at the highest possible level. The opportunity within EU should be seized, if it becomes confirmed that FP7 will be more open to unsolicited programs in fundamental research, than FP6 has been.

- A proposal should be considered as a scientific complement to ELT/Owl, and not in competition with. This view will impact on scientific, technical, financial, management aspects. Yet, it does not imply to tie the project to the future OWL site, which may or may not have the expected area for a kilometric instrument.

- It seems that any large size project could hardly be executed outside ESO, given the existing human, technical, managerial expertise in this organisation. Consequently, it would have to be implemented as early as possible in the ESO long term plan.

- There are a few options for a future project (see below), which could hardly be decided immediately. Yet, the project needs to start within less than a year, with a name, clear science goals and design requirements (baselines, telescope size and number), and several options to be discussed progressively. In parallel, technical studies should begin on the critical issues (e.g. delay lines, or telescope motion).

Possible options This was not discussed in detail during the Workshop, and represents probably more the view of the author of these lines. The separation in three options is made for clarification, but may be oversimplified, as they have some common R&D requirements, and some paths may be common between them. Their time scales may also be different;

9.2.1 Option A

The VLTI should be considered as the main ground based interferometer for the 15-20 years to come. It should be boosted in all possible ways, including kilometric baselines with additional telescopes (of a different concept than current ATs). This goes much beyond the existing plans. This focusing on Paranal interferometric activities would be complemented by an effort in space interferometry, hence considered in this option as the real future of optical interferometry.

9.2.2 Option B

A Next Generation Optical Interferometer (NGOI) should be planned in complement to ELT/Owl by Europe. It should become part of ESO/ESA/EU plans and be planned in a site which will not necessarily be tied to the OWL site, as the NGOI requirements may turn out to be entirely different in term of site area.

9.2.3 Option C

The Dome C in Antarctica. This option is made distinct from the previous ones for the following reasons:

- Dome C site characteristics, as far as they are known today, appear to be of an entirely different class than any other ground-based site: in fact, this site classifies as an intermediate one between space and conventional ground. They appear especially favorable for interferometry (transparency, isoplanetism, stability of the atmosphere, area) .However, more observations need to be carried out in order to confirm the exceptional atmospheric conditions expected to prevail at Dome C in Antarctica.

- Dome C operation is made in a fully international (Antarctica Treaty), politically interesting ("continent of science") context, which may help to gather resources and foster international cooperation on a NGOI (Australia, USA, China). ESA and the EU might have a special interest to contribute to this site.

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