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Perspectives for next generation ground- and space-based interferometers

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Abstract: In this review paper, we first recall the basic principles and rationale for building stellar interferometers. The characteristics and major scientific results of current interferometric facilities are then briefly presented as well as the main features of upcoming ones. This review is used as a basis for discussing the scientific case for a next generation interferometric facility and the associated technological challenges. Finally, we present some concepts already envisaged on the ground and in space, and conclude with the necessity of defining priorities that could lead to a consensus for this next generation facility.

1 Introduction: basics of interferometry

The capability to distinguish very small details in visible and infrared images has been a major design driver for telescopes and astronomical instrumentation during the past decades. The angular resolution ($\theta = 1.22\lambda/D$) of a single-dish telescope being limited by its diameter D, larger and larger mirrors have been built over the 20th century, finally reaching 10 m with the most recent telescopes. Adaptive optics systems have been designed to achieve the full potential of these giant dishes in terms of angular resolution, overcoming the harmful influence of atmospheric turbulence. Even larger telescopes (up to 100 m) are foreseen to be built within the next ten years, but these heavy and cumbersome structures are not expected to grow in size indefinitely because of technical limitations. Therefore, another way to improve the angular resolution of astronomical images without building a telescope of enormous size has been developed: optical interferometry[1]. The idea is to synthesize a large aperture by combining light beams from several small telescopes. Even if the technique itself dates back to Fizeau (1868) and Michelson & Pease (1921), the first application to two separate telescopes was achieved only 30 years ago by Labeyrie (1975). At that time, a maximum angular resolution $\theta = \lambda/2b$ of 5 mas was achieved in the visible range on a $b = 12$ m baseline. Since this pioneering work, many interferometric facilities have been built around the world with enhanced capabilities, as described in the next sections.

[1]The terminology "optical" refers here to the way to handle the routing and recombination of light, using optics, and thereby restricting the application to the visible and infrared domains.

2 Interferometric facilities from the 1980s and 90s

Following the successful demonstration of stellar interferometry with separate telescopes, various interferometric projects have been pursued around the world. A number of permanent interferometric facilities have been constructed between the mid-1980s and the mid-1990s and used up to now. These facilities are generally characterized by the use of small telescopes, mostly modest baselines ($\leq$ 100 m) and operation in the visible or near-IR domains. In this section, we briefly review some technical aspects and the major scientific results from these facilities, starting with the oldest ones.

- **Grand Interféromètre à 2 Télescopes (GI2T, 1985).** Operating since 1985 with two 1.5-m telescopes separated by up to 65 m, GI2T works nowadays with a visible beam combiner (REGAIN) including a spectrograph for enhanced spectral capabilities (spectral resolution up to 30,000). GI2T has been successful in studying the circumstellar environment of active hot stars (Be stars), thanks to the combination of high angular resolution and high spectral resolution (Stee, 2003). In addition, the polarimetric mode of the GI2T is a powerful tool to study stellar magnetism and activity (Rousselet-Perraut et al., 2004).
- **Infrared Spatial Interferometer (ISI, 1988).** The ISI is the only infrared stellar interferometer working with heterodyne beam combination, using CO_2 lasers as local oscillators at wavelengths around 10 μm. With its three 1.65-m telescopes arranged over baselines up to 70 m, it allowed detecting cool dust shells around many late-type stars, and provides some imaging capabilities thanks to closure-phase measurements. In particular, the diameters of supergiant and Mira stars were found to be significantly (up to twice) larger in the mid-IR than in the near-IR (Weiner et al., 2003), suggesting the presence of a semi-opaque H_2O shell surrounding the star (Weiner, 2004). ISI was also used to image the dust disks around young stars (Tuthill et al., 2002).
- **Sydney University Stellar Interferometer (SUSI, 1992).** With its 11 aligned 20-cm siderostats, SUSI has potential baselines up to 640 m, but the longest operational baseline is currently restricted to 160 m. Pair-wise beam combination is performed in the visible range. While scientific results from SUSI have been mostly limited to the measurement of fundamental stellar parameters in the past, including binaries (Davis et al., 2005), scattering by atmospheric dust around Mira-type stars has recently been observed in the polarimetric mode (Ireland et al., 2005).
- **Cambridge Optical Aperture Synthesis Telescope (COAST, 1992).** The facility comprises five 40-cm siderostats arranged in a Y-shaped configuration, with baselines up to 67 m. It was the first to produce a true synthesis image at optical wavelengths (visible and near-IR). Scientific results from COAST include stellar surface imaging, leading for instance to the discovery of brightness asymmetries on Betelgeuse's photosphere (Young et al., 2000).
- **Infrared-Optical Telescope Array (IOTA, 1993).** With its three 45-cm siderostats arranged on short baselines (< 40 m), IOTA has been one of the most successful facilities so far. It has been extensively used to measure the diameters of Mira and supergiant stars, especially with the innovative near-IR fiber-linked beam combiner FLUOR (at IOTA until 2003). These studies have finally led to a new model for the structure of these stars, which are now understood to be surrounded by an extremely thin and nearly

transparent molecular envelope whose opacity in the infrared is dominated by a single high layer (Perrin et al., 2004a). The study of Young Stellar Objects (YSO) has also greatly benefited from the IOTA capabilities, with the important result that the characteristic sizes of the near-infrared emitting regions are larger than previously thought (Millan-Gabet et al., 2001). The addition of a third telescope and of a new 3-way integrated optics beam combiner (IONIC) has improved the facility with imaging capabilities.

- **Navy Prototype Optical Interferometer (NPOI, 1994).** Two operational modes are available at NPOI: a Y-shaped, 6-element array with baselines up to 437 m is used for imaging, while a kite-shaped, 4-element array is used for wide-angle astrometry. The arrays are composed of 50-cm siderostats connected by vacuum pipes, and work in the visible range. The 6-way imaging beam combiner has provided important scientific results on various objects, such as elongated rapid rotating stars (Peterson et al., 2004), multiple stars (Hummel et al., 2003), stellar surfaces (Ohishi et al., 2004) or Be stars and their environment (Tycner et al., 2005). The astrometric mode is still in a commissioning phase.

- **Palomar Testbed Interferometer (PTI, 1995).** Built as a testbed for interferometric techniques such as dual-star narrow-angle astrometry, phase referencing and fringe tracking, the PTI has been one of the most scientifically productive interferometers. Three 40-cm apertures are recombined pair-wise in the near-IR K band with baselines between 85 m and 110 m. Recent results include high-precision astrometric measurements of multiple stars (Muterspaugh et al., 2005; Lane & Muterspaugh, 2004), but also "classical" $\mathcal{V}^2$ observations of various objets. For instance, the oblateness of a rapid rotating star was first discovered at PTI (van Belle et al., 2001). Other major scientific results concern the inner region of dusty disks around late- and early-type young stars (Akeson et al., 2005; Eisner et al., 2004) or a revised distance to the Pleiades star cluster (Pan et al., 2004).

- **Mitaka optical and Infrared Array (MIRA, 1998).** MIRA is a small Japanese interferometer with two 30-cm siderostats separated by 30 m and working in the visible regime (Nishikawa et al., 2004). It has been mainly used for technical purposes and has not provided scientific results up to now.

3 A new generation of arrays

Based on the success of the facilities from the 1990s, new interferometers with improved performances have been built and commissioned: the VLTI (Glindemann et al., 2004), the Keck-I (Colavita et al., 2004) and the CHARA Array (ten Brummelaar et al., 2005). The main features distinguishing these new facilities from the old ones are of various types. First, they generally benefit from larger telescopes, equipped with adaptive optics in order to provide a stable image despite atmospheric turbulence. This is a major improvement as it largely increases the (usually low) sensitivity of interferometers and allows extragalactic targets to be observed. In the same context, fringe tracking is now becoming a standard feature, and also increases the sensitivity of the instruments as they are not forced to record the interferograms within the coherence time of the atmosphere (typically a few milliseconds). The use of spatial filtering, which provides a very stable interferometric throughput, is also becoming a standard. Dual-feed capabilities are being developed to allow for precise astrometric measurements. The new arrays also benefit from new recombination techniques (multi-way beam combiner, integrated optics, etc), and are generally equipped with state-of-the-art infrared detectors.

Even if they have only been used for a few years, these new facilities have opened the path to new discoveries and have brought major scientific results in various fields. One of the major breakthroughs is related to extragalactic studies: both the Keck-I and the VLTI have been used to study the nucleus of Active Galactic Nuclei (AGN). In the near-infrared, the Keck-I has revealed an unexpectedly compact nucleus for NGC 4151 (Swain et al., 2003), suggesting that the emission mainly originates in the central accretion disk. Measurements with the VINCI instrument at VLTI (Wittkowski et al., 2004) favor a multi-component model for the intensity distribution of NGC 1068, where a part of the flux originates from scales smaller than 5 mas (0.4 pc), and another part of the flux from larger scales. Finally, additional observations of NGC 1068 obtained in the mid-infrared with MIDI at VLTI (Jaffe et al., 2004) reveal warm (320 K) dust in a structure 2.1 pc thick and 3.4 pc in diameter, surrounding a smaller hot structure. Such a configuration requires a continual input of kinetic energy to the cloud system from a source coexistent within the AGN.

Another field where the new facilities have brought an important contribution is the study of Cepheids. Thanks to precise measurements of their angular diameters and pulsations with the VLTI (Kervella et al., 2004b), the distances to several of these "standard candles" have been precisely determined, using a modified version of the Baade-Wesselink method. Moreover, these observations have allowed for the calibration of the period-radius and period-luminosity relations (Kervella et al., 2004a), which are at the basis of extragalactic distance measurements. Another critical parameter weighing in distance estimations, the projection factor, has also recently been determined with the FLUOR instrument at the CHARA Array (Mérand et al., 2005).

The VLTI has also been very productive in various topics of stellar physics. The coupling of interferometric and asteroseismic observations have provided new insights on the evolutionary status of various stars (Kervella et al., 2003; Thévenin et al., 2005). Radius measurements of very low mass stars have been obtained for the first time (Ségransan et al., 2003), showing a good agreement with theoretical models. Rapid rotating stars have also largely benefitted from the new interferometers, with the first observations of a rapid rotating Be star (Domiciano de Souza et al., 2003), direct measurements of stellar winds (van Boekel et al., 2003), and first estimations of the gravity darkening coefficient, both at the VLTI (Domiciano de Souza et al., 2005) and the CHARA Array (McAlister et al., 2005). The study of evolved stars such as Miras, AGBs and supergiants has also been pursued with the new facilities, greatly benefitting from multi-wavelength observations and providing more precise models for these stars and their environments.

Finally, in the field of YSO, observations with the Keck Interferometer have validated the early results obtained at PTI and IOTA, that an optically thin cavity was present in the inner zone of YSO disks, while the classical model assumed the presence of optically thick gas. This thin gas component probably extends down to the magnetospheric truncation radius and can also be a significant component to the inner disk flux (Eisner et al., 2005). At the VLTI, the MIDI instrument has provided the first spatially and spectrally resolved mid-IR view of these objects, with characteristic sizes of 1 to 10 AU for the mid-IR emitting regions (Leinert et al., 2004). This study supports the phenomenological classification of Herbig Ae/Be stars into groups by their mid-infrared color, and the distinction of these groups by flaring-dominated versus non-flaring-dominated circumstellar dust distributions. The spectroscopic capabilities have also shown the dust in the innermost regions of the disks to be highly crystallized and dominated by olivine, while outer regions have a lower degree of crystallinity (van Boekel et al., 2004). These observations imply that silicates crystallize before any terrestrial planets are formed. Even more recently, the first scientific results of the AMBER instrument have focused on MWC 297, an embedded Be star, showing the star to be surrounded by a flat equatorial disk that is possibly still accreting and an outflowing wind which has a much higher velocity in the polar region than at the equator (Malbet et al., 2006).

4 Near-term future

The Large Binocular Telescope (LBT), consisting of two 8.4-m primary mirrors on a single mounting, will be the next facility to see its first fringes, expectedly in 2006 (Herbst & Hinz, 2004). With its 14.4 m center-to-center spacing, it provides a spatial resolution equivalent to a 22.8-m telescope in the Fizeau imaging mode (between the outer edges of the two pupils). It will also host a nulling beam combiner with 14.4 m baseline. Both instrument will strongly benefit from the original design of the LBT, where delay lines are not needed and a small number of mirrors are required to propagate the light to the interferometric beam combiner. Deformable secondary mirrors, a very interesting application of Micro Electro-Mechanical Systems (MEMS), is another key feature of the innovative array.

The technology of optical fibers has also reached a sufficient reliability to support impressive projects like 'OHANA (Perrin et al., 2004b), which plans to link the Mauna Kea telescopes with fibers over baselines up to 800 meters. Such baselines would provide an angular resolution as good as 0.25 mas at 1.2 μm and the combination with large apertures would open the way to more discoveries in the field of extragalactic studies. Injection of stellar light into the fibers has already been demonstrated, as well as a first fiber-linked recombination of the two Keck telescopes (Perrin, 2005).

Let us also cite the MRO Interferometer (Creech-Eakman et al., 2004), which is envisaged to comprise ten 1.4-m movable telescopes in a Y-shaped configuration with baselines extending from 8 to 400 meters, delay lines capable of tracking well-placed sources during 6 continuous hours, fringe-tracking in the near-infrared, and to undertake science observations at both near-IR and optical wavelengths. The science reference mission includes studies of young stellar objects, a full range of stellar astrophysics, and imaging studies of the nearest and 100 brightest active galactic nuclei. Its first fringes are expected in 2007.

In addition, new extensions of current facilities are foreseen within the next few years. For example, at the VLTI, a dual feed facility (PRIMA) will soon allow astrometric measurements with an accuracy of a few tens of micro-arcseconds and also increase the limiting magnitude of the first generation instruments thanks to fringe tracking (Quirrenbach et al., 2004). Still at the VLTI, several concepts for second generation instruments are currently under evaluation for implementation around 2010, such as a 4 to 8-way integrated optics near-infrared imager (Malbet et al., 2004), a mid-infrared 4-way spectro-interferometer (Lopez et al., 2004), or a demonstrator of nulling interferometry (Gondoin et al., 2004). Some of these instruments will benefit from new technologies derived from the tremendous micro-optics progresses. Indeed, over the last years, these new techniques have come to maturity for actual implementation, and should be used in the future.

5 Long-term future

The VLTI is the most powerful, versatile and reliable existing ground based interferometer. The science already carried out and published is impressive, and the full VLTI potential will be exploited in the next 10 years thanks to second generation instruments. However, in 10–15 years from now, the VLTI era is already expected to come to an end due both to its fundamental limitations in terms of science case and to the advent of extremely large telescopes. New and exciting science goals will then require a next step in the field of interferometry.

5.1 Scientific goals

In this section, we will expose the scientific goals for a next generation interferometer.

5.1.1 Fundamental stellar parameters, multiple stars, stellar imaging

Our understanding of the physical processes taking place in the inner regions of stars and also of the evolution of stars is currently based on some fundamental parameters such as mass, luminosity, radius, age, etc. Further constraining these parameters for all spectral types will allow testing the stellar evolutionary and atmosphere theories. Moreover, improved description of physical phenomena such as convection and magnetic activity could be derived. Finally, different material tables, such as opacity tables, and nuclear reaction rates, could be tested for their consistency. Therefore, the science case for a next generation interferometer can be summarized by the high accuracy measurements of all fundamental parameters of stars in all evolutionary stages across the HR diagram (Quirrenbach, 2001).

The analysis of stellar populations over the past decades has demonstrated that most stars happen to be bound in binary or multiple systems and only a small fraction of stars live on their own. The components can be very different, from brown dwarfs to black holes. One of the major scientific objectives of the next generation of interferometers is a better characterization of the initial mass function. In order to learn more about the evolution of binary and multiple systems, it is also important to increase the number of known objects and their diversity. The goal could be to increase the number of accessible binary systems by a factor of 10 (Armstrong et al., 2004). A large amount of observing time will probably be required and the dynamic range of the instruments will have to be increased.

The internal structure of stars is still not well understood. The study of stellar oscillations by interferometric imaging will bring new constraints on the evolution models. There are currently two main observation methods in the asteroseismology toolbox: photometry and spectroscopy. Photometric observations allow detecting periodicity of oscillations but are limited by scintillation on ground. Only stars with large amplitude oscillations can be studied with this technique. Spectroscopy is currently the best way to study stellar oscillations on solar-type stars by measuring radial velocity variations for example. Asteroseismology through interferometry should reveal a lot more information about the structure of the stars, like the depth of the convection zone, the rotation profile in latitude and radius, the quantity of helium or the temperature of the core which governs the nuclear reactions. The main vibration excitation mechanisms are of two types: interaction with convection excites a large number of modes but with limited amplitudes (like in the Sun), while instabilities (kappa-mechanism, for instance) drive a smaller number of modes but with much larger amplitudes. This is the case of Cepheids, delta Scuti, gamma Dor, and many more.

High angular resolution stellar spectro-imaging through interferometry is of course the ultimate goal for asteroseismology (Provost & Schmider, 1997). Radius and oblateness can be obtained by very high resolution visibility measurements (baselines from 1 to 10 km). Increasing the number of resolution elements will give access to higher and higher oscillation modes. Rotation measurements and mode identification can be obtained by differential phase measurements within spectral lines. For that purpose, the spectral resolution has to be finer than the intrinsic line width, i.e. around 120,000. The precision of such measurements is limited by the number and depth of spectral lines. Here also long baselines are required, but most important is the wavelength range, which should allow measurements as far as possible toward the blue.

5.1.2 Circumstellar environments

The scenario of star formation has been divided, according to different stages of evolution, in four classes, from class 0 to class III. 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 the forming star-disk system appear. 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 remain in the disks are subject to many forces and frequently collide with each other. Class II objects see their spherical envelope dissipate 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 a debris disk. The most natural explanation for the presence of planets is that the growth from micron-sized dust to planetesimals is extremely efficient. Possible mechanisms for such an efficient growth are the gravitational instability of the solids themselves or due to turbulence induced by shear, or the collisional aggregation of particles. 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. This scenario of planet formation is now currently approved for low and intermediate mass stars but is still to be proven for massive stars. 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).

In order to answer questions concerning planet formation in the inner region, a spatial resolution of 0.1 to 1 mas is needed, i.e. kilometric baselines. Such baselines are also required to investigate the interaction zone between accretion, ejection, disk and stellar surface. Concerning wavelength, the constraint on the interferometer is to cover a range extending from the near-IR to the mid-IR in order to observe both scattered light and dust re-emission and to study the geometry, chemical composition and structure of the (inner) disk. An extension to the visible would allow probing emission line regions and forbidden emission lines in jets, the most prominent being $H\alpha$. 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 a few hundred km/s), a spectral resolution between 1000 and 10,000 is required. 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 and 10^4 are expected in the near-IR depending on the age and geometry of the disk. Imaging of large regions with a high dynamic range is essential for studying outflows and jets, expected structures like outbursts due to increased accretion rates, larger patterns (e.g. potential spiral structures caused by planets), small-scale structures in the "outer" disk, etc.

5.1.3 Extrasolar planets

Since the first discovery of a hot extrasolar planet orbiting 51 Peg by Mayor & Queloz (1995), about 170 extrasolar planets have been discovered, mainly by means of radial velocity measurements. This technique allows for the characterization of the orbital parameters of the planets and 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 corresponds to planets as small as about ten Earth masses. Radial velocity measurements should therefore not allow for the detection of 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 provide an estimation of 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 of several exoplanets so far. Imaging has also recently allowed detecting a few probable young planets. The main objectives for the 10-20 years to come in exoplanet studies are the following:

- 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 or 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 carrying out such a study from the ground. Moreover, bio-signatures in the exoplanet 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. 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 ground-based interferometric facility, especially in a very good astronomical site as Dome C.

Two main interferometric modes can be used to characterize exoplanets: direct detection (by means of interferometric nulling or differential visibility/phase measurements) and astrometry. Astrometry with interferometers will allow exploring the prevalence of Neptune-type and larger mass planets for all stellar types in our part of the Galaxy. This goal requires an accuracy around 3 micro-arcseconds. One of the most important and challenging science goals for astrometry is a search for terrestrial planets around the $\sim$250 nearest stars. This program is the most demanding in terms of astrometric accuracy with measurement resolutions at the 1 microarcsecond level. Astrometry will therefore be a powerful tool for broad surveys, but the physical characterization of exoplanets will still require high dynamic imaging, with the help of nulling interferometry for instance.

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 from a Sun-like star). The requirement on the baseline is straightforward: in the mid-infrared, one kilometer is required to detect a planet orbiting at 0.1 AU from 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. 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. The actual detection capabilities from the ground have to be assessed in light of the expected performance of fringe-tracking and adaptive optics devices. Once again, the gain of building an interferometer at Dome C should be substantial.

Besides nulling, other techniques can be used to characterize exoplanets. Visibility and differential phase measurements are two possible techniques. These techniques are also sensitive to background emission and instrumental effects and should thus lead to similar 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.

5.1.4 Extragalactic studies

So far, extragalactic astrophysics has not been a privileged science case for interferometry due to the limitations in sensitivity. However, the recent results obtained at the VLTI and the Keck interferometer have definitely changed the past situation and convinced the community of the great potential offered by interferometry to make new and revolutionary science in this field.

The easiest and historically first accessible observables in the study of galaxies are the main features they are composed of: bars, dust, gas, star groups, etc. As our understanding of galaxies progresses, our need for finer details at larger distances increases accordingly. The problem is that galaxies are faint and extended objects, thus not adapted to interferometers in general. In fact, classical interferometers are still complex instruments with a catastrophic global optical efficiency (about 1%) and by nature with a limited field of view (about 50 mas in K band for 8-m telescopes). However, the observations obtained with VINCI and MIDI on NGC 1068 and with the Keck interferometer on NGC 4151 have clearly proved that next generation long-baseline interferometry will certainly allow us to study nearby galactic centers in more and more details, and 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 both in terms of luminosity ($L = 10^8 - 10^{13} L\odot$) and in terms of spectrum (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. Observationally, the orientation of the AGN with respect to the line of sight is supposed to account for the two main classes, Seyfert 1 (broad emission lines) and Seyfert 2 (narrow lines). The dominating contribution to the Seyfert 1 signal is supposed to come from the so-called Broad Line Region, composed of small high density gas clouds orbiting around the nucleus, with a characteristic size 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 predicted to be surrounded by an obscuring torus of cold gas and dust, the 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 the BLR geometry and kinematics? What is the origin of the BLRs?
- The Obscuring Torus: does it really exist (crucial test of the unified model)? What is its geometry? What is the dust composition?

Two main interferometric modes can be used to characterize galaxies depending on their "activity": the nulling mode is preferable in the case of bright AGNs (Seyfert I), while classical visibility/phase measurements are appropriate for less contrasted objects (Seyfert II). The main requirements concern the sensitivity, which should be around $K = 20$. Large telescopes are therefore required. A good (u, v)-plane coverage is also necessary to provide full imaging capabilities. This requires a consensus to be found between the number and the size of the telescopes. A good spatial resolution (around 0.1 mas) is also mandatory to detail the structure of dust tori (clumpiness, outflow, cavities) and of BLRs. Moreover, the dynamic range will have to be of 100 at least for the detection of circumnuclear components and the spectral resolution should range from 50 (low) to 1000 (medium) for the study of BLRs.

5.2 Techniques and projects

The scientific drivers for a next generation interferometer have various associated requirements, which can be summarized as follows (Léna et al., 2004):

- long baselines from 1 to 10 km are required for resolutions better than 0.1 mas;
- telescopes have to be large enough to go faint, i.e., at least 8-m class to peer up to $K = 20$ (with the help of fringe tracking);
- fringe tracking is a major issue since it is the key to deeper integration on faint objects;
- snapshot imaging capabilities requires a large number of apertures, i.e. at least 10;
- the wavelength coverage should extent from the visible to the thermal infrared with spectroscopic resolutions up to 100,000;
- the field of view has to be sufficient for extended objects such as circumstellar disks, i.e., at least 1 arcsec, but also to allow for fringe tracking on a nearby object (a dual field facility will be of great help);

- last but not least, a high dynamic range is required to beat contrasts up to 10^6 in the thermal infrared.

It is very unlikely that all these constraints can be achieved by one facility. Priorities are therefore absolutely needed, all the more because these requirements are associated with a number of technological challenges that we describe in the next section.

5.2.1 Technological challenges

New generation interferometers will have to face a lot of technological challenges for almost every sub-systems. Many dishes will be needed, involving mass production of mirrors. Synergies with ELT's construction will surely be benefic. Beam transport is another important issue: in this field, R&D is very active and precursors like the 'OHANA project should pave the way to very long baseline fiber linking. Several issues are still to be solved, like the production of loss-less fibers for instance. Still concerning the practical problems of beam propagation, modal filtering in the thermal infrared is currently being developed but further efforts of industry in this sector are required to apply these new technologies on real instruments. Delay line technology for long baselines has to be refined to lower the costs. High performance (rapidity and length) as well as mass production will be needed. Downstream, just before the recombination, beam shaping and achromatic phase shifting have to be further investigated. At the combination stage, several solutions are envisaged, not only to artificially increase the field of view by sampling the focal plane with bundles of fibers, but also to shape the diffraction pattern by remapping the entrance pupil.

Of course, ground-based future facilities will have to overcome the degradation of images due to the atmospheric turbulence. Extreme adaptive optics systems will have to operate very efficiently down to the visible at the lower possible cost. Fringe tracking is another critical topic to be developed. It is indeed mandatory to allow for tracking on faint objects in order to cover the whole sky. In space, technological challenges are the same with some specific and unfortunately severe issues like formation flying which is the key to long baseline space-based interferometers.

Despite these challenges, several groups are proposing new concepts. None of them pretends to solve all the problems at once but focusses instead on very precise objectives.

5.2.2 Ground-based projects

OVLA/ELSA The Optical Very Large Array project (Labeyrie & Mourard, 1990) consists of a kilometric-size optical interferometer composed of 27 or more 1.5-m mobile telescopes designed to provide high-resolution infrared and visible snap-shot images. The Extremely Large Synthesis Array concept (Quirrenbach, 2004) is a similar alternative with larger telescopes (10 m) and a Y-shaped instead of a circular one. Beam transport and combination are implemented in different ways in the two concepts, with air transport vs fiber bundles and with densified vs homothetic mapping.

Carlina The Carlina concept (Labeyrie et al., 2002) is interesting in the sense that it does not need any delay line. Its spherical configuration allows for a direct densified recombination at a common focal plane. It is configured like a diluted version of the Arecibo radio-telescope. Above the diluted primary mirror, made of fixed co-spherical segments, a helium balloon carries a gondola containing the focal optics and detector.

ALADDIN The ALADDIN concept is an integrated Antarctic-based L-band nulling breadboard with relatively modest collectors (1 m) and baselines ($\leq$ 40 m). Because of its privileged location, this is sufficient to achieve a sensitivity (in terms of detectable exozodiacal dust levels) which is 1.6 to 3.5 times better than an equivalent nulling instrument on a large interferometer (such as GENIE at the VLTI), bringing it below the 20-zodi threshold value identified to carry out the DARWIN precursor science. An integrated design would enable top-level optimization and full access to the light collectors for the duration of the experiment, while reducing the complexity of the nulling breadboard.

API The Antarctic Plateau Interferometer (Swain, 2005) is an instrument concept capable of extensive unique discovery space science in a variety of areas, including exoplanets, accretion, YSOs and AGNs. To study exoplanets in the habitable zone, API would use three 2-m class telescopes with high-resolution spectroscopy and differential closure phase to achieve a dynamic range up to 10^5. At Dome C, Antarctica, the combination of low levels of atmospheric turbulence (above the ground layer) and low thermal background enables an interferometer with 2-m class telescopes to exceed substantially the performance of existing instruments. Combining existing interferometer technology (adapted to the Antarctic environment) and containerized packaging would make it possible to begin operation at Dome C in 5 years.

KEOPS The Kiloparsec Explorer for Optical Planet Search (Vakili et al., 2003) is a nulling interferometer to be placed on the Dome C plateau of Antarctica. It consists of an interferometric array of 39 telescopes 1 to 2 m in diameter spread over kilometric baselines and operated in the thermal infrared region. It could search and characterize all potential exoEarths within the 1 kpc diameter region observable from Dome C. Even in the very difficult operation conditions of Antarctica, such a facility could compete with future space missions but at a much lower cost, both for exoplanet studies and for sub-milliarcsecond snap-shot imaging of galactic and extra-galactic compact sources.

5.2.3 Space-based projects

SIM The Space Interferometry Mission (Marr, 2003) is the first space project designed to use 2-telescope interferometry to measure the positions of stars (astrometry). It will do so to a degree of accuracy (a few μas) unprecedented by earlier ground-based or space-based instruments. During the course of its five-year mission, SIM, operating from 450 to 900 nm, will perform a survey of the whole sky, using interferometric techniques to tie the optical reference frame it defines firmly to the radio reference frame already established.

Pegase This is a concept proposed as an answer to the CNES call for ideas for a scientific payload on its Formation Flying technological mission (Ollivier et al., 2005). It consists of a Bracewell interferometer operating in the infrared ($1.5 - 6$ μm) and visible regimes. It has small telescopes (40 cm) but a substantial baseline (25 to 500 m). Its angular resolution reaches 1 mas at 4 microns and 100 micro-arcsecond at 0.4 μm. Its main scientific objectives are the spectroscopic study of low-mass companions including Pegasides (hot giant exoplanets) and brown dwarfs bounded to other stars, with the goal of determining the composition of the atmospheres of these objects as well as their internal structure.

DARWIN/TPF-I DARWIN (Fridlund, 2004) is the ESA mission for Earth-like planet detection and characterization and for the search of biosignatures on these planets. TPF-I is the corresponding project of NASA. It will consist of a 3 to 6 free-flying telescope interferometer in the nulling mode, with baselines ranging from 30 to 500 meters. Low resolution spectroscopy in the 6-18 micron wavelength range should reveal three classical biomarkers: water, ozone and carbon dioxide. A secondary objective of the mission is to carry out imaging of astrophysical objects with unprecedented spatial resolution. The InfraRed Space Interferometer Darwin is an integral part of ESA's Cosmic Vision 2020 plan, intended for a launch towards the middle of the next decade. It has been the subject of a feasibility study and is now undergoing technological development. New designs have recently been proposed for implementation on four spacecrafts and search for planets around a minimum of 165 stars within the mission lifetime.

6 Conclusion

Stellar interferometry has been very successful in the past years, with many exciting scientific results coming from both senior and junior facilities. The advent of a new generation of instruments lets us predict that a bright future is still to come. However, it is shown here that many ambitious scientific cases are still not within reach, and will require new facilities to be designed and built within the next decade. Ideally, they would comprise a whole battery of (movable) 10-m class telescopes arranged over kilometric baselines, capable of surveying the whole sky up to faint magnitudes from the visible to the mid-infrared, with a high spectral resolution and a high dynamic range. Realistically, only some of these requirements will come to reality, because they are all associated with a number of technological challenges. It therefore appears necessary for the European astronomical community to express its needs and expectations in the context of future optical interferometric facilities. We suggest that the choice of scientific and technological priorities should be undertaken, which could eventually lead to a consensus for this new generation facility. The next action would then be to initiate further R&D on the critical issues and design studies for the future array.

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