TECHVIEW: ASTRONOMY

Snapshots of Alien Worlds—The Future of Interferometry

Antoine Labeyrie

The recent discovery of extrasolar planets provides a challenge for astronomers. With current technology, the existence of a planet can only be inferred from the periodic motion of the parent star, detected as a weak Doppler oscillation in the star's spectrum. Little doubt remains about the validity of the interpretation of these observations in terms of extrasolar planets. But, it will not be possible to unambiguously determine the orbital characteristics of these planets and their mass until direct images showing the planet as a faint dot appearing near its parent star are obtained. It will be even more difficult to obtain images at a sufficient resolution to identify features on the planet, such as oceans or continents, that may indicate the presence of photosynthetic life.

Astronomers are increasingly looking to optical and infrared interferometry, ground based and in space, to obtain such images. Ambitious as this goal may be, simulations of hyper-telescope images (Fig. 1) suggest that the required resolution may indeed be achievable with long-baseline interferometers (that is, having widely spaced mirrors).

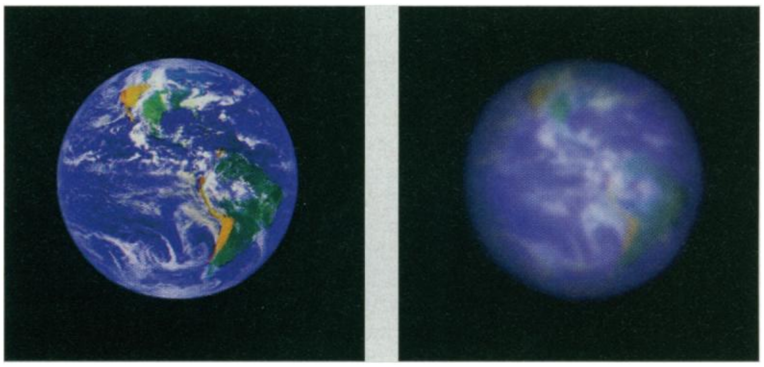

Fig. 1. Simulated image (right) of Earth (starting image on the left) seen from 10 light-years away with the Exo-Earth Imager hyper-telescope. The simulation assumes 150 mirrors (each 3 m in diameter), arrayed in three concentric rings with a total diameter of 150 km, and a single exposure lasting 30 min to freeze the 24-hour rotation of the Earthlike planet. The green color in the Amazon area indicates that photosynthetic life is potentially detectable from such images of extrasolar planets.

In an interferometer, widely separated mirrors capture light from a distant object and combine the light beams from the various mirrors onto a central detector, essentially creating one large light-collecting area with higher resolution than any single mirror on a telescope. Interference between the beams provides information on the phase and coherence structure of the incoming light wavefront and, therefore, on its remote source. First proposed by Fizeau in 1868, the principle was brilliantly exploited in the 1920s by Michelson, whose 6.5- and 17-m optical interferometers at Mount Wilson provided the first measurements of angular diameters of stars, confirming the large size of supergiant stars, such as Betelgeuse, which are hundreds of times as large as the sun.

Radio interferometry has been performed since the 1950s with arrays of antennae on the ground and, more recently, with a radiotelescope in space (*1*), but large-scale interferometric arrays at shorter wavelengths—desirable because they require shorter baselines to achieve the same resolution—proved much harder to achieve. Radio interferometry was easier to implement than optical interferometry because longer wavelengths enhance the geometry tolerance for phasing electromagnetic signals. Also, the existence of detectors with amplifiers preserving the phase information enabled amplified signals to be carried along cables from remote antennae to a central signal correlator. Radio arrays like the Very Large Array (VLA) in New Mexico (*2*), which employs 27 antennae on dozens of kilometers of railway tracks, allow detailed images to be reconstructed from sequences involving different arrangements of the antenna arrays, and radio astronomers have increased the length of their baselines to thousands of kilometers, providing resolution in the milli–arc-second range, 60,000 times better than the angular resolution of the naked human eye.

Over the years, radio interferometry was extended toward shorter and shorter wavelengths, from metric all the way to the far and near infrared. But, the implementation of optical interferometry was still hampered by the turbulence of Earth's atmosphere, which has restricted the imaging resolution of large telescopes. The combination of light beams from widely separated locations was also difficult, because Earth's rotation had to be compensated for and the system geometry had to be controlled very accurately to preserve the light's coherence and phase uniformity. Technical advances and the emergence of observation methods known as speckle interferometry and adaptive optics have, in the past two decades, led to a major breakthrough for optical interferometry, which may transform our vision of the universe.

Optical wavelengths carry more information than longer wavelengths, owing to the higher density of spatiotemporal field modes. The high angular resolution of a micro– to a nano–arc second with 100- to 100,000-km baselines, respectively, which is potentially achievable in optical interferometers at sizes similar to existing radio interferometers, is expected to show fine structure on celestial bodies. This does not only apply to the above-mentioned prospect of imaging extrasolar planets. No usable image of a star's surface (other than the sun's) has yet been obtained, but this should become commonplace with forthcoming interferometers. Such images are of considerable interest for constraining the physical models of stars, especially because the high angular resolution improves the spectroscopic resolution by separating components of spectral lines that originate from different parts of the star and have different wavelength shifts owing to rotation, local motions, convection, turbulence, or magnetic field effects. Detailed images of stars will likely improve our understanding of these diverse objects, including matter transfer and accretion disks on multiple stars.

Extrasolar planets are particularly difficult but fascinating targets. Potentially habitable planets are typically one or several billion times fainter than their parent star at optical wavelength and a few million times fainter in the infrared. With large enough baselines (about 150 km in the visible range) and a sufficient number of subapertures (that is, mirror segments collecting light and channeling it to the central detector), they should nevertheless

The author is at the Collège de France, 11 Place Marcelin Berthelot, 75005 Paris, and the Observatoire de Haute-Provence, 04870 St.Michel l'Observatoire, France. E-mail: labeyrie@obs-hp.fr

become imageable at a resolution that is high enough to see landmasses and photosynthesis signatures. Optical wavelengths provide information on chemical and photochemical processes activated by radiation temperatures of a few thousand kelvin. Life on Earth involves such chemistry and photochemistry, which may be detectable on extrasolar planets from chlorophyll-like absorption bands.

Producing images of extrasolar planets with radio arrays such as those in New Mexico would require baselines longer than a million kilometers, which is impractical. In contrast, at optical wavelengths resolving a 1000-km chunk of the Amazon forest at a distance of 30 light-years (10^{14} km) requires a resolution of 0.7 micro–arc sec, attainable in yellow light (wavelength 500 nm) with an interferometer with a baseline of 150 km. For light at a wavelength of 10 μm, the required baseline is 3000 km. Existing optical interferometers on Earth have baselines on the order of 100 m, and may reach a kilometer within the next decade.

A 5000-km infrared baseline is planned by NASA for its Terrestrial Planet Imager concept, involving two clusters of 8-m-aperture telescopes. Sequences of observations with different spacings of the clusters are expected to provide resolved infrared images of extrasolar planets. Precursor missions, defined in NASA's Origins program, are as follows: (i) The Space Interferometry Mission, utilizing several small mirrors carried by a 20-m truss, currently under development at Jet Propulsion Laboratory. (ii) The Terrestrial Planet Finder (TPF), expected to detect extrasolar planets with diameters similar to Earth's at 10 μm with a 100-m baseline (*3*, *4*). The European Space Agency (ESA) is also studying a similar infrared interferometer, the Infra-Red Space Interferometer (IRSI), but with separate free-flying units (called free flyers) carrying the elements (*5*). NASA and ESA have recently decided to merge both projects for a possible launch in 2012. (iii) Space Technology–3 (ST-3), scheduled to fly in 2003 to test space interferometry with free-flyer elements. This mission is modest in cost but important as a proof of concept; it involves a pair of 15-cm mirrors flying 1 km apart. Once free-flyer arrays are validated, array sizes may be increased to several hundred kilometers within a few years. The delicate control technology needed for stabilizing free-flyer arrays and shaping them with nanometric accuracy is not significantly affected by the size of the array.

Taking these considerations one step further, I now consider the possibility of a new instrument class (*6*, *7*), which may be called a "hyper-telescope," in which many mirror segments, spaced kilometers apart but only meters in diameter, can form a "sparse giant mirror" spanning hundreds or thousands of kilometers. These segments focus light toward a secondary optical system (Fig. 2), which compresses the light beams and produces a directly usable combined image. Under such conditions, an infinite number of vanishingly small apertures tend to form the same image as a giant filled telescope of identical size, although with a lower luminosity. With fewer, and larger, subapertures, the image has an envelope, or window, limiting the field size. The maximal number of resolved pixels in the image area equals the number of subapertures or its square, depending on whether the aperture elements are arrayed as a grid or along a ring. The Exo-Earth Imager (EEI) represents such a hyper-telescope, which should be capable of providing extrasolar planet images (Fig. 1). Hyper-telescope models are being tested in our laboratory at the Observatoire de Haute-Provence (*8*), and the following ground-based precursors of space versions are now being considered: (i) CARLINA, named after a composite alpine flower, a 100-element hyper-telescope with a diameter of 200 m, shaped somewhat like the Arecibo radio telescope and (ii) the Optical Very Large Array project, which is currently being upgraded to incorporate the hyper-telescope concept, consists of 27 telescopes that have mirror diameters of 1.5 m and are mobile across a platform of 10 km. A prototype unit is approaching completion at Haute Provence.

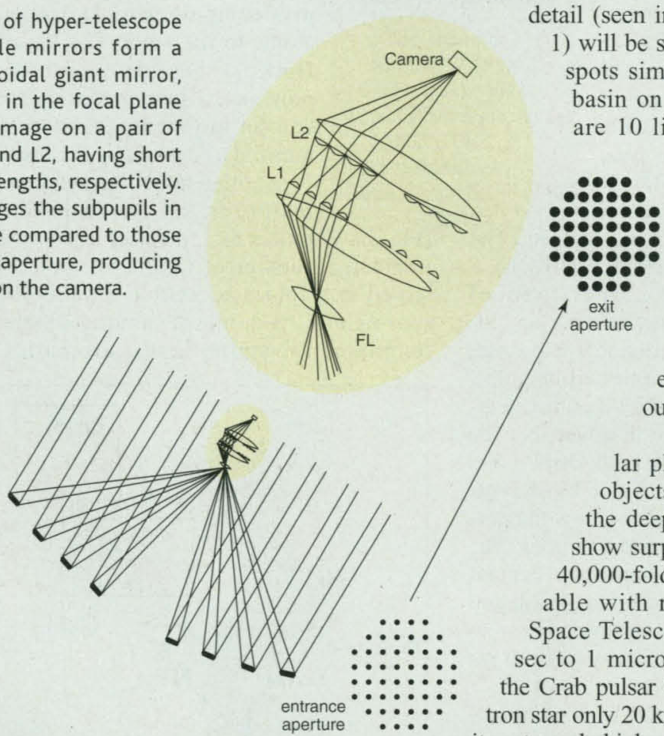

Fig. 2. Example of hyper-telescope optics. Multiple mirrors form a sparse paraboloidal giant mirror, and a lens (FL) in the focal plane forms a pupil image on a pair of lens arrays L1 and L2, having short and long focal lengths, respectively. This setup enlarges the subpupils in the exit aperture compared to those in the entrance aperture, producing a usable image on the camera.

A space-based hyper-telescope version is also proposed for the TPF/IRSI mission. Called the Exo-Earth Discoverer (EED), it can improve the sensitivity for detecting extrasolar planets, with its 36 mirrors of 0.6-m diameter providing the same collecting area as the IRSI.

When hyper-telescopes like the EEI exceed 100 km in diameter, the level of detail (seen in the simulation of Fig. 1) will be sufficient to detect green spots similar to Earth's Amazon basin on extrasolar planets that are 10 light-years from Earth. The detection of such spots, which are not necessarily green, and their seasonal changes would provide evidence for whether photosynthetic life similar to life on Earth exists on other planets outside our solar system.

In addition to extrasolar planets, billions of other objects will be observable in the deeper cosmos. Some may show surprising details, given the 40,000-fold resolution gain achievable with respect to the Hubble Space Telescope, from 40 milli–arc sec to 1 micro–arc sec. For example, the Crab pulsar is believed to be a neutron star only 20 km in size, but because of its extremely high surface brightness, hyper-telescopes as large as 300,000 km would be required to obtain resolved images. Hyper-telescope images may also provide further insights into the properties of matter and space-time in objects where extreme physical conditions prevail.

References and Notes

1. See, for example, http://www.gb.nrao.edu/ovlbi/pressRelease/press97july.html, on the radio interferometer made by combining the signals from HALCA, an orbiting spacecraft with a radio telescope, with those from radio telescopes on the ground.
2. See www.nrao.edu/vla/html/VLAhome.shtml
3. J. R. P. Angel and N. J. Woolf, *Astrophys. J.* **475**, 373 (1997).
4. C. A. Beichman, N. J. Woolf, C. A. Lindensmith, *JPL Publ. 99-3* (1996).
5. A. Léger *et al.*, *Icarus* **123**, 249 (1996).
6. A. Labeyrie, *Astron. Astrophys. Suppl. Ser.* **118**, 571 (1996).
7. ———, paper presented at the Dana Point Conference, "Working on the Fringe," Dana, CA, 24 to 27 May 1999.
8. See www.obs-hp.fr/~laberyrie/index.html for information on recent interferometry papers and projects at the Observatoire Haute-Provence.