Course B

Astrometry and Interferometry

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Introduction

The subject of the course B workshop was the Astrometry and Interferometry cornerstone mission of Ilorizon 2000 plus. According to the Horizon 2000 plus report there are two candidate missions for this cornerstone. The first is an astrometric mission with 10 microarcsecond capability, addressing a wide range of astronomical issues. The second is an infrared interferometer with the principle purpose of detecting planets around other stars. For this workshop we have addressed the common objective of these two missions, namely the detection of planets. We have also broadened the subject to a review of other techniques including those from the ground.

After a few decades of solar system exploration, we seem to be at the dawn of the discovery of other planetary systems possibly similar to our own, which may in itself sound extraordinary. As instruments making use of new techniques are being built and proposed, many fundamental questions arise. The essential one seems to concern the nature of the planetary system or more precisely of the "exoplanet" that we may search for. The planets of our own system are divided into two categories - inner and outer planets- and it seems natural to choose our earth as representing the first category and the Giant planet Jupiter for the second one. The second question that comes to mind is whether or not life could exist on these planets and could it then be detected by these instruments ? In our current state of knowledge, it is believed that carbon-based life is more likely to happen on an earth-like planet. Therefore, the mere detection of a Jupiter-like planet would not inform us on the existence of any extra-terrestrial life form. It is important to note that the detection of an earth-like planet, if strengthened by spectroscopic data on the composition of its atmosphere would be a good indication of the presence of life. The detection is direct or indirect depending on whether a signal emitted by the planet is observed or only indirect effects induced by the presence of the planet are observed. Some of these techniques are already being use on the ground: a giant step towards the detection of exoplanets was taken when an accretion disk around a star, ß Pictoris, which is believed to host a Uranus-like planet, was first observed. The quest for new planetary systems would enter a new era with the launch of space-based instruments.

I. Direct detection techniques.

With these techniques, a signal coming directly from the exoplanet is looked for. The proper emission of the planet is generally extremely weak compared to the star. However, this difficulty could possibly be overcome in the optical and infrared domain and avoided when switching to very low frequencies.

1. Optical imaging

Figure 1 shows the flux of a Sun-like star and of an earth-like planet in a broad

domain of the electromagnetic spectrum, from the ultraviolet to the far infrared. At visible wavelengths, the brightness of the star is about 10 orders of magnitude greater than that of the planet and about a billion times greater than the brightness of a Jupiter-like planet.

The direct optical imaging method nevertheless aims at Producing an image of a sufficiently bright planet, i.e. a jupiter-like planet, by attenuating the star light by. several orders of magnitude. The use of a stellar coronograph to mask off the signal from the star seems compulsory but is not at all sufficient because of scattering effects due to non-perfect optical surfaces. If observed from the ground, atmospheric effects would furthermore require powerfuladaptive optics for their correction, hence the advantage of bringing the instrument up to space. In that case, active optics correcting the optical defects of the surfaces, along with image analysis algorithms, could considerably reduce the ratio between star and planet signals to a somewhat acceptable level for detection. Indeed, a method using a 37x37 deformable mirror corrected at a slow rate (0.1-0.001 Hz) has been proposed for which the achieved dynamic range is of the order of 10^8 at a wavelength of 0.8 μm, thus opening the possibility to detect Jupiter-Sun systems with sufficiently long integration time. An interesting alternative solution using a distant stellar occulter located on a separate spacecraft has also been proposed as a result of this workshop.

2. Infrared interferometry

The relative brightness of the star and the orbiting planet is reduced by 3 orders of magnitude when switching to infrared observations, at a working wavelength of 10 μm. The immediate downside of this choice is the need for a larger instrument since longer wavelength implies lower resolution for a given size of the instrument. A diameter of about 30 meters is then required to resolve a planetary system similar to ours located at 10 parsecs (pc), making an interferometer the logical choice. The method proposed in order to deal with the still prohibitive ratio of brightnesses is the use of a nulling multi-aperture interferometer which works as a coronograph: the wavefronts coming from a pair of apertures are de-phased by half a wavelength before being re-combined. This would result in an interference pattern that has a null only on axis but which keeps the off axis sources signal at a normal level. The light from the star is then masked off and nearby orbiting objects could be seen. By varying either the baseline of the interferometer or the wavelength, one could detect earth-like planets located from 0.5 to 1.5 astronomical units (AU) from the central star.

To avoid perturbations from the zodiacal light of our solar system, the instrument should be placed at least 4 AU from the Sun. In these conditions, the instrument could not only detect earth-like plane but, if completed by a spectrometer operating in the infrared as well, could also provide information on the composition of the atmosphere of the planet, looking in particular for H2O, CO2 and 03 spectral features, which are believed to be good indicators of life.

3. Very Low Frequency observation

Radio astronomers have been trying to detect artificial signals sent by other life forms for a few decades already. The low frequency part of the electromagnetic spectrum (500 kHz - 30 MHz) seems particularly interesting for the search for exoplanets since the emission of Jupiter in this range exceeds the emission of the Sun, when in a quiet stage, by more than 6 orders of magnitude. Figure 2 shows the relative intensity of these emissions, as well as from other types of planets. However, the signal from potential planets can be swamped by a solar burst which makes it sensible to have the observations begin during a quiet solar cycle. The instrument would consist of an array of short dipoles operating at 20 MHz (l=15 m). A few hundred lightweight dipoles arranged over a circular area of 500 m diameter appears as a good compromise in terms of signal-to-noise ratio and resolution, as both scale with the inverse of the largest separation between two dipoles (the so-called diameter of the array), and would be necessary to obtain a sufficient collecting area. Each element of the array observes isotropically and should therefore be adecluately located so as to minimize the emissions from our own solar system: a distance of 2 AU from our planet seems reasonable,:an alternative solution being the dark side of tie moon. The array would then conduct a surveyof the sky over patches of several square-araminutes and should detect the signal coming from a strongly magnetized planet similar to Jupiter. A problem that arises is the number of candidate stars located in this wide field. In the eventuality that a strong signal is detected, one would have to carefully discriminate among these candidates by looking at their distances, hopefully given by a catalog such as that provided by Hipparcos.

II. Indirect detection techniques.

The three techniques reviewed here cover a broad domain of astronomical methods: astrometry, spectroscopy and photometry.

1, Astrometry

A planet orbiting around a star slightly perturbs the star itself. The astrometric detection method aims at obsenring these non-linear wobbles. The amplitude of such a perturbation for a Sun-Jupiter system located 10 pc away is 500 micro-arcseconds (μas), way within the 10 μas nominal accuracy that a space-based interferometer like GAIA would reach for positions and proper-motions. GAIA could survey several hundred thousand candidates stars with a wide range of distances and planetary system characteristics. However, the detection of an earth-like planet orbiting around a Sun-like star at 10 pc requires an astrometric accuracy of 0.3 Iras which is believed can not be reached. Figure 3 shows an interesting way to look at the problem: considering a planet of the mass of Jupiter (a thousandth of the solar mass) and a wobble due to the presence of this planet of 30 μas, i.e. the worst expected case, we look at the maximum distances up to which one could expect a detection, for various orbital periods of the planet, with respect to the mass of the central star. For a mass of the central main sequence star greater than

0.6 solar mass, Jupiter-sized planets with orbital period of 5 years could be detected out to 150 pc representing a search volume inwhich around 200,000 candidate stars lie.

Recent developments in ground-based interferometric astrometry have shown that the atmospheric error on a differential measurement is significantly reduced when operating over very narrow-angles (20 arcseconds) with a very long baseline interferometer (100 m). It could then reach the 30 yas level on stars as faiat as magnitude 15. Operating in the infrared (2.2 μm), so that both the target and the reference star lie within the isoplanatic patch, the Palomar Testbed Interferometer will do a deep survey on about 200 stars during 10 years and could detect a Jupiter-like planet located out to 7 AU from the star.

2. Radial velocities

Along with variations on the position of the star as described in the previous section, the presence of a planet will affect its radial velocity (the proper motion of the star along its line of sight). This change in' radial velocity depends on the period of the planet, its mass and the inclination of the orbit with respect to our line of sight. Therefore, very accurate spectroscopic Doppler measurements, in the range of 5-10 m.s-1, would be able to detect a Jupiter-sized planet around various types of stars located at 10 pc. Existing ground-based instruments already achieve this accuracy for bright stars. Efforts are being made so as to extend these results to dimmer stars, by means of larger apertures, higher photon sensitivity and longer integration time. Radial velocities represent an extremely important astrometric parameter, leading to the third dimension for proper motions of stars: their observations from the ground could complement a space astrometric mission such as GAIA which will already provide five astrometric parameters per star, two for positions, two for proper motions and one for parallaxes.

3. Planet transit

This method aims at detecting the variations of the flwe coming from a star that would occur during the transit of a planet in its line of sight. The geometrical probability that a transit could actually be observed when a planet is present around a star is 0.5 %. The three essential parameters of this technique are the value of the drop in the photometric flux, its duration and its period of occurrence. This last parameter restricts the detection to earth-like planets for which the orbital period is of the order of a year, for obvious reasons of logistics. The method is then well suited for the detection of terrestrial planets and could be conducted over 6 years, on 8000 candidates with a 9x9 square-degrees Schmidt camera. The reduction of the star flux is proportional to the ratio of the square of the apparent angular diameter of the planet to that of the star. For an earth-like planet orbiting around a G type star such as our Sun, located 10 pc away, the duration of the transit would be of the order a few tens of hours (5-30 hours).

One of the main problems of this technique is the distinction between stellar variations such as Sun spots from the actual transit of a planet. A way to overcome

this would be to Perform multi-color photometry, as a true transit should have no color bias. Because continuous observation during several years is required in order to detect these transits, the instrument should be sent to space.

The relative capabilities and merits of each technique are given in Table 1. After careful considerations, a proposed strategy for implementing a program for the detection of extra-solar planets has been derived. This strategy is compatible with the Horizon 2000 plus program but also assumes cooperation with other space agencies. Central to this program is the launch of a global astrometric mission with 10 μas accuracy as cornerstone 5.