EXTRA-SOLAR PLANET DETECTION

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ABSTRACT

Since the discovery in 1995, extrasolar planets become a central topic in astronomy. In this review, briefly summarized are various methods for indirect detection of planets around nearby stars and related future projects. The difficulties associated with the direct detection, the next milestone in extrasolar planet studies, are discussed. A NASA's approach for detecting and characterizing terrestrial extrasolar planets, TPF, is introduced. The Japanese working group for planet finding projects and its activities are also explained.

(Key words: astronomy, extrasolar planets, optical/infrared, coronagraph, interferometer)

1. Introduction

The existence of extrasolar planets (ESPs), planets orbiting the normal stars other than our Sun, is now established by many observations since its first discovery by the Doppler velocity method in 1995. As of May 2002, about 80 Jupiter-like giant planets have been discovered. Encouraged with these successes, a number of ESP discovery programs are in progress and planned from ground and in space. However, most of these detection methods are "indirect", not directly imaging the planets or obtaining their spectra. The next milestone thus should be the "direct" observations of ESP. The direct detection of giant planets like Jupiter is considered to be one of the most important themes for the 8-10 m class ground-based telescopes currently under regular operations. However, finding small and light-weight planets like our Earth is extremely difficult even with the indirect methods (note that the mass of Jupiter, the largest planet in our solar system, is about 1/1000 of that of the Sun, while the mass of the Earth is only about 1/300 of that of Jupiter.) The TPF (Terrestrial Planet Finder) mission, now under consideration by NASA, will challenge this most difficult task, the direct detection and characterization of extra-terrestrial planets. TPF will detect the light from Earth-like planets in the "habitable zone" around about 150 main sequence stars near the Sun, either via reflection of the central star light or thermal emission from the planet itself. Then TPF will elaborate the orbital and other physical properties including their atmosphere, and try to detect any signs of life. Several architectures to achieve these aims have been reviewed. The most promising appears to be the space interferometry at infrared wavelengths and space coronagraphy at optical wavelengths.

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2. Methods of extrasolar planet detections

Due to the orbital motion of planet(s), the central star is dynamically affected, which results in a periodical change of the position and velocity of the central star. The astrometry is to precisely measure the positional change of the central star and to show the presence of the planet(s). This is one of the oldest methods in search for extrasolar planets. However, the planets implied by astrometry via tens of years' measurements had been denied by later independent measurements. The main reason is that the necessary astrometry accuracy is much smaller than the atmospheric seeing fluctuations of our Earth. For example, if we look at our solar system from a distance of about 33 light years (10 parsec), the Sun wobbles by 0.5 milli-arcseconds due to the orbital motion of Jupiter. The dynamical effect of the Earth is much smaller, about 1/300 of that of Jupiter, which requires an accuracy of a few "micro"-arcseconds. Such a high accuracy astrometry is only possible from space where there are no atmospheric fluctuations. It should also be noted that the astrometry of ESPs distant from the central star needs a long time span, which is difficult to be confirmed. There are several futuree astrometry missions to search for terrestrial planets: the NASA/SIM mission planned to be launched in around 2010 and the ESA/GAIA mission in around 2010-12.

The radial velocity method (a.k.a. the Doppler method) is to measure the velocity shift of the central star due to the orbital motion of planets. This has been the most successful method since the discovery of periodical velocity variations of 51 Peg in 1995 [1]. In our solar system, the velocity shift of the Sun due to Jupiter's motion is 13 m/s, thus the accuracy of a few m/s is necessary for detecting giant planets. Currently an accuracy of 1 to a few m/s is achieved. There was a debate on the interpretation of this velocity shift: it could be 'intrinsic' to the central star such as stellar pulsations. However, an independent method, the transit method, has recently detected a decrease of stellar brightness by about 2% toward HD209458, synchronized with the radial velocity variation [2]. These observations have beyond doubt established the existence of extrasolar planets around normal stars.

The transit method is relatively simple, thus a number of observations are currently conducted from ground. However, the photometric accuracy is limited by the atmospheric seeing. The required accuracy to detect the Earth-like planets is about 0.01%. To overcome this, photometry from space is needed. The planned space transit searches include COROT (France, launch planned in 2004), Kepler (USA, 2007-8, recently approved as a NASA Discovery mission), and Eddington (ESA).

Other indirect methods include the gravitational lensing and the pulsar timing method, both of which are not discussed here. Readers are encouraged to see the following review article [3].

As introduced above, the indirect searches for extrasolar planets have been successful for the last several years. As a natural next step, a race of the direct searches for Jupiter-like and Earth-like planets is started.

3. Difficulties in Direct Detection of Extrasolar Planets

There are a number of obstacles to the step of direct detection of Earth-like planets apart from Jupiter-like giant planets. This is because it requires to simultaneously achieve the following factors: (1) a very high sensitivity,

(2) a sharp image (a high spatial resolution), (3) and an ability to study faint object in the vicinity of bright objects (dynamic range). As an illustration, if we see our solar system at a distance of 33 light years, the brightness of the Earth is about 29 mag in V-band (at a wavelength of 0.6 micron) and about 20 mag in N-band (10 micron). The angular distance between the Earth and the Sun is 0.1 arcsec (1/36000 degrees). It is not always difficult to achieve these values if they are independent with each other. For example, the sensitivity is comparable to that obtained by the optical instrument on the Subaru telescope in 3 hours (integration time), while the angular resolution is comparable or less than that obtained with the adaptive optics on the Subaru telescope. The most problematic is the contrast ratio between the Sun and the Earth. The spectral energy distribution of the Earth is dominated by the reflection of the solar spectrum between the optical wavelengths of 0.4 and 1 micron (till the near-infrared wavelength of about 3 micron), while it is dominated by the thermal emission of the planet itself at the mid-infrared wavelengths of 7 and 17 micron and longer. The brightness ratio is about 10,000,000,000 at V and about 10,000,000 at N. There are currently no astronomical instruments to achieve this dynamic range at the small angular separation above.

The reduction of the dynamic range problem at mid-infrared wavelengths mentioned above is indeed attractive over the optical wavelengths for the extrasolar planet detection. However, the angular resolution decreases as the observed wavelength increases. Therefore, the interferometer (with smaller telescopes separated apart) is more attractive than a single large mirror telescope. In addition, in order to get rid of the thermal noises of the Earth atmosphere, telescope, and instrument, and to achieve a very high sensitivity, it is necessary to conduct the observations from space rather than from ground. This is the basic requirement of the space infrared interferometer idea. It should also be noteworthy that the absorption bands of oxygen (9.6 micron ozone) and water (6-8 microns) are readily detectable as tracers of the Earth-like atmosphere. The original idea of the NASA/TPF was based on these discussions [4]. However, there are several possible problems. One is the effect of “zodiacal light” both in our solar system and in the target system, which could be the main source of the background noise in the infrared observations. The zodiacal dust is a byproduct of the planetary formation, thus might be ubiquitous in any planetary systems. The amount of dust appears vary from system to system. So, it is imperative to access the effect of zodiacal and exo-zodiacal light from the near-future IR missions. The ISAS ASTRO-F mission to be launched at the beginning of 2004 will conduct observations of infrared-excesses of various types of stars and is expected to statistically reveal the evolution of circumstellar dust. Another problem is the technical difficulties associated with the space infrared interferometry. The feasibility could be higher for the more recently proposed optical coronagraph (see Chapter 4). Therefore, we are again at the starting point of the discussion whether the extrasolar planet should be detected via reflected light or thermal emission.

4. Status of TPF and JTPF working group

The original idea of the NASA/TPF in 1999 was a space infrared interferometer with 4 telescopes of 3.5-m mirror lined-up on the baseline of 75-m to 1 km. The wavelength coverage is from 3 to 30 microns. Furthermore, it makes use of the “nulling” interferometry [5]. In contrast to the conventional interferomtry, this approach cancels the interference of light from the object on the symmetrical (rotation) axis of the interferometer, while the light from nearby objects (such as planets) are not canceled. This is a key technique to achieve the necessary dynamic range for planet detection. This ambitious idea is now regarded as the "classical" TPF. Since then, the associated technical difficulties are re-considered and several new ideas emerged. For about 2 years, 4 teams comprising of companies and academia independently considered a number of possible architectures, and presented a Preliminary and Final Architecture Reviews in 2000 and 2001, respectively. As a result, two architectures, infrared interferometer and optical coronagraph, are chosen for the further considerations. A launch target of the NASA/TPF is around 2014.

Interests in extrasolar planet detection are also high in Japan. One reason might be that a direct detection of young giant planet becomes feasible with the completion of the Subaru 8-m telescope. For example, an infrared coronagraph CIAO [6] suitable for observing a faint object very near a bright young star will be useful for young Jupiter-like planets in nearby star forming regions. Several indirect EPS detection approaches with the Subaru telescope are also planned.

SPICA (Space Infrared Telescope for Cosmology and Astrophysics) is a proposed Japanese mission as a next generation infrared mission [7]. One of the scientific aims of SPICA is to detect and characterize outer giant planets, if any. As stated, the dynamic range problem is eased at infrared wavelengths. By making use of the large diameter (3.5-m) of SPICA and a sophisticated coronagraph, it is expected to directly detect and make spectroscopy of the outer planets of nearest stars [8]. A launch target of SPICA is around 2010.

It is without saying that the Japanese theoretical groups in planets and planetary formation have been very active.

If any Jupiter-like planets are discovered in such ways, the next step will be the direct detection of the Earth-like planets with possible signs of life. A working group to discuss such a Japanese mission (JTPF-WG) has been setup under these circumstances [9]. The WG currently discusses several possibilities: one is the optical/near-infrared coronagraph with a medium size (3-4m) telescope and another is interferometer with some original idea. Any international collaboration or possible joining in the TPF is also discussed.

Such an "optical/near-infrared" space telescope could be a natural extension of the planned "infrared" SPICA telescope. It could not only detect and characterize the Earth-like planets around nearest stars but also be used as a general 3-4 m optical telescope, such facilities the Japanese astronomers currently do not have. The contributions to general astronomy and planetary science will be thus tremendous.

The extrasolar planet detection is no more astronomy-proper problem. It is the common targets for planetary science, Earth science, biology, and technology. Any Japanese researchers who have an interest are encouraged to join the discussion on this challenging but possibly historical mission.

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