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SEARCH FOR EXTRA-SOLAR PLANETS

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Abstract. A number of different observational techniques are used today for the detection of planets beyond our solar system. Most of them are indirect methods, based on dynamical or photometric effects induced by the planet and measured on the parent star. The most successful technique so far has been the Doppler (radial-velocity) method, based on precise measurements of small variations in the radial velocity of the parent star. About one hundred extra-solar planets have been discovered by this technique. Other methods are based on astrometric measurements, direct imaging, photometry, interferometry and gravitational microlensing. Some of these techniques are already able to produce positive results, but many of them are future projects needing more advanced instrumentation. In this paper the most important techniques for extra-solar planet detection will be reviewed and their results summarized. In the second part, two different projects carried out at Mt John University Observatory, Lake Tekapo, New Zealand will be presented, both involved in planet hunting. One is the HERCULES radial-velocity programme and the other is the MOA microlensing project.

1. INTRODUCTION

The search for planets orbiting stars other than our own Sun has become some sort of scientific 'holy grail' quest of modern days. It is one of those 'hot' areas of astronomy that attract not only the scientists, but also a wide variety of star-gazers and others who might throw occasional looks at the sky wondering about other worlds. Any discovery of a new planet around some distant star is very likely to find its way to the media, as well. It is not difficult to understand this, since finding planets around other stars might help answering the ultimate question: "are we alone?".

The actual direct detection of an extra-solar planet is still an extremely difficult task, since a typical planet can be billions of times fainter than its host star, while the angular separation between the two bodies is not likely to be larger than a few seconds of arc. However, a number of indirect methods, based on the dynamical perturbation of the star by the orbiting planet, on planetary transits, or on gravitational microlensing, have been developed in recent years. Some of these methods have been successful and the list of extra-solar planets detected is now rapidly growing.

At the time of this Conference (October 2002), the total number of planets detected around stars other than our own Sun is 101, as given in *The Extrasolar Planets Encyclopedia* by Jean Schneider at *www.obspm.fr/encycl/catalog.html*. These planets belong to 87 planetary systems, of which 11 are multiple.

Most of the material on various detection methods found in this presentation has been taken from an excellent review paper on extra-solar planets by Perryman (2000). The same review gives also an extensive historical account on the subject and additional technical and scientific details on existing and future projects in this area.

2. DETECTION METHODS

There is a number of slightly different ways of classifying the extra-solar planet detection methods. For example, Perryman (2000) introduces three main groups of detection methods, based on: dynamical effects, gravitational microlensing and photometric signal. These three general groups are further divided into more specific techniques, so that, for example, both the radial-velocity and astrometric methods are derived from the dynamical effects, while the direct imaging and transit methods belong to photometry.

In this presentation we are going to use a somewhat simplified classification consisting of the following five detection methods:

- Direct imaging
- Radial-velocity method
- Astrometric method
- Transit photometry
- Gravitational microlensing

2. 1. DIRECT IMAGING

Imaging of an extra-solar planet here refers to the detection of a *point source* image of the object seen in the reflected light from the parent star. This is very difficult to achieve due to a huge brightness ratio and small angular separation between the star and the planet. Sophisticated observational techniques and data reduction procedures have to be applied in order to make the actual detection possible. No success using this method has been reported so far. The most prospective are projects based on interferometry from space.

2. 2. RADIAL-VELOCITY METHOD

This method is based on measuring small variations in the radial velocity of the parent star, induced by the orbital motion of one or more planets surrounding the star. This has, practically, been the only working method for the detection of extra-solar planets so far. A typical Jupiter-size planet moving around a solar-type star at a distance of a few astronomical units would produce a periodic perturbation in the stellar radial velocity of the order of a few times 10^1 or 10^2 metres per second, which is quite possible to detect with modern instruments (a typical precision of radial velocity measurements today can be as high as 5 m/s, or even better). The first planet around a solar-type star, 51 Pegasi, was detected by Mayor & Queloz (1995) using this technique. The discovery was announced after 18 months of precise

Doppler measurements made with the ELODIE spectrograph of the Observatoire de Haute-Provence. The planet has a mass of about 0.5 Jupiter masses and it moves in a circular orbit at about 0.052 AU from the parent star. A number of other research groups all over the world have also been successful in discovering planets around other stars, such as 47 UMa (Butler & Marcy 1996), 70 Vir (Marcy & Butler 1996), υ And (Butler et al. 1997,1999), HD 75289 (Udry et al. 2000) and others. At present, only massive planets in close orbits are likely to be detected. A much higher precision is needed for less massive planets and planets moving in larger orbits. One should note here that our own Sun exhibits radial velocity oscillations of only 10–15 m/s, mainly caused by the Jupiter revolving at about 5 AU.

2. 3. ASTROMETRIC METHOD

The astrometric method is based on the same dynamical effect as the radial-velocity technique, namely on the reflex motion of the parent star induced by the orbital motion of the planet. However, this time the effect is monitored in the stellar proper motion as a periodic wobble around the expected linear motion. In order to be able to detect such perturbations, astrometric measurements of very high precision are needed. As an illustration, our own Sun would exhibit variations of only 0.5 mas, caused mainly by the Jupiter, when viewed from a distance of 10 pc. in the same example, the effect of the Earth at 10 pc is only 0.3 μas. Numerous astrometric projects for the future offer precision high enough for this technique to really work. So far it has not been successful.

2. 4. TRANSIT METHOD

When a planet moves in an edge-on orbit (i.e. perpendicular to the plane of sky), periodic transits will occur producing small dips in the photometric signal from the parent star. The variations are typically of the order of a few per cent, so that high precision photometry is required. An example of this technique working is the confirmation of a planetary companion to HD 209458 by Charbonneau (2000). The star had already been known to have a planet, as it was discovered by Henry et al. (2000) using the radial-velocity technique.

2. 5. GRAVITATIONAL MICROLENSING

The gravitational lensing effect is based on the deflection of light in the field of gravity of a massive object, as described by Einstein's general relativity. The term *microlensing* is used when the actual lens is a star. In a typical configuration, the *lensing star* can be several kiloparsecs away and it is too faint to be seen. On the other hand, the *source star*, if it happens to be a super-giant, can be seen even if it is a few kiloparsecs further behind the lens. In this geometry, there will be two images of the source generated by the lens. As the source star moves with respect to the lens, the two images move and change their shapes, as shown in Fig. 1.

In practice, the individual images are not resolved and only the integral light is detected in a form of a characteristic light curve. If the lensing star is surrounded by planets, the light curve may get perturbed, depending on the actual geometry. This enables the detection of planets over a wide range of masses. So far there have been reported some possible candidates for planetary microlensing events (Bond et al. 2002).

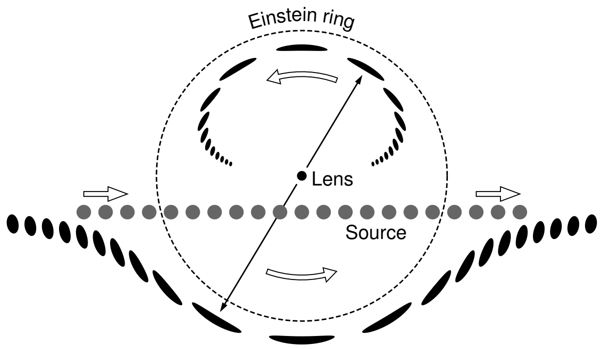

Figure 1: Microlensing by a single star. Two oval-shaped images of a distant source star are generated. At any given time the two images are aligned with the source and the lens.

3. PLANET HUNTING IN NEW ZEALAND

Two different research programs currently carried out in New Zealand will be presented in the following two sections, both in the field of extra-solar planet detection:

- Project MOA
- Project HERCULES

The first one is based on gravitational microlensing, while the second one is a radial-velocity project.

4. PROJECT MOA

MOA (Microlensing Observations in Astrophysics) is a collaboration programme involving astronomers from Japan and New Zealand. The observations are made from Mt John University Observatory (MJUO) in New Zealand using a 60-cm Boller & Chivens telescope at f6.25 and a mosaic 6K $\times$ 4K CCD camera covering a field of view of $83' \times 55'$. A number of fields towards the Galactic bulge are observed covering a total area of ~ 17 deg^2. The data reduction process is based on difference imaging photometry (Bond et al. 2001). Further analysis of microlensing light curves and search for possible planetary companions is made at the University of Auckland, using a cluster of over 200 PCs working together as a single super-computer. The light curves are analysed using the inverse ray-shooting algorithm and the actual code has been optimized taking into account some special properties of the microlensing mapping function (Rattenbury et al. 2002).

An example of a possible planetary microlensing event, as analysed by MOA (Bond et al. 2002) is MACHO 98-BLG-35, shown in Fig. 2. The mass of the planet is $q = 1.3 \times 10^{-5}$, relative to the mass of the central star.

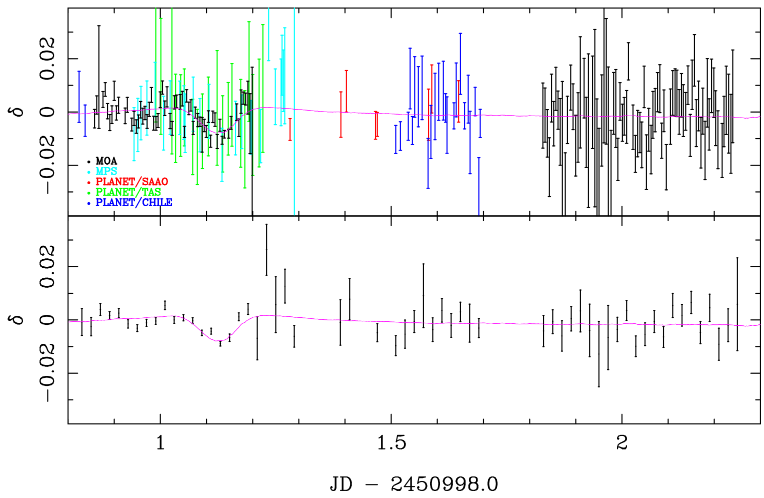

Figure 2: MACHO 98-BLG-35 as a possible planetary microlensing event. The data points represent residuals after the single-lens fit has been subtracted. The continuous line shows the best fit assuming one planet orbiting the star.

5. PROJECT HERCULES

A new high-resolution spectrograph called HERCULES has been installed at Mt John University Observatory, to be used on the 1-m telescope (Hearnshaw et al. 2002). A 1024×1024 SITe CCD camera is currently used as a detector in four different spectral regions.

Over the past twelve months a large number of stellar spectra has been collected and a dedicated reduction software package has been developed. Some preliminary analysis of the results has been made in order to examine the overall stability and final precision of stellar velocities obtained with this spectrograph.

5. 1. SPECTROGRAPH DESCRIPTION

The High Efficiency and Resolution Canterbury University Large Echelle Spectrograph (HERCULES) is a fibre-fed échelle spectrograph that was designed and built at the University of Canterbury and has been in operation at Mt John University Observatory since April 2001 (Hearnshaw et al. 2002). HERCULES receives light from the f/13.5 Cassegrain focus of the 1-m McLellan telescope. Resolving powers of $R = 41\,000$, $70\,000$ and $80\,000$ are available, depending on the optical fibre used (100-μm with no slit, 100-μm with a 50-μm slit and 50-μm with no slit). An R2 200×400-mm échelle grating provides dispersion, while a large BK7 prism is used for cross-dispersion in double pass. The spectrograph has no moving parts except for the positioning and focusing of the CCD. The wavelength coverage is designed to be 380–880 nm in a single exposure on a 50×50-mm CCD chip. The maximum efficiency of the whole system (fibre, spectrograph and detector) is about 18% in 2 arc second seeing. The whole instrument is installed in a large vacuum tank at 2–4 torr. The tank is in a thermally isolated and insulated environment.

Table 1: HERCULES specifications

Parameter	Value
Echelle grating size	204×408 mm
Groove spacing	31.6 per mm
Collimator	$D_{\rm coll} = 210$ mm, $f_{\rm coll} = 783$ mm (parabolic)
Cross-disperser	BK7 prism
Prism apex angle	$\alpha = 49.5\,\deg$
Prism triangular face	$a = 258$ mm, $h = 276$ mm
Prism width	$b = 255$ mm
Camera type	Folded Schmidt
Camera primary mirror	$D_{\rm cam} = 500$ mm, $f_{\rm cam} = 973$ mm (spherical)

Some basic characteristics of the spectrograph are presented in Table 1.

5. 2. REDUCTION PROCEDURE

A dedicated computer program called HRSP (Hercules Reduction Software Package) has been developed in order to achieve the maximum efficiency in the reduction of HERCULES CCD images. The program has been written in C and has been optimized for HERCULES échelle spectra.

A standard échelle reduction procedure is used, including: the background and cosmic ray subtraction, order extraction, flat-fielding, continuum normalization and wavelength calibration. Relative radial velocities are obtained by cross-correlation between two spectra of the same star. Every order is cross-correlated separately and the arithmetic mean velocity is calculated. Spectra are prepared for cross-correlation by first subtracting the mean flux and then by applying a cosine-bell window to the edges (Simkin 1974).

5. 3. BLUE SKY VELOCITIES

Blue sky spectra are used for monitoring the stability of radial velocity determinations. There are many advantages of using the blue sky as a calibration source and these include the fact that the sky is uniformly bright, which eliminates any possible problems caused by poor fibre scrambling. Also, the radial velocity of the Sun is known to high accuracy.

A typical short-term precision of HERCULES sky spectra is about $3-4$ m s^{-1}, which is close to the photon-noise limit. This has enabled us to detect some subtle effects, such as the slowly increasing blue shift towards the sunset (Fig. 3a). This is caused by the differential extinction in the Earth's atmosphere, combined with the Sun's rotation. The upper solar limb appears slightly brighter than the lower one and this produces an apparent shift in the average radial velocity of as much as $40 - 50$ m s^{-1}, when the Sun is on the horizon.

Our long-term precision is somewhat lower (~ 6 m s^{-1}), as seen in Fig. 3b. One of the reasons is that some of the observations were made close to the sunset, so that they were affected by the differential extinction effect described above. It is essential that the observations of the blue sky are performed at least one hour before the sunset in order to eliminate this effect.

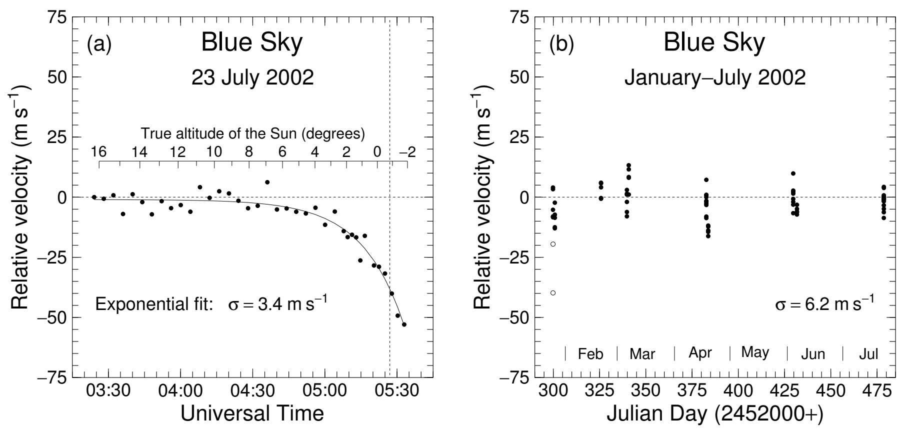

Figure 3: (a) Radial velocities of the blue sky and the effect of differential atmospheric extinction. A vertical dashed line at 5:27 UT marks the sunset. (b) Long-term velocities of the blue sky. Open circles represent the observations with residuals larger than 2.5 σ.

5. 4. STELLAR VELOCITIES

The precision of stellar velocities is somewhat lower when compared to the blue sky. The measurements are affected by insufficient scrambling of the optical fibre, so that the velocity depends on the actual position of the stellar image with respect to the fibre. An experiment has been made in which a bright star (α Cen) was observed using very short exposure times (of a few seconds), while the sidereal rate of the telescope was made slightly slower, so that the star drifted westward across the fibre. No guiding or repositioning of the telescope was made while a series of exposures was taken. The result of this experiment is shown in Fig. 4a. The radial velocities show relative differences of as much as 70 $\mathrm{m\,s^{-1}}$ when the star moves from one side of the fibre to the other.

The effect of poor scrambling becomes especially prominent with very short exposure times, when an instantaneous stellar image is captured on the fibre. As a result, the precision of radial velocities of very bright stars is only about $10-15\ \mathrm{m\,s^{-1}}$. When a star is exposed for a few minutes, both the atmospheric scintillation and frequent repositioning of the telescope during the guiding process produce an averaging effect, so that all parts of the optical fibre entrance get equally illuminated. A precision of $5-10\ \mathrm{m\,s^{-1}}$ is obtained for moderately bright stars, as shown in Fig. 4b. Finally, a typical precision for a sixth-magnitude star (exposure times of several minutes) is about 5 $\mathrm{m\,s^{-1}}$.

6. CONCLUSION

A number of detection methods is used by astronomers today to search for planets beyond our solar system. The most successful technique is based on the reflex motion of the parent star induced by a planetary system. This motion is detected as a periodic variation in the stellar radial velocity. Over one hundred extra-solar planets have been detected so far. Other detection methods will become more successful in

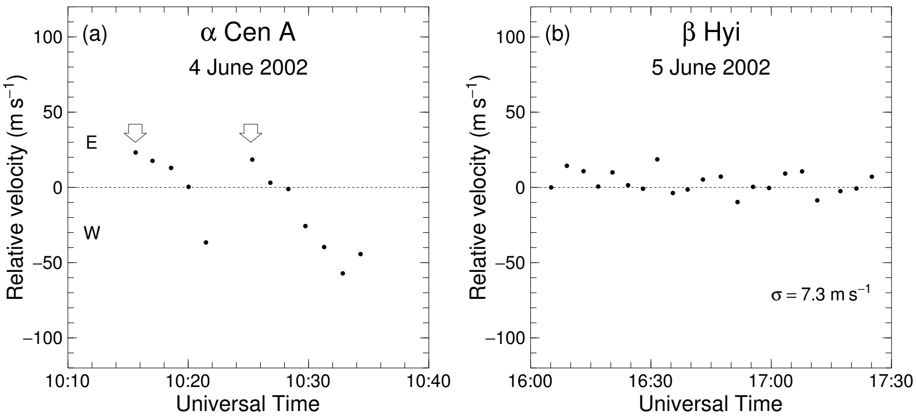

Figure 4: (a) The effect of poor scrambling by the optical fibre. The star drifts westward across the fibre while a sequence of observations is made. The telescope is repositioned only at the beginning of each sequence (as indicated by arrows). (b) Radial velocity of β Hyi over a short period of time. The star has been re-centred on the fibre before each exposure. Exposure time: 30–40 s.

the near future.

Two independent planet-hunting programmes are carried out in New Zealand, one using the microlensing technique (MOA) and the other based on the radial velocity measurements (HERCULES). The MOA project has already produced some positive results, while the HERCULES project is still in its early phase. Some preliminary analysis has demonstrated that the overall stability of the spectrograph will provide a precision of a few metres per second in stellar radial velocities, which will make this instrument fully capable of detecting planets around other stars.

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