Gravitational Microlensing vs. Transit Photometry for the Detection of Extra-Solar Planets and the Results of Stage III of the Optical Gravitational Lensing Experiment (OGLE III)

Sammy Yousef
University of Western Sydney, Nepean
Prepared as part of the subject "Astronomy Written Project" of the Astronomy Internet Masters Program, 2002.
Email: syousef@bigfoot.com

1 Introduction

Gravitational Microlensing is described as "the focusing and hence amplification of light rays from a distant source by an intervening object" (Perryman M.A.C. 2000). It occurs due to the curvature of space associated with a mass, first hypothesized by Einstein, and in accordance with his Theory of General Relativity. A point source lensed by a point mass creates 2 images, with a total brightness greater than that of the source. This is Gravitational Lensing. Where the two images are not sufficiently separated to be resolved, the object appears unchanged except that it is brighter. This is Gravitational Microlensing. (Mao S, Paczynski B. 1991).

The phenomenon was considered as early as 1912, before General Relativity theory was complete, as shown by Einstein's own notes. At the time the idea was considered speculative and unlikely to have a chance of being confirmed. In 1920 Eddington consider the formation of multiple images of a star through microlensing and a while later in 1924, Chwolson first speculated about "Einstein Rings" – a star will be seen as ring-shaped if viewed through an appropriately aligned gravitational lens, with the mass of the lens, and distances between observer, lens and star dictating the geometry of the scene. Einstein eventually published the idea in 1936, apparently in ignorance of prior consideration of the idea by others.(Renn J., Sauer T. et al. 1997).

Theoretical contributions continued to be made until the first gravitational microlens was observed by D. Walsh, R.F. Carswell and R.J. Weymann in 1979. R. J. Weymann discovered a second lens in 1980, and was involved in the discovery of the third in 1981 (see Weedman D. W., Weymann R. J. 1981). The confirmation of the existence of gravitational lenses now meant that they could be considered for use as a tool in observation. However, the first detection of an extra-solar planet through any means was still a decade and a half away.

. In the late 1980s it was realized that if the primary lens were a binary object (a binary star or a star and large planet), the resulting image and light curve would differ from that of a single object, yielding information about the lens system as well as the target. In 1986, the first serious mathematically rigorous theoretical models of a two point gravitational microlens were explored in detail by Schneider and Weiss (1986). The geometry of imaging of point and extended sources seen through a two-point-mass gravitational lens were considered as were the light curves produced. The light curves formed by the primary lens differs depending on the number of components of the lens and their masses. Early considerations were for binary star systems (not planetary systems) since most stars were known to be binaries.

2 Gravitational Microlensing and Extra-Solar Planetary Detection

Until the first practical steps were taken in the early 1990s, the application of this theory to the search for extra-solar planets was hindered by the technological ability to simultaneously monitor enough stars photometrically to make it statistically likely that a microlensing event, where the primary lens is orbited by a planet, would occur.

The first half of the 1990s saw a number of classic theoretical papers published on the topic of gravitational microlensing as a tool for planetary detection. A paper describing the expected light curves produced by a star and planetary system acting as a gravitational lens, the likely duration of the events, and the probability of their occurrences was published by Mao S, Paczynski B. (1991). 1992 saw the publication of another classic by A. Gould and A. Loeb suggesting that the monitoring of gravitational microlens candidates among Galactic disk stars situated such that they may lens Galactic bulge stars. This paper demonstrated that for roughly 20% of stars with a planetary system similar to our own acting as a lens, the planetary system will produce a noticeable change in the light curve of the lens event.

In 1995, the first extra-solar planets were discovered around main sequences stars based on the radial velocity (Doppler) technique. Meanwhile the automation of sky surveys, the ability to analyze data for millions of stars simultaneously, and the accuracy with which these simultaneous measurements were made had reached a point where the observation of gravitational lensing events were at last feasible. A number of groups have made undertaken surveys/observations worldwide throughout the 1990s. Among these projects are DUO (Disk Unseen Objects), EROS (Experience de Recherche d'Objets), EXPORT (Extra-Solar Planet Observation Research Team), GMAN, MACHO (Massive Compact Halo Objects), MAO (Microlensing Observations in Astrophysics), MPS (Microlensing Planet Search), OGLE (Optical Gravitational Microlensing Experiment), and PLANET (Probing Lensing Anomalies Network).See Perryman M.A.C. (2000) for details and references.

To date, results have been disappointing, with only one convincing detection of a planet documented using this method. The MACHO project produced this first – detecting a 3 Jupiter mass planet orbiting a binary stellar system consisting of a late K-dwarf and an M-dwarf. (Bennett D. P., Rhie S. H. et al.1999).

Theoretical work has continued to advance with the technique being theoretically applied to more earth-like planets (Bennet D.P., Rhie S.H., 1996). Other areas of research since then include detecting lensing events while they occur, improving estimates of detection probabilities for planets, and maximizing the information that can be obtained from the light curve of a lensing event.

3 Gravitational Microlensing and Transit Photometry

The detection of a gravitational microlens involves the accurate photometry of a large number of stars. A gravitational microlens appears as a brightening of a light source, as a lens passes in front of it, typically over a time scale of hours to days. Essentially the same technique is used in detecting planetary transits directly as for detecting microlensing events. However planetary transits manifest themselves as a dimming of the source over a timescale of hours, for planets similar to those of our own solar system, rather than the brightening characteristic of a microlens event. (Perryman M.A.C. 2000)

For large planets in close orbit to the parent star, it isn't hard to appreciate that transits, while short-lived will repeat often. (Gould A, Loeb A 1992). In contrast, a microlens detection requires two stars, the lens and target, in precise alignment. Planetary transits should therefore be easier to detect, at least for large, close orbiting planets.

The nature of these techniques means that with only slight adaptation, the same photometric instruments used to detect gravitational microlenses may be used to detect planetary transits. (Udalski A., Paczynski B. et al. 2002). One project which has adapted equipment in such a way is the Optical Gravitational Lensing Experiment (OGLE), which will be the focus of the rest of this discussion.

4 The Optical Gravitational Lensing Experiment – OGLE

4.1 Overview

The Optical Gravitational Lensing Experiment (OGLE) is a decade-long running project that has successfully detected hundreds of (non-planetary) gravitational microlensing events. The first stage was successful in discovering the first microlensing events in the direction of the Galactic bulge, the discovery of the first binary microlensing objects, and the development of an early warning system for detecting lensing events in progress. Stage I was completed in 1995 and observations were carried out on the 1m Swope Telescope at the Las Campanas Observatory, Chile (LCO), operated by the Carnegie Institution of Washington.

Stage II was more extensive resulting in the in the detection of hundreds of gravitational microlensing events, and further provided information on stars in the Galactic bulge and Magellanic Clouds. A real-time early warning system evolved for microlensing events and a catalog of events is maintained. In 2001 the CCD cameras used by the project were updated providing greater sensitivity. Analysis of Ogle II data continues as at the time of writing of this paper, but the project has moved to phase III.

4.2 Stage III – Low Luminosity Object Transits

4.2.1 Overview

OGLE Stage III commenced on June 12, 2001. The goal was specifically the detection of low-luminosity transit objects through photometry (observed as short timescale stellar variability). The results have been spectacular, as OGLE phase III has detected 46 transiting low-luminosity objects. The majority of the data was collected in just 32 nights (over a 45 day period). Subsequent observations followed every few nights until October 2001. 5 million stars were monitored in 3 fields in the direction of the Galactic centre.

This yielded 52,000 stars with sufficient photometry for transit analysis. (Udalski A., Paczynski B. et al. 2002)

4.2.2 Instrumentation

The 1.3-m Warsaw Telescope at the las Campanas Observatory, Chile was combined with the large field mosaic camera installed for the survey. This consists of eight 2048x4096 pixel SITe ST002A CCDs which gives an 0.26 arcsec/pixel scale at the focus of the telescope. The array can be read in 98 seconds and produces a 137MB frame. The instrumentation is operated by the Carnegie Institution (Udalski A., Paczynski B. et al. 2002)

4.2.3 Data Reduction

Initial reduction procedures such as de-biasing and flat-fielding were implemented in almost real time for this stage of the survey. Procedures were based on IRAF CCDRED and were automated so that they were performed as the data was collected. Flat-field data was compressed (using the RICE algorithm) and stored on to hard disk, then dumped onto tape. Photometric data was reduced based on the new Difference Imaging Analysis (DIA) method (as opposed to the classical PSF method), modified to operate in real time and improve performance/stability. The results of this analysis were fed to a photometric database, with each of the eight chips being treated as a separate field.

4.2.4 Results

185 transits were observed for 46 objects of 52,000 candidates with sufficiently good photometry (out of a field of about 5 million stars). Multiple transits were observed for 42 of the 46 objects. See Udalski A., Paczynski B. et al. 2002 for positional and photometric data on each of the transit objects. These result are also presented graphically in the form of a transit "atlas".

An accurate determination of the sizes of these transit objects awaits spectroscopic analysis, however since the approximate radii of many of the stars around which these objects orbit is known, the OGLE III team have used statistical modeling to estimate the physical and orbital characteristics of the stellar companions, including inclination, semi-major axis, radii and masses of the planets. Modeling was based on formulae introduced in Sackett, P.D. (1999).

A large range of masses appears in the data set, indicating that some of the transit objects are likely faint M-type stars. These include objects OGLE-TR-5 and OGLE-TR-16. Some of the transits exhibit light curves that indicate the parent star is tidally distorted. Eight of the transits are for objects with radii 1.5 R_{Jup} or less and are likely to prove to be planets (although they may also be brown dwarves or low-luminosity stars). These include objects OGLE-TR- 8, 10, 12, 29, 32, 35, 39 and 40. Three transits of OGLE-TR-10 and 4 of OGLE-TR-40 give accurate periods and likely radii of 1.0 and 1.1 R_{Jup} respectively. There is some speculation that these are "hot Jupiter" type planets of the kind observed around HD209458. In stark contrast only 1 transit was observed for 4 objects (OGLE-TR- 43 through 46), indicating the likelihood of an orbital period greater than the observation period. For some transit objects the possibility that they are large stellar spots has not been ruled out and will not be until spectroscopic observations are carried out.

4.2.5 Significance

In this undertaking, the OGLE team have shown that millimagnitude accuracy can be reached in the simultaneous observation of millions of stars in crowded star fields is feasible. Detection of 10-20 millimagnitude events has become routine for OGLE III. Now proven, this technique opens up a new, relatively fast way of detecting low-luminosity stellar companions.

Given the number of previously known extra-solar planets (<100) this result is certainly impressive. The results of OGLE III would appear to confirm that success rates for planet finding using the transit photometry will be much higher than for gravitational microlensing. This initial search was considered a pilot, and follow-up observations are under way. It is important to note that it is not known how many of the objects are Jupiter type planets, as opposed to brown dwarfs or M dwarfs.

Nevertheless, even if many or all of the transit objects detected are indeed brown dwarves and not planets the results will have been worthwhile, since objects in the range 10 M_{Jup} -100M_{Jup} have generally not been detected – a phenomenon known as the “Brown Dwarf Desert”. Follow-up spectroscopy will therefore likely either disprove the existence of this “desert” or confirm that these objects are planetary in nature – either of which would prove an astronomical boon.

While cross-over from gravitational lensing to transit photometry appears to have paid off in terms of results for larger planets, a notable trade-off is that, unlike gravitational microlensing, the transit technique is not as promising in terms of locating earth-sized planets, particularly from ground-based telescopes. (Bennet D.P., Rhie S.H., 1996; Perryman M.A.C. 2000).

4.2.6 The Future

Though some parameters have been established for the detected objects, (Doppler) spectroscopy will now be used to determine if each of the objects detected is a (Jupiter size) planet, brown dwarf, M-type dwarf or exotic stellar spot phenomenon. The combination of spectroscopic and transit data will provide better constraints for the sizes, masses and orbital parameters of the observed transit objects.

As noted, the initial results of OGLE III are considered pilot results, which have proven that this scale and accuracy of observation is both feasible and productive. Phase III of the survey has not come to a conclusion and further work is to be undertaken in 2002. As both the length of the observation period and the sensitivity of observations continue to improve, corresponding increases in orbital periods and decreases in transit-object size should occur. Data from the 2001 results and beyond will also be further mined for lesser light curves, allowing each survey to yield a greater field of transit candidates.

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