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MOA Extra-Solar Planet Research via Cluster Supercomputing

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Abstract. Developments in the search for extra-solar planets via gravitational microlensing by the Japan/New Zealand group MOA are discussed. The use of the Kaláka cluster computer is introduced and preliminary results presented.

1. Introduction

The Microlensing Observations in Astrophysics (MOA) collaboration is a joint Japanese/New Zealand experiment established in 1995. The project is designed to perform large scale photometry for the detection and analysis of microlensing events. The research goals of the MOA project include the investigation of dark matter, extra-solar planets, difference imaging, GRBs and variable stars. The telescope used by the MOA collaboration is a 61cm Boller & Chivens Cassegrain with optics modified to f/6.25. The telescope is one of three at the Mount John University Observatory, Lake Tekapo, New Zealand (170.465 E, 44 S). The MOA camera uses three 2k × 4k SITe CCDs with 15μm × 15μm pixels, each covering $0.81''$on the sky. The overall FOV is $1.38^\circ \times 0.92^\circ$. The target fields are in the Galactic Bulge, and the Magellanic Clouds. Searches for Gamma Ray Burst optical transients are made within a Target of Opportunity observation mode.

2. Extra-Solar Planet Search

The detection of extra-solar planets via gravitational microlensing was first suggested by Mao & Paczynski (1991). A planet in orbit around the lens star may introduce a perturbation to the standard single lens light curve. In events of high magnification, planets, including those with masses less than that of Jupiter, can be detected with high efficiency (Griest & Safizadeh, 1998).

2.1. Modelling of Planetary Systems

Light from a background source star is deflected to an observer by the gravitational effect of an intervening lens star system. The position in the source plane of a ray originating in the lens plane is given by:

$$\mathbf{y} = \mathbf{x} - \frac{m_1 \mathbf{x}}{|\mathbf{x}|^2} - \sum_{i=2}^{n} \left\{ \frac{m_i(\mathbf{x} - \mathbf{x_i})}{|\mathbf{x} - \mathbf{x_i}|^2} \right\}$$

where $\mathbf{x}$ and $\mathbf{y}$ are positions in the lens and source plane respectively, in units of the Einstein ring radius. m_1 is the mass of the lens star, and m_i are the masses of planets orbiting the lens star. The positions of the planets (projected onto the lens plane) are given by $\mathbf{x_i}$. To obtain a theoretical lightcurve for a microlensing event we need to invert the above equation. This is not possible for multi-planet lens systems. We used the inverse ray shooting technique of Wambsganss (1997) to model planetary systems of arbitrary complexity. Rays are shot from the observer, through the lens plane and their position in the source plane computed via the above equation. Rays that fall within the radius of a source star are counted and are used to generate a model lightcurve.

Using the data from each high magnification microlensing event,we compute the χ^2 values for a wide range of model light curves, generated using the inverse ray shooting method. For each model we assume the following about the lens and source stars: Lens star mass, $M_L = 0.3M_\odot$; observer-lens distance, $D_{OL} = 6$ kpc; lens-source distance $D_{LS} = 2$ kpc and source star radius, $R_S = R_\odot$.

The Kaláka computer cluster The inverse ray shooting technique allows us to model lens systems with any number of planets. It also allows us to vary the source star radius. It is a numerical technique which is relatively computationally expensive. In order to analyse a large number of systems, we have made use of a computer cluster at the University of Auckland. The Kaláka cluster was created by P. Dobcsányi and comprises around 200 Pentium II 350MHz computers. These machines are used in the undergraduate computer science laboratories. When these laboratories are not in use, the computers are linked together to form the cluster. Using the Kaláka cluster, we are able to search the parameter spaces for lens systems of arbitrary complexity. Details of the cluster and the ray shooting technique are in Rattenbury et al (2001).

3. Results

Three high magnification events, MACHO 98-BLG-35, MACHO 99-LMC-2 and OGLE 00-BUL-12 are currently under analysis. Images obtained by the MOA and OGLE groups for these events were analysed using the image subtraction method of Alard (1999) as modified by Bond (2001). We present the results from one of these events, MACHO 98-BLG-35.

Data for this event originated from the microlensing groups MOA, MPS and PLANET. The Kaláka cluster was used to compute light curves for several million lens configurations. A search for a single planet lens system was performed initially. The light curves were generated at observation times in the interval $[-t_E, t_E]$ where t_E is the Einstein ring radius crossing time. The planet position co-ordinates (x_p, y_p) were allowed to vary across the interval $[-2R_E, 2R_E]$ where R_E is the Einstein ring radius. A total of 129 steps for each of x_p and y_p were used. Given the above assumptions about the system geometry, $R_E = 1.9$ AU.

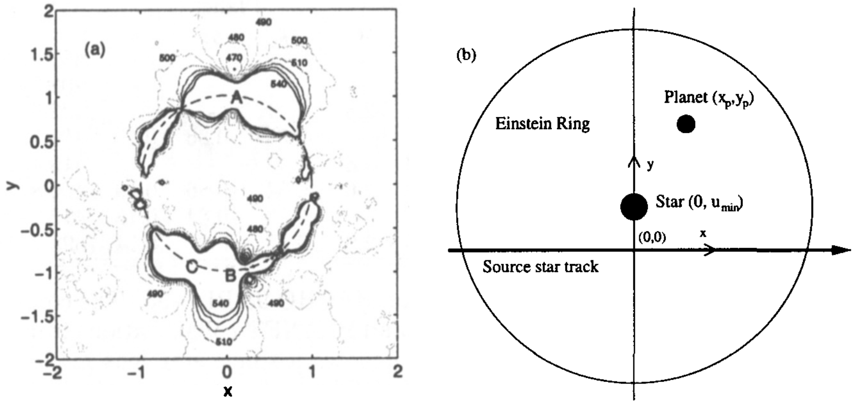

Figure 1. (a) Contour χ^2 map for MACHO event 98-BLG-35. The mass ratio used was $\epsilon = 10^{-5}$. The projected planet positions are in units of R_E. Three pairs of minima are indicated. Deeper χ^2 minima can be found at the different positions by varying ϵ. (b) Co-ordinate system used for the inverse ray shooting method. In the lens plane, the projected planet positions are at (x_p, y_p). The lens star is placed at position $(0, u_{min})$. The source star's position of minimum projected distance to the lens star is thus at co-ordinates $(0, 0)$.

The planet-lens mass ratio, ϵ, was allowed to vary in 33 logarithmically spaced steps across the interval $[10^{-7}, 10^{-3}]$. A χ^2 map was generated for each of the mass ratios used. Minima in these maps indicate the approximate mass and position (projected onto the lens plane) of possible planets around the lens star at the time of the microlensing event. Figure 1 shows the χ^2 map for mass ratio $\epsilon = 10^{-5}$. This mass ratio corresponds to an Earth-mass planet. There are three pairs of minima shown in Figure 1. This pairing of minima is due to a degeneracy inherent in the microlensing method. Deviations in a lightcurve due to a planet at projected planet-lens distance a are indistinguishable from a planet at distance a^{-1} (Griest and Safizadeh 1998). We create multi-planet models by placing planets at two (or all three) of the χ^2 minima. We use these planet position and mass parameters as starting values for a further χ^2 minimisation using the Simplex method. Table 1 shows the results from this minimisation. The parameters u_{min}, t_0 and t_E where also allowed to vary in this minimisation.

Model "A" appears to be the most likely single planet model. The improvement in χ^2 of this model over a single star (no planet) lens model corresponds to about 9σ. Model "B+C" appears to be the best two planet model. The lens system of model "B" appears to correspond with that previously found by Rhie et al (2000). Model "B+C" of this work seems to be a generalisation of the Rhie model, to which a second, low mass planet has been added. The χ^2 value for model "A" improves only slightly for models "B+C" and "A+B+C". A statistical argument would favour the simplest model, model "A".

The 2σ limits on planet mass ratio for model "A" are $(0.4 - 1.5) \times 10^{-5}$ which corresponds to a planet of mass $\sim (0.4 - 1.5) \times M_\oplus$. The orbital radius

Model	Planet A			Planet B			Planet C			χ^2/dof
	x_p	y_p	ϵ	x_p	y_p	ϵ	x_p	y_p	ϵ	
S	-	-	-	-	-	-	-	-	-	487.9/296
A	0.11	1.22	1.3	-	-	-	-	-	-	402.0/293
B	-	-	-	0.30	-1.11	2.8	-	-	-	432.9/293
C	-	-	-	-	-	-	-0.37	-0.86	0.17	461.7/293
A+B	0.16	1.25	0.79	0.35	-1.14	2.8	-	-	-	419.4/290
B+C	-	-	-	0.30	-1.12	2.6	-0.34	-0.86	0.19	400.8/290
A+C	0.15	1.21	0.99	-	-	-	-0.33	-0.84	0.18	412.7/290
A+B+C	0.19	1.28	0.30	0.34	-1.15	2.9	-0.35	-0.87	0.17	398.2/287

Table 1. χ^2 minimisation results for MACHO 98-BLG-35. The combined data set from the MOA, MPS and PLANET collaborations from $-t_E$ to $+t_E$ were used. Model "S" denotes a single star lens model. The planet positions are in units of R_E. The mass fraction ϵ is in units of 10^{-5}. A typical χ^2 map and the co-ordinate system used is shown in Figure 1.

of the planet in this model is either $0.82R_E$ or $1.22R_E$. This corresponds to either ~ 1.5 or ~ 2.3 AU. Figures 2 and 3 show the light curves for models "A" and "B+C" respectively. The planetary perturbation is negative for model A because the source star track does not pass between the lens star and the planet for this model (see Fig. 1).

4. Further Work

In the 2000 Galactic Bulge season, the MOA project monitored several interesting transient events. Table 2 lists some of these events. The majority of these events are probably due to microlensing, but some are nova-like events. Additional events with $A \geq 10$ are candidates for planetary searches.

5. Discussion and Conclusion

The detection of extra-solar planets in high magnification gravitational microlensing events has been demonstrated. Earth-mass planets with orbit radii ~ 2 AU can be detected by terrestrial 1-m class telescopes. The critical requirement for this research is the dense sampling of the peak of a high magnification microlensing event. This can be done by several co-ordinated telescopes across the world. Using the image subtraction process can give higher accuracy in the analysis of crowded field images, such as those encountered in microlensing surveys. The inverse ray shooting method has been successfully implemented on a cluster computer to sample densely the parameter spaces for multi-planet lens systems.

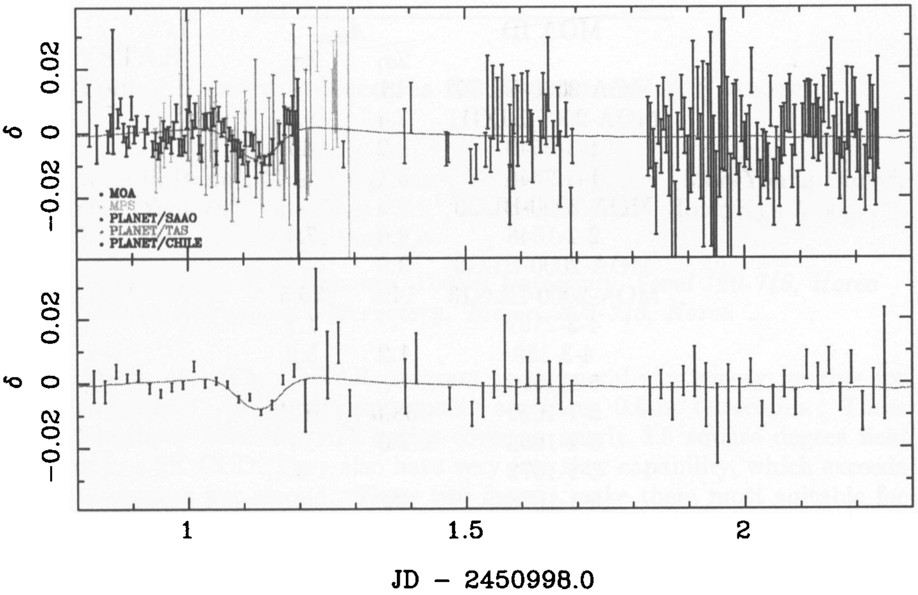

Figure 2. MACHO 98-BLG-35 observed data and fitted lightcurve for the single planet lens model “A”. The bottom plot shows the same data weight averaged and binned into 0.02 day intervals. The y-axis of each plot shows δ, the fractional deviation from a single lens system.

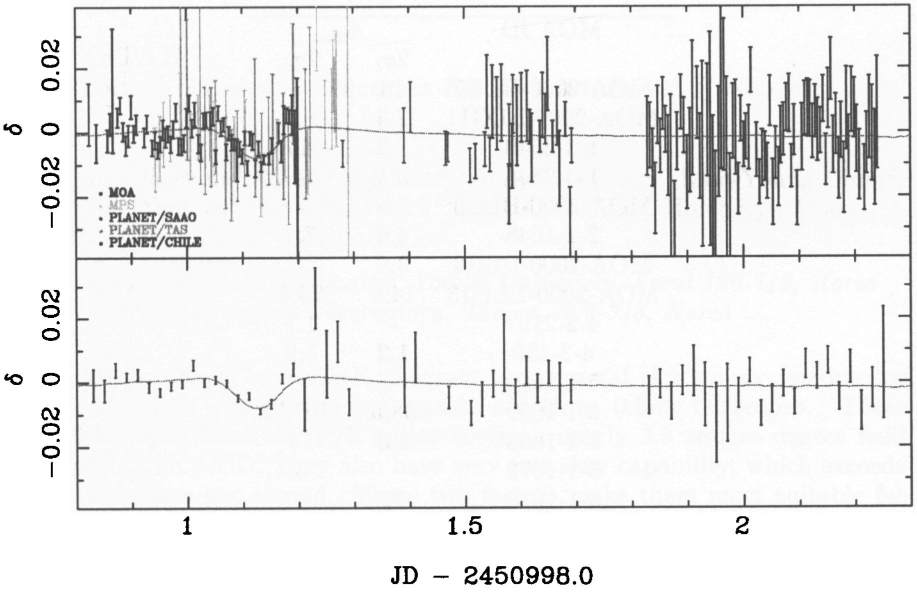

Figure 3. As Figure 2 but showing the two planet model “B+C”.

MOA ID	A_{max}	
	$2\sigma_l$	$2\sigma_u$
MOA-2000-BLG7	14	-
MOA-2000-BLG11	7.4	8.8
1-3-2540	8.2	46
1-3-2548	5.1	-
MOA-2000-BLG3	9.6	-
2-2-1648	4.0	7.4
MOA-2000-BLG9	3.0	-
MOA-2000-BLG13	14.8	20.5
4-2-2197	-	1.7
4-3-159	1.2	5.9
5-1-1616	-	-
5-1-1629	38.6	(101.7)
5-1-1668	2.0	14
5-1-1672	-	3
5-1-1673	22	-
MOA-2000-BLG12	6.2	11.6
MOA-2000-BLG8	1.6	2.2
9-3-841	-	4.0
MOA-2000-BLG10	9.0	11.2
12-2-1052	7.7	21.3

Table 2. A sample of Galactic bulge events observed by MOA in the year 2000 season. Events with a MOA-2000-BLGn designation were issued as transient alerts. Upper and lower 2σ limits are given for the amplification of each event.

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