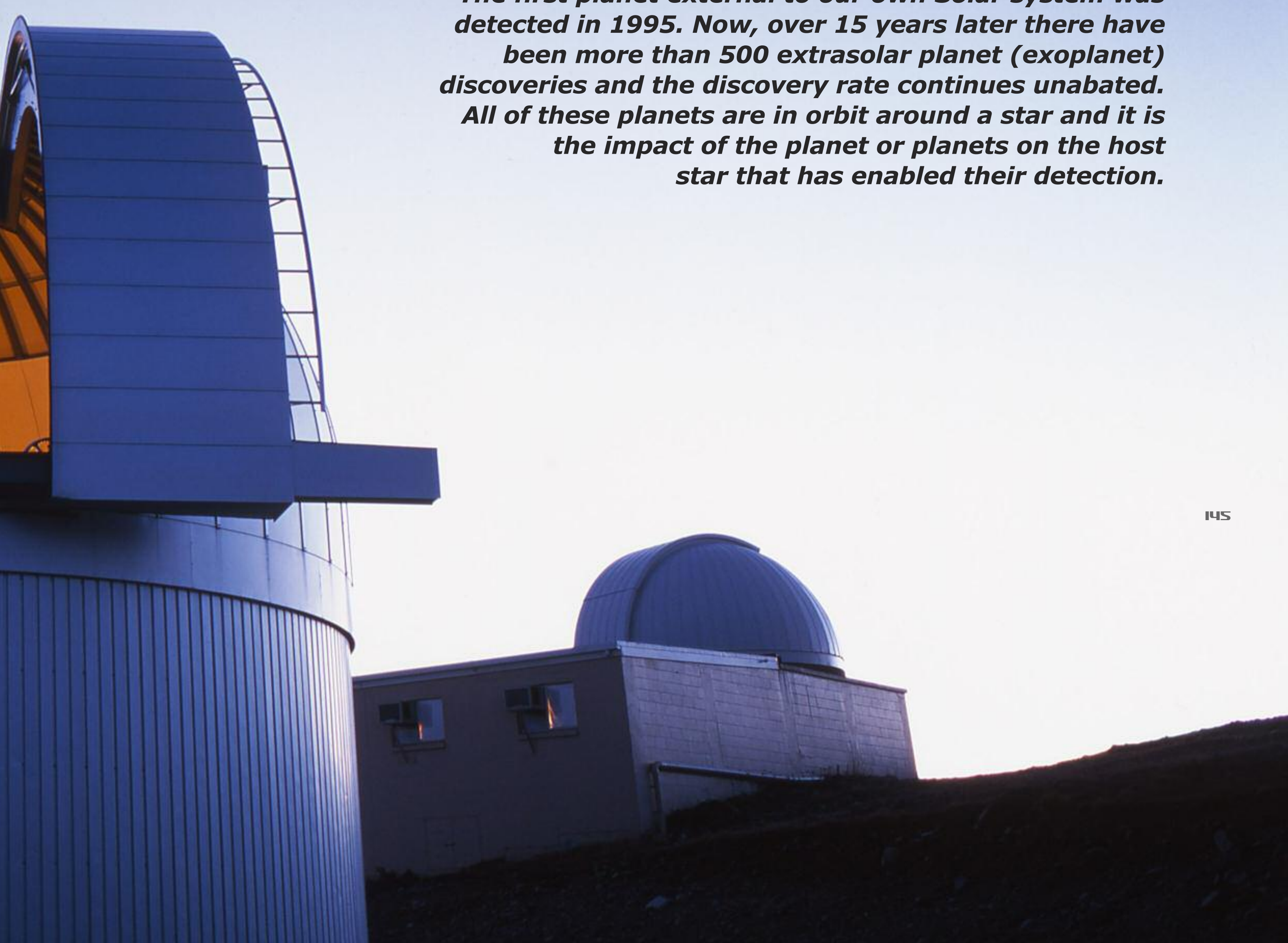
Free floating planets revealed by microlensing

A twilight view of the 1.8 metre MOA telescope at Mt John Observatory in NZ's South Island.

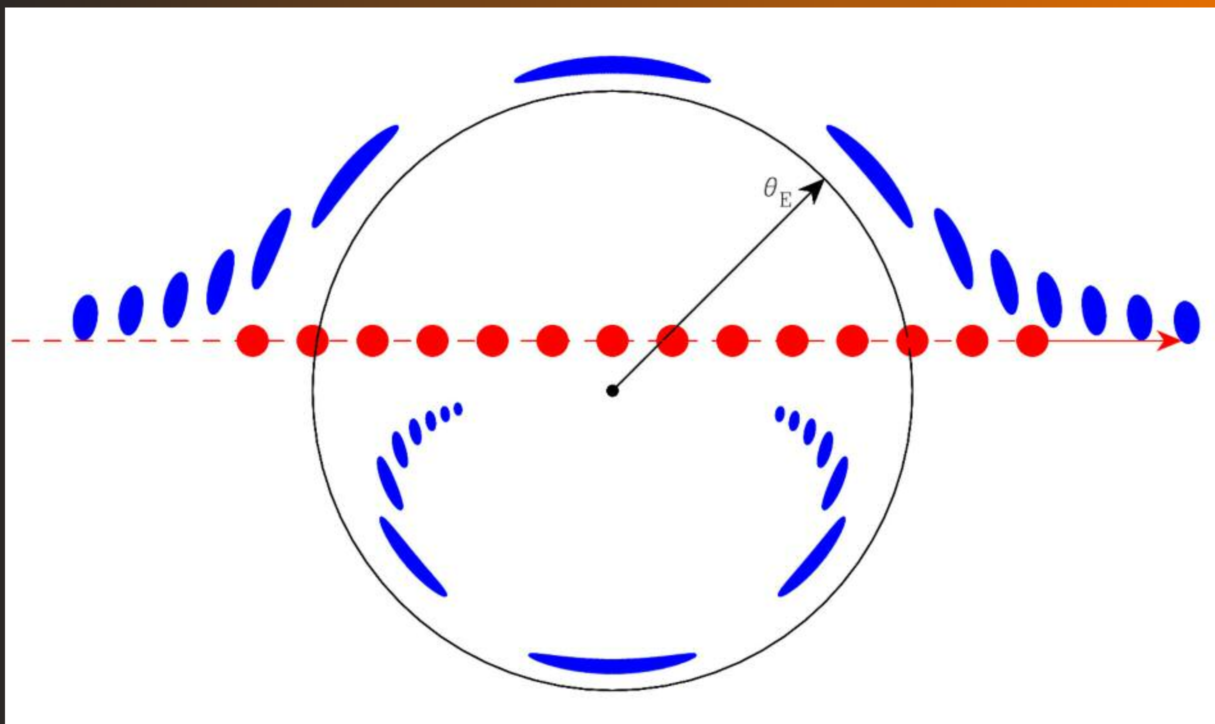
The first planet external to our own Solar system was detected in 1995. Now, over 15 years later there have been more than 500 extrasolar planet (exoplanet) discoveries and the discovery rate continues unabated. All of these planets are in orbit around a star and it is the impact of the planet or planets on the host star that has enabled their detection.



A collaboration of NZ and Japanese astronomers known as MOA (for 'Microlensing Obsevations in Astrophysics') along with another group called OGLE have recently published research in *Nature* (19 May 2011, Sumi et al.) that reveals the existence of a collection of Jupiter-mass planets that appear to be unbound to any star system. The group has discovered ten of these so-called free-floating planets.

The detection of exoplanets

The radial velocity detection method, involving the measurement of small oscillatory forward and backward line of sight motion of the host star, has dominated the exoplanet discoveries to date. The transit method, whereby the planet passes in front of the host star dimming the received light by a small amount, is now making a significant



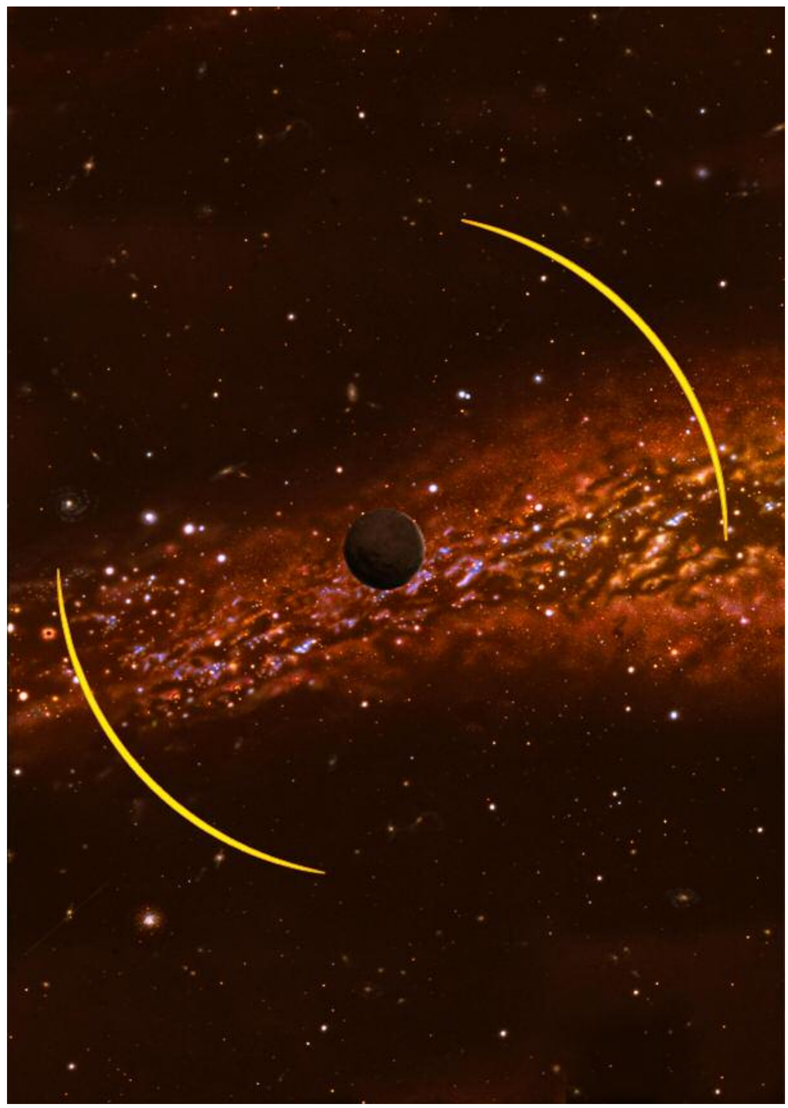
Pictorial representation of the observer's view of the two images formed in a single mass microlensing event. The red disks correspond to various positions of the background star moving relative to the direction of the lensing mass at the centre of the circle. Due to light ray deviations in the gravitational field of the lens, the observer will not see the star disk but will instead see two distorted images (represented by the blue shapes) that are on a line joining the lensing mass to the star. The angular scale of the phenomenon is set by the Einstein angular radius represented by the circle.

impact (especially with recent Kepler mission contributions). However, both these methods rely on the light emitted by the host star. One method – gravitational microlensing – does not utilise light from the host star. Although microlensing studies to date have yielded not much more than ten planets, the lack of reliance on host star radiation leads to several advantages. One of these is the ability to detect isolated planets. In stellar terms, planets are relatively cold objects so they emit little radiation and are therefore difficult to detect directly. We see our own solar system planets via reflected light from the Sun, so seeing isolated planetary objects at stellar distances is essentially impossible at present. The MOA group used the microlensing technique to identify these solitary objects.

The microlensing technique

Microlensing uses the behaviour of light rays in the gravitational field of a massive object to detect the presence of the object; therefore it doesn't rely on any radiation emitted or reflected by the object. The particular geometry involved is the very precise alignment of a background star, an intermediate lensing object, and an observer. The distortion of space predicted by Einstein's gravitational theory (general relativity) in the vicinity of the lensing mass bends the passing light rays, which leads to distorted images of the background star. If these images cannot be resolved the net effect seen by an observer is an increase in star brightness. For microlensing events in our Galaxy involving stars or planets the

image separations are no larger than milliarcseconds. Microlensing events are identified by a variable stellar intensity and this is distinguished from other causes of stellar variability by a characteristic increase and decrease in brightness caused by the changing alignment geometry due to relative proper motion of the objects. Given the vast distances involved, constant velocity relative transverse motion of the lens is a good approximation and this yields the symmetrical so-called Paczyński light curve, which was actually first predicted by Sidney Liebes in a paper published in the Physical Review in 1964.
This light curve shape resembles a Lorentzian resonance curve as it has wider "wings" than the classic Gaussian shape.
The relevant physical information of interest in the light curve is encoded in its width, and this yields the Einstein radius crossing time. The Einstein radius is the cone angle of the circular ring image that is formed in the case of perfect alignment of the lens system and it sets the angular scale for all microlensing events. This radius depends directly on the mass of the lens, but it also depends on the distances from the observer to the lens and the background star. Consequently, in order to extract lens mass data from measured Einstein radius crossing times, one also requires information about the relative transverse motion of the lens along with the lens and source distances.
The free-floating planet discoveries were ten short time-scale events (cros-



An artistic impression by Jon Lomberg of the microlensing images formed around a planet.

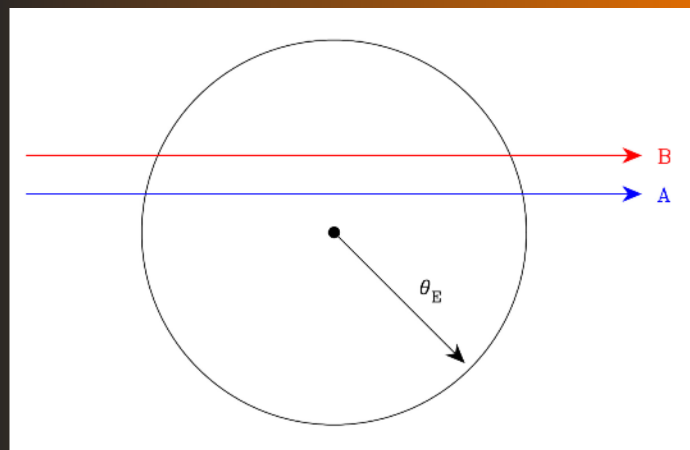
sing times less than days) that were part of a sample of 474 microlensing events detected by MOA over two consecutive Galactic Bulge observing seasons in 2006 and 2007. All of these 474 events satisfied strict selection criteria that ensured they were isolated microlensing events.

Using Einstein crossing times to infer mass distributions

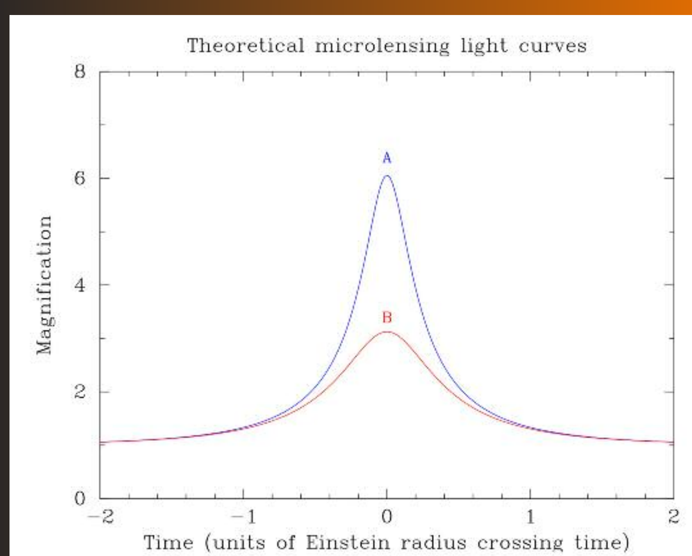
The distribution histogram of the Einstein crossing time values of these events ranged from half a day to about 100 days and this distribution is used as a statistical probe of the mass function of the lens objects. This is possible because the spatial and velocity distributions in the Galactic disk and Bulge are reasonably well known. The key result of the analysis is that the ten short time-scale events were predicted to be caused by Jupiter-like lens masses with no other stellar mass closer than about ten astronomical units.
The crossing time distribution also provides some insights into the Galactic population of brown dwarf stars. These "failed stars" are also difficult to detect due to their very low luminosities, as their low masses prevented the objects from reaching sufficiently high central temperatures and pressures such that the hydrogen nuclear fusion reactions that power normal stars occurred. The microlensing Einstein crossing time distribution for events longer than a few days implies that brown dwarfs could be nearly as common as main sequence stars.

Finding rare microlensing events

The extremely precise alignment required to produce observable microlensing events means that even when one is looking towards the dense star fields in the direction of the Galactic Bulge the chance of this occuring for a particular background star is around one part in ten million. The microlensing survey groups (currently MOA and OGLE) detect these highly improbable events by regularly monitoring about 50 million stars using large format electronic CCD cameras attached to wide-field imaging



Diagrams showing the theoretical microlensing light curves that occur for motion of the background star relative to the lensing mass. It is assumed that the two images cannot be resolved, the size of the source disk is relatively small (a point source), and constant velocity relative motion occurs. The plot above shows two different source tracks and the plot below shows the corresponding magnification curves versus time, in units of the Einstein ring radius crossing time.



telescopes. The key to the free-floating planet discoveries lies in several historical developments in the MOA operation. In 2005 a purpose-built 1.8 metre telescope along with a 80 megapixel CCD camera system was installed at Mt John Observatory in NZ. This was largely funded by a Japanese Government grant obtained by the MOA astronomers at Nagoya University, then led by Professor Yusushi Muraki. With this increased monitoring capability the MOA group decided to search for short time-scale microlensing events by adopting a high cadence photometric survey with time intervals between observations in the 10 to 50 minutes range. Although the primary motivation for this strategy (signalled in several earlier MOA publications) was aimed at detecting bound planets in very high magnification events, it was rewarded with the discovery of these short time-scale events, now interpreted as isolated planets.

After MOA had identified the ten events of interest from their 2006 and 2007 observations, they requested independent light curve data for these events from the OGLE group.

Seven of the ten events were also seen in the OGLE data set and none of them exhibited any brightening in the eight-year OGLE light curves. In addition, for six of these seven events, the OGLE data obtained during the lens brightening confirmed the MOA microlensing model predictions.

Initial mass function and the "missing mass"

These discovered isolated planets could provide important data on the key initial mass function for isolated stellar body formation under the influence of gravitational contraction.

Little is known about the possible low mass (planet-mass) end of this distribution due to the difficulty of detecting such objects.

However, the *Nature* paper speculates that the detected isolated planets may have actually been formed in protoplanetary disks around stars and then been ejected out of the formed multiplanet system by planet-planet scattering events. This hypothesis is certainly not conclusive and is based on an abrupt change in the shape of the Einstein crossing time distribution below the 2-day interval corresponding to the detected planetary masses. Although the planet sample is not that large, the data imply a high density of these objects – probably about two for every star.

It is interesting to note that the detection of these non-luminous isolated masses has brought the use of the microlensing technique in astronomy almost full circle. The first microlensing experiments were commenced about two decades ago by the MACHO collaboration, and their basic aim was to search for non-luminous massive objects – the so-called massive compact halo objects – that might explain the "missing mass" in our Galaxy. These experiments by the MACHO group and others (including MOA and OGLE) failed to detect the presence of any significant MACHOs, and their attention was then directed at finding and analysing multiple lensing systems, which eventually led to the detection of planetary systems around distant stars.

Of course the ten isolated planets don't explain the missing mass, but their detection obviously enhances another important area of astrophysics.

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