Gravitational Microlensing Evidence for a Planet Orbiting a Binary Star System

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The study of extra-solar planetary systems has emerged as a new discipline of observational astronomy in the past few years with the discovery of a number of extra-solar planets. The properties of most of these extra-solar planets were not anticipated by theoretical work on the formation of planetary systems, although the radial velocity technique used for these discoveries is not yet sensitive to planetary systems like our own. Here we report observations and light curve modeling of gravitational microlensing event MACHO-97-BLG-41, which indicates that the lens system consists of a planet orbiting a binary star system. According to this model, the mass ratio of the binary star system is 3.8:1 and the stars are most likely to be a late K dwarf and an M dwarf with a separation of about 1.8 AU. A planet of about 3 Jupiter masses orbits this system at a distance of about 7 AU. If our interpretation of this light curve is correct, it represents the discovery of a planet orbiting a binary star system and the first detection of a Jovian planet via the gravitational microlensing technique. It suggests that giant planets may be common in short period binary star systems.

The Microlensing Planet Search (MPS) Collaboration aims to detect planets that orbit distant stars by detecting the influence of planets on gravitational microlensing event light curves. Gravitational microlensing events are observed via the time varying magnification of the sum of the gravitationally lensed images as the lens system passes in front of the background source star. The separation of the images is too small to observe with current instruments. A planet orbiting the lens star can be detected via a brief deviations of the microlensing light curve from the normal single lens light curve.

The microlensing event MACHO-97-BLG-41 was discovered by the MACHO team and announced on 19 June, 1997. MPS observations from the Mt. Stromlo 1.9m telescope began on that night. On 29 June, MACHO issued a further announcement that the light curve of this event did not have the shape expected for a single lens event, and the PLANET team issued a similar announcement on 2 July. Regular observations by the GMAN follow-up team began shortly after this second MACHO announcement with nightly observations from the CTIO 0.9m telescope and less frequent observations from the Wise Observatory 1.0m telescope. The MACHO and GMAN data were previously presented without analysis by the MACHO/GMAN group. Here, we present a combined analysis of the MPS and MACHO/GMAN data.
The modeling of MACHO-97-BLG-41 has proven to be more difficult than any other multiple lensing event observed by MACHO/GMAN or MPS to date. Figure 1 shows the light curve of the combined data set along with the best fit model, while Figure 2 shows the trajectory of the source star with respect to the lens masses and the overall lens system caustic structure. Most of the features of these multiple lens light curves can be understood by inspection of diagrams like Figure 2 because the regions of high magnification are associated with the caustic curves. The spikes and U-shaped light curves that commonly occur in binary lens light-curves\footnote{\ref{lb1}} are easily understood as caustic crossing features.

Our initial attempts to fit the MACHO-97-BLG-41 light curve focused on both static and orbiting binary lens models. Static binary lens models have been successful in fitting the light curves of all the other known multiple lens events\footnote{\ref{lb1},\ref{lb2},\ref{lb3}}, but such a model is unable to account for the two caustic crossing features of MACHO-97-BLG-41. A static binary lens model would necessarily have a light curve peak around July 21 that is much larger than what is actually observed, because a cusp of the central caustic must point in the direction of the caustic that was crossed on June 20-21. The inclusion of binary lens possible orbital motion\footnote{\ref{lb1}} also failed to generate an acceptable fit.

When we concluded that binary lens models would not fit the data, we turned to triple lens models (Rhie & Bennett, in preparation), and our fitting code quickly converged to a model which appears to correspond to a stable dynamical system. The light curve for this model is shown in Figure 1. The model parameters are expressed in terms of the Einstein ring radius, $R_E$, which is the size of the ring image that would be seen with perfect lens-source alignment (i.e. with the source and all the lens masses in a line). For a typical Galactic bulge lens system, $R_E \sim 3 \text{ AU}$. The fit parameters are as follows: The Einstein ring radius crossing time is $t_E = 27.832\text{ days}$. The closest approach between the angular positions of the source and the lens system center of mass is $u_{\text{min}} = 0.0679$ (in units of $R_E$) which occurs at time $t_0 = 23.593$ July 1999, UT. The mass fractions of the three masses are 0.7870, 0.2086, and 0.0044, and the separations are 0.4822 $R_E$ and 1.768 $R_E$ between the mass pairs 1-2 and 1-3, respectively. The opening angle between the mass 1-2 and mass 1-3 vectors is $108.30^\circ$, and the source trajectory intersects the lens 1-2 axis at an angle of $-64.81^\circ$. The measured widths and magnifications at the caustic crossings allow us to determine the time for the source star to move by its own radius with respect to the lens axis: $t_*= 0.16\text{ days}$, assuming linear limb darkening parameters of 0.656 for the standard R-band, 0.632 for the MACHO-R band, and 0.777 for the MACHO-V band\footnote{\ref{lb1}} based upon a spectrum of the 97-BLG-41 source star\footnote{\ref{lb1}}. The relative locations of the lens masses, the caustics, and the source trajectory are shown in Figure 2. This model also indicates that 10-20\% of the flux (depending on the pass band) identified with the source star is unlensed, indicating that one or more unlensed stars lie within 1-2” of the lensed source. Such blending is quite common in such crowded stellar fields. Our model has a $\chi^2 = 1102.96$ for 779 degrees of freedom, which is typical of other microlensing events without binary or planetary light curve deviations. The best fit orbiting binary source model has a $\chi^2$ that is larger by 67.57 and an implied orbital velocity larger than the escape velocity of the binary system.

Orbital stability is an important concern for triple star systems because many such systems are dynamically unstable. Our gravitational microlensing model indicates that the planet is separated from the stellar system center of mass by 3.9 times the binary star separation, in the plane perpendicular to the line of sight. A recent stability study by Holman and Wiegert\footnote{\ref{lb7}} indicates that the stability of planets orbiting binary star
systems depends somewhat on the stellar system orbital eccentricity. For our best fit mass ratio and assuming a circular stellar orbit, they find that planetary orbits are stable if their median separation is at least 2.2 times that of the stars while for an eccentricity as high as 0.7, the critical ratio of the median separations climbs to about 3.1. Thus, our triple lens fit appears to correspond to a stable system as long as the separation ratio is not substantially reduced when the unobserved line-of-sight component is added.

Further details regarding the properties of the lens system can be obtained by comparing the source star radius crossing time, $t_∗$, to the properties of this star as determined by Lennon et al.\textsuperscript{[3]} Their spectrum indicates $T_{\text{eff}} = 5000 \pm 200$ K, $\log g = 3.2 \pm 0.3$, and $[\text{Fe/H}] = -0.2 \pm 0.3$ dex, while our model and the MACHO Project’s photometric calibration\textsuperscript{[22]} indicate that the unlensed magnitude and color of the source star are $V = 19.66 \pm 0.20$ and $V - R = 1.24 \pm 0.10$. This allows us to estimate the extinction to be $A_V = 2.9 \pm 0.4$, and this leads to an estimate of the angular size of the source star: $\theta_\ast = 2.9 \pm 0.7\mu\text{arc sec}$. The distance to the source star is not known precisely, but it is likely to be at or slightly beyond the center of the Galaxy at $D \sim 8.5 \text{kpc}$. At this distance, the source star would have a radius of $5.3 \pm 1.3 R_\odot$. A comparison to the Bertelli et al.\textsuperscript{[15]} isochrones indicates that a number of possible early K class III-IV stellar models are consistent with these parameters. These range from a 10 billion year old $1 M_\odot$ star to a 1.5 billion year old star of $1.7 M_\odot$.

Our estimate of the angular size of the source star, combined with our measurement of the stellar radius crossing time, yields the relative proper motion of the lens with respect to the source: $\mu = 6.7 \pm 1.7 \text{mas/yr}$. Projected to the likely source distance of $8.5 \text{kpc}$, this is $270 \text{km s}^{-1}$ which is a reasonable value for the relative transverse velocity between a pair of Galactic bulge stars. The measurements of $\mu$ and $t_E$ allow us to solve for the single parameter family of solutions relating lens mass and distance shown in Figure 3. This Figure also shows likelihood function for the lens system location which is based upon a simple model of Galactic kinematics and our upper limit on the lens brightness.

The likelihood function in Figure 3 implies $D_{\text{lens}} = 6.3^{+0.6}_{-1.3} \text{kpc}$ and $M_{\text{tot}} = 0.8 \pm 0.4 M_\odot$. The individual lens masses are $M_1 = 0.6 \pm 0.3 M_\odot$, $M_2 = 0.16 \pm 0.08 M_\odot$, and $M_3 = 0.0033 \pm 0.0017 M_\odot$ (or $M_3 = 3.5 \pm 1.8 \text{Jupiter masses}$). The implied transverse separations are $1.5^{+0.1}_{-0.3} \text{AU}$ for the two stars, and $5.7^{+0.6}_{-1.1} \text{AU}$ for the planet from the center of mass of the system. Assuming a random orientation, the most likely three dimensional separations are a stellar separation of $1.8 \text{AU}$, and a planetary separation of $7.0 \text{AU}$. Thus, the most likely lens system consists of a K-dwarf–M-dwarf binary star pair orbited by a planet of about 3 Jupiter masses.

One alternative explanation of this event might be a binary source star system lensed by a binary lens system\textsuperscript{[21]} This would require that the secondary source star be much fainter than the primary, and that it be lensed by a much greater amount so that the width of the secondary source light curve will be much narrower than the primary source light curve. In general, one would expect a significant color shift between the secondary and primary peaks in such a situation. The MACHO data show no evidence for such a color shift. The PLANET Collaboration apparently has additional data on this event\textsuperscript{[24]} in the I-band and perhaps in the V-band as well, so future attempts to model the light curve may be able to place tighter constraints on any color change. A definitive test of the binary source-binary lens hypothesis would be to search for radial velocity variability of the source star due to its orbital motion if it is indeed a binary.

Our apparent detection of a planet orbiting a binary star system represents both the first discovery of a
Jovian planet via gravitational microlensing and the first discovery of a planet orbiting a binary star system. (MPS and MOA have recently reported a possible detection of a low mass planet via microlensing). A number of planets have been discovered orbiting individual members of widely separated binary systems, but these are systems that probably became binaries by gravitational capture after the planets had formed. The planet orbiting the MACHO-97-BLG-41 lens system is likely to be the first example of a planet that formed in a binary system although circumbinary disks which might be in the process of forming planets have been observed. It is somewhat curious that the first detection of a planet via gravitational microlensing should apparently be orbiting a binary star system. Such planets have not been seen in planetary searches using the radial velocity technique because the radial velocity search programs have avoided short period binary stars. Microlensing planet search programs tend to concentrate on binary lensing events because they provide better opportunities for non-planetary science. Since these events comprise $\lesssim 10\%$ of the total number of microlensing events, many more single lens events are observed, and it was expected that microlensing would detect Jovian planets orbiting single stars first. Our present result suggests that Jovian planets may be more common in short period binary systems than in single star systems.

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Fig. 1.— The light curve and best fit model for the MACHO-97-BLG-41 microlensing event are plotted as a function of time. The data consist of 356 MPS R-band observations from the Mt. Stromlo 1.9m telescope, 197 MACHO-R and 194 MACHO-V band observations from the Mt. Stromlo 1.3m telescope, 35 R-band observations from the CTIO 0.9m telescope, and 17 R-band observations from the Wise 1.0m telescope. The MACHO-R, MACHO-V, Wise-R, CTIO-R, and MPS data are plotted in red, blue, green, cyan, and magenta, respectively. The inset figures show closeups of the caustic crossing regions of the light curves, and the tick interval for these figures is 1 day. The last 5 observations from the night of June 20 were short exposures taken in bright moonlight over a span of 40 minutes. These have been averaged into a single data point for the inset figure in the upper left. The MPS and MACHO data were reduced with the SoDophot photometry routine \(^9\) while the CTIO and Wise data were reduced with ALLFRAME \(^10\). The MACHO, CTIO, and Wise data were previously presented by Alcock et al. \(^4\). The solid curve is the best fit triple lens model described in the text, and the dashed curve in the inset figures is the “best fit” orbiting binary lens light curve which requires an “orbital velocity” larger than the escape velocity of the binary system and is therefore unphysical. This large orbital velocity is due to the large distance that the binary stars must move to account for both caustic crossing features and the small \(t_e\) value for this fit which is required to achieve the magnifications observed on June 20-21.

Fig. 2.— The caustic curves for the best fit model for the MACHO-97-BLG-41 microlensing event are shown along with the lens positions and the source trajectory which is the diagonal line running from the top left to the bottom right. High magnification occurs when the source passes inside a caustic curve where the magnification is proportional to the inverse square root of the distance to the caustic from the interior. High magnification also occurs outside a caustic curve in the vicinity of a caustic curve cusp. The observed light curve of MACHO-97-BLG-41 has the following features that can be seen in this Figure and in Figure 1: 1) the passage of an isolated caustic curve on June 19-20, 2) an approach to a cusp on July 21 that gives rise to the light curve shoulder, 3) an extremely bright spike indicating the crossing of a very narrow caustic structure during July 24-25. The triangular caustic curve located near the planetary mass is due to the two stellar mass lenses and has no effect on the light curve although a similar caustic does play a role in the unphysical orbiting binary lens fit. The orbiting binary lens fit allows this triangular caustic to intersect the source trajectory to produce the June 19-20 caustic crossings, but only if the orbital velocity exceeds the escape velocity of the binary system.

Fig. 3.— The mass-distance relation for the MACHO-97-BLG-41 lens system is plotted along with a likelihood function for the lens system distance. The measurements of \(\mu\) and \(t_e\) provide two constraints on the three unknowns of a microlensing event (the lens distance, mass, and transverse velocity), which allows us to solve for the single parameter family of solutions shown above. The transverse velocity of the lens is also determined as a function of the distance to the lens. Taking the velocity distributions from a standard Galactic model \(^20\), we are able to construct a likelihood function for the distance and mass of the lens system. For a lens distance \(\gtrsim\) 7 kpc, the primary lens must be more massive than the Sun and will contribute a significant amount of unlensed light superimposed on the source star. Using an upper limit on the brightness of the primary lens star of 20 \(\pm\) 10% of the source brightness and assuming that the V-band brightness of a main sequence star \(\propto M^{4.5}\) (which is appropriate for \(M \gtrsim 1\) M\(_\odot\)), we find the likelihood function shown...
above. The very steep cutoff at $D_{\text{lens}} > 7 \text{ kpc}$ is due to this constraint on the brightness of the lens. Our main sequence assumption could be avoided if the primary lens was a white dwarf, but since white dwarfs with masses $> 1 M_\odot$ are rare, it is unlikely that our limits on the mass and location of the lens system are violated.
MACHO–97–BLG–41 Triple Lens Model

![Graph showing magnification over days from 31 May 1997 UT]
