

# Planetary Microlensing from the MACHO Project

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**Abstract.** We present the lightcurves of two microlensing events from the MACHO Project data that are likely to be due to lenses with masses similar to Jupiter's mass. Although the MACHO Project survey data are not sufficient to definitively establish the identification of planetary mass lenses in these cases, observations by microlensing follow-up networks such as GMAN and PLANET should be able to definitively determine the planetary nature of similar events which may occur in the near future.

## 1. Introduction

Gravitational Microlensing has been demonstrated to be a powerful observational tool to study populations of stellar or planetary mass objects which emit little detectable radiation. To date the major emphasis of gravitational microlensing survey teams has been the determination of the composition of the Galactic dark matter (Alcock, *et al.*1996a, 1997b, Ansari, *et al.*1996.), but microlensing observations toward the Galactic bulge have yielded a surprisingly high microlensing rate (Alcock, *et al.*1997a, Bennett, *et al.*1995, Udalski, *et al.*1994a). This has important implications for the structure of the Galaxy, but it also yields a relatively large sample of microlensing events that can be used for other studies.

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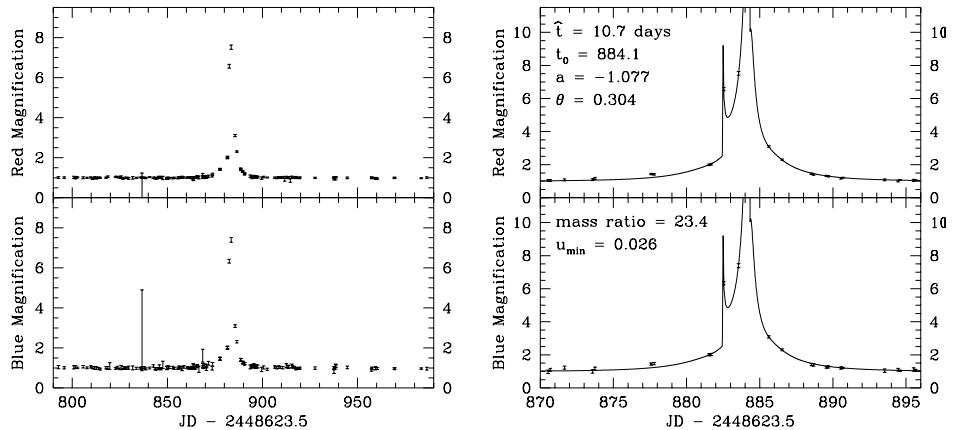


Figure 1. The dual-color lightcurve of event 94-BLG-4 during the 1994 Galactic bulge season and a close-up of the lightcurve showing the binary lens fit.

One of the most exciting possibilities is to use microlensing as a tool to search for planets orbiting the lensing stars (Mao & Paczyński 1991, Gould & Loeb 1992). Microlensing is unique among ground based planetary search techniques for its ability to detect low mass planets (Elachi 1995; Bennett & Rhie 1996); its sensitivity extends down to an Earth mass. The microlensing lightcurve deviations caused by planets are generally quite brief and they will affect only a fraction of all microlensing events even if every lens star hosts its own planetary system. For these reasons, microlensing planet searches require real-time event detection (Alcock, *et al.* 1996b, Udalski, *et al.* 1994b) and frequent microlensing event follow-up observations in order to have high sensitivity to planetary lensing events. It is still possible to detect planetary signals with microlensing survey observations, and in this paper we present two events from the MACHO Project Galactic bulge data which are likely to have been caused by lenses with masses close to  $M_{\text{Jup}}$  (Jupiter's mass).

## 2. Events

Figure 1 shows the lightcurve of event 94-BLG-4 from the 1994 bulge season. This star is a clump giant star with  $R = 16.7$  and  $V - R = 1.1$  which has maintained constant brightness during the 1993 through 1996 bulge seasons with the exception of the short period of brightening shown in Figure 1. This lightcurve shows a unique brightening which is achromatic but also asymmetric, and it is also well explained by the binary microlensing fit shown. The parameters for the binary fit are shown.  $\hat{t}$  is the Einstein diameter crossing time;  $t_0$  is the time of closest alignment between the source and lens center of mass;  $a$  is the separation of the lens components in units of the Einstein radius;  $\theta$  is the angle between the motion of the source relative to the line separating the lenses; and  $u_{\text{min}}$  is the transverse distance of closest approach between the source and lens center of mass. The  $\chi^2 = 430.8$  for the fit shown with 648 data points and 8

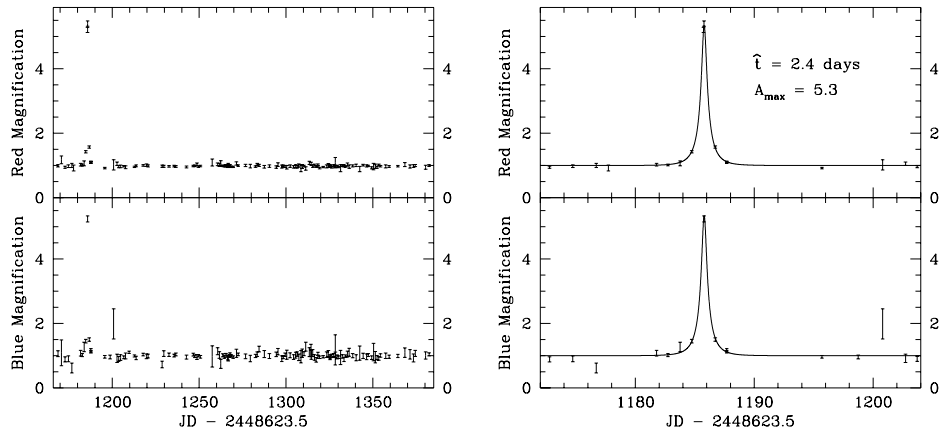


Figure 2. The dual-color lightcurve of event 95-BLG-3 during the 1995 Galactic bulge season and a close-up of the lightcurve showing the lens fit.

parameters. If we add two other parameters to allow for a blended source, the  $\chi^2$  is not improved significantly, and we find that the amount of unlensed light superimposed upon the lensed source is limited to less than 3% (as expected for a clump giant source).

For comparison,  $\chi^2 = 2835$  for a 5 parameter single lens fit, and if we arbitrarily remove both the blue and red measurements at day 882.5, we obtain  $\chi^2 = 491.9$  for the single lens fit. Thus, while we have undersampled the deviation from the best single lens fit, the deviation is not completely confined to the pair of data points obtained in the observation at day 882.5. Formally, the binary fit constrains both the event timescale and the lens mass ratio quite accurately—to better than 3%. The value  $\hat{t} = 10.7$  days indicates a lens mass of  $0.04 M_\odot$  with a  $1 - \sigma$  uncertainty of a factor of 3, but the overall  $\hat{t}$  distribution suggests that the mass is not much less than  $0.1 M_\odot$ . This indicates that the mass of the secondary lens is likely to have  $m \sim 5 M_{\text{Jup}}$  with a factor of 3 uncertainty. Thus, the most likely explanation of this event is that the lens is an M-dwarf system with a giant planet at a projected separation of (very) roughly 1AU.

Figure 2 shows the lightcurve of the shortest event ever seen by the MACHO collaboration with  $\hat{t} = 2.4$  days. This event was detected with our alert system, but it also passes the cuts used in our analysis of the '93 bulge data set. If we apply the standard relationship between  $\hat{t}$  and lens mass we find a most likely lens mass of about  $2 M_{\text{Jup}}$ , but perhaps we should not use the “most likely” mass formula for our shortest event. Couldn't this event be part of the tail of the event timescale distribution caused by more massive lenses? The timescale distribution of events from two bulge seasons is shown in Figure 3. If we assume that mass distribution of lenses has a lower cutoff (of order  $0.1 M_\odot$ ), then it follows that the distribution of detected events will scale as  $\hat{t}^3$  for small  $\hat{t}$ . (We have used the fact that our event detection efficiency scales as  $\hat{t}$  for small  $\hat{t}$ .) This implies that the number of events with  $\hat{t} < \hat{t}_c$  should scale as  $\hat{t}_c^4$ . We can now compare this

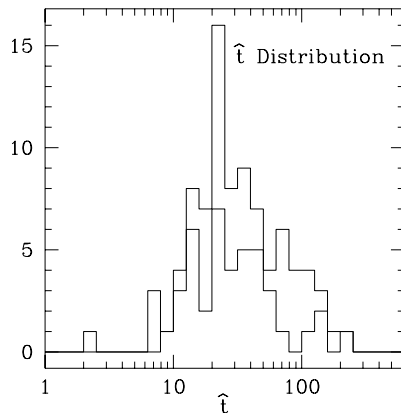


Figure 3. The  $\hat{t}$  distributions of the 1993 MACHO bulge events and the combined 1993 and 1995 bulge events (bold) are shown.

prediction to the timescale distribution shown in Figure 3. The '93 data set has 1 event with  $\hat{t} < 10$  days and 12 events with  $\hat{t} < 20$  days while the '93+'95 data set has 5 events with  $\hat{t} < 10$  days and 24 events with  $\hat{t} < 20$  days. Scaling from these numbers with the  $\hat{t}_c^4$  scaling law implies that we should expect to detect between 0.003 and 0.01 events per year with  $\hat{t} < 2.5$  days, so it is unlikely for us to have detected such an event as a part of the short timescale tail of stellar mass lenses. Thus, we can treat this event as a part of a separate population and the mass estimate of  $2M_{\text{Jup}}$  is a reasonable one. If it is a planet, then it would have to either be in a distant orbit with a projected separation of  $> 5$  or 10 AU, or it could be a planet that has been removed from the planetary system it was born in.

### 3. Conclusions

Unfortunately, we cannot treat either of these two events as definitive detections of planetary mass objects. For the first event, 94-BLG-4, we would require additional observations to fully characterize the binary lightcurve and to definitively establish that our fit is the correct one. For event 95-BLG-3, additional observations taken less than 24 hours after the event peak could have determined if the finite size of the source star was resolved which would have established this event as a *bona fide* planetary mass lensing event. Had this event occurred in 1996, we would have recognized this event in time to request follow-up observations, but in early 1995 our alert system was operating with a time lag of about 30 hours. At present, the time lag for MACHO alerts is typically less than 6 hours. When similar events occur in the future, we can look forward to prompt alert announcements and to higher quality data sets from the ever expanding microlensing follow-up teams such as GMAN and PLANET (Pratt, *et al.*1995, Albrow, *et al.*1995)

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