The Astrophysical Journal, 556:L113–L116, 2001 August 1

LIMITS ON THE ABUNDANCE OF GALACTIC PLANETS FROM 5 YEARS OF PLANET OBSERVATIONS

M. D. Albrow,[1,2] J. An,[3] J.-P. Beaulieu,[4] J. A. R. Caldwell,[5] D. L. DePoy,[3] M. Dominik,[6] B. S. Gaudi,[3,7,8] A. Gould,[3]
J. Greenhill,[9] K. Hill,[9] S. Kane,[2,9] R. Martin,[10] J. Menzies,[5] R. M. Naber,[6] J.-W. Pel,[6] R. W. Pogge,[3]
K. R. Pollard,[1] P. D. Sackett,[6] K. C. Sahu,[2] P. Vermaak,[5] P. M. Vreeswijk,[6,11]
R. Watson,[9] and A. Williams[10]
(The PLANET Collaboration)

Received 2000 August 7; accepted 2001 July 9; published 2001 July 16

ABSTRACT

We search for signatures of planets in 43 intensively monitored microlensing events that were observed between 1995 and 1999. Planets would be expected to cause a short-duration (∼1 day) deviation on the smooth, symmetric light curve produced by a single lens. We find no such anomalies and infer that less than one-third of the $\sim 0.3\ M_\odot$ stars that typically comprise the lens population have Jupiter mass companions with semimajor axes in the range of $1.5\ \mathrm{AU} < a < 4\ \mathrm{AU}$. Since orbital periods of planets at these radii are 3–15 yr, the outer portion of this region is currently difficult to probe with any other technique.

Subject headings: gravitational lensing — planetary systems — stars: late-type — stars: low-mass, brown dwarfs — techniques: photometric

On-line material: color figure

1. INTRODUCTION

Searches for extrasolar planets are being carried out using several methods. More than 60 planets have been discovered by the Doppler shift technique (Marcy, Cochran, & Mayor 2000). While ground-based astrometric searches have not yielded any definitive detections, future astrometric satellites are expected to radically improve the sensitivity of this technique (Lattanzi et al. 2000). The occultation method has yielded an important null result for planets in 47 Tuc (Gilliland et al. 2000) and one confirmation (Charbonneau et al. 2000; Henry et al. 2000). All of these methods are fundamentally restricted to planets with orbital times shorter than the experiment and hence to relatively close (and also generally massive) companions.

Microlensing provides a method to search for planets (Mao & Paczyński 1991) that does not suffer from this limitation. When two stars are approximately aligned with an observer, the nearer star (the "lens") splits the light from the more distant star (the "source") into two images whose brightnesses change as the relative alignment changes. The characteristic angular scale, θ_E ("Einstein ring"), and timescale, t_E, of such a microlensing event are

$$\theta_\mathrm{E} = \sqrt{\frac{4G}{c^2}\frac{M}{D_\mathrm{rel}}}, \quad t_\mathrm{E} = \frac{\theta_\mathrm{E}}{\mu_\mathrm{rel}}, \tag{1}$$

where M is the mass of the lens, $D_\mathrm{rel} \equiv \mathrm{AU}/\pi_\mathrm{rel}$, π_rel is the lens-source relative parallax, and μ_rel is the relative proper motion. Note that $D_\mathrm{rel}^{-1} = D_L^{-1} - D_S^{-1}$, where D_L and D_S are the lens and source distances. For typical events seen toward the Galactic bulge, $\theta_\mathrm{E} \sim 320\ \mu\mathrm{as}(M/0.3\ M_\odot)^{1/2}$, which is too small to resolve directly. However, since the images are magnified, the event can be identified photometrically. For typical bulge events, $\mu_\mathrm{rel} \sim 25\ \mathrm{km\ s^{-1}\ kpc^{-1}}$, so $t_\mathrm{E} \sim 20$ days, and hence nightly monitoring is sufficient to find most events. Four groups—OGLE, MACHO, EROS, and MOA—have carried out such microlensing searches and combined have detected over 700 events, most in the direction of the Galactic bulge (Udalski et al. 2000; Alcock et al. 1997; Abe et al. 1997). All four teams recognize these events in real time and electronically alert the community soon after the onset of the event.

If the lens has a planet that lies close to one of the lensed images of the source, that image is further perturbed and the magnification changes significantly during a time t_p:

$$t_p = \frac{\theta_p}{\theta_\mathrm{E}} t_\mathrm{E}, \quad \theta_p = \sqrt{\frac{m_p}{M}}\theta_\mathrm{E}, \tag{2}$$

where m_p is the mass of the planet. Hence, a planet betrays itself as a short (∼1 day) "bump" on an otherwise normal single-lens light curve (Refsdal 1964; Paczyński 1986). Gould & Loeb (1992) showed that, with photometric precision of about 1%–2%, Jupiter mass planets present a reasonable probability for detection throughout a wide zone centered on the Einstein ring. For typical lens distances of ∼6 kpc, this sensitivity peaks at projected separations $2\ \mathrm{AU}(M/0.3\ M_\odot)^{1/2}$. Since t_p is of order or shorter than the sampling time of the microlensing search teams, Gould & Loeb (1992) advocated setting up a globe-straddling network of observatories to do continuous follow-up observations of alerted events.

---

[1] University of Canterbury, Department of Physics and Astronomy, Private Bag 4800, Christchurch, New Zealand.

[2] Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218.

[3] Department of Astronomy, Ohio State University, 140 West 18th Avenue, Columbus, OH 43210.

[4] Institut d'Astrophysique de Paris, INSU CNRS, 98 bis Boulevard Arago, F-75014 Paris, France.

[5] South African Astronomical Observatory, P.O. Box 9, Observatory 7935, South Africa.

[6] Kapteyn Astronomical Institute, Postbus 800, 9700 AV Groningen, Netherlands.

[7] Institute for Advanced Study, Einstein Drive, Princeton, NJ 08540.

[8] Hubble Fellow.

[9] University of Tasmania, Physics Department, G.P.O. 252C, Hobart, Tasmania 7001, Australia.

[10] Perth Observatory, Walnut Road, Bickley, Perth 6076, Australia.

[11] Astronomical Institute "Anton Pannekoek," University of Amsterdam, Kruislaan 403, 1098 SJ Amsterdam, Netherlands.

The PLANET (Probing Lensing Anomalies NETwork) collaboration was formed in 1995 (Albrow et al. 1996) expressly to carry out such observations and demonstrated in that pilot year that the program was feasible (Albrow et al. 1998). PLANET obtained substantial observing time at four southern locations (Tasmania, Western Australia, South Africa, and Chile) during 1995–1999. During these 5 years, we monitored ~50 microlensing events sufficiently well to have good to excellent sensitivity to planets, none of which displayed a clear photometric anomaly that was best explained by a planet orbiting the lens. We quantify this statement by characterizing the statistical sensitivity of our 5 yr data set to planets. We then use these results to build mass-separation exclusion diagrams for the typical Galactic stars (i.e., microlenses) that our survey probes. The basic method of analysis is given in Gaudi & Sackett (2000) and applied to event OGLE 1998-BUL-14 in Albrow et al. (2000b). The details of its application to the present data set are given by Albrow et al. (2001).

2. PLANET 5 yr PHOTOMETRIC DATA SET

Our data were acquired over 5 years from six telescopes: the Canopus 1 m near Hobart, Tasmania; the Perth/Lowell 0.6 m at Bickley, Australia; the Elizabeth 1 m at the South African Astronomical Observatory (SAAO) at Sutherland, South Africa; the ESO/Dutch 0.9 m at La Silla, Chile; the Yale 1 m; and the Cerro Tololo Inter-American Observatory (CTIO) 0.9 m at La Serena, Chile. Data were collected in Cousins *I* and Johnson *V*, with strong emphasis on the former.

The bulk of events analyzed here have median sampling times of 1–2 hr, or $O(10^{-3}t_{\rm E})$. Observations from four observatories permit round-the-clock monitoring of events; the best events rarely have gaps in the data longer than a day. For such events, the typical photometric precision (as judged by the scatter) is of order 1%–2% for points near the peak, which contain most of the sensitivity to planets. The data set contains five to six high-magnification events with well-sampled peaks. These events contribute at least one-half of our overall sensitivity. For the final event sample, the median number of photometric points within $t_{\rm E}$ of the peak magnification is about 140, with 75% of events having more than 65 points and 25% having more than 250 points within $t_{\rm E}$ of the peak. Details are given in Albrow et al. (2001).

3. EVENT SELECTION

We begin with the complete sample of Galactic bulge events monitored by PLANET during 1995–1999, discarding those of extremely poor quality and those known to contain anomalies characteristic of roughly equal mass binaries or other anomalies unrelated to binarity. Normal point-source/point-lens (PSPL) microlensing events are described by

$$F(t) = F_s A(t) + F_b,$$
$$A[u(t)] = \frac{u^2+2}{u(u^2+4)^{1/2}},$$
$$u(t) = \sqrt{u_0^2 + \frac{(t-t_0)^2}{t_{\rm E}^2}}, \qquad (3)$$

where F is the observed flux, F_s is the source flux, F_b is the flux from any background light that is not magnified, u_0 is the projected source-lens impact parameter, and t_0 is the time of closest approach. Separate F_s and F_b are required for each observatory and wave band.

Nonplanetary light-curve anomalies are identified through explicit modeling. We discard such anomalous light curves from our analysis because we do not currently have the ability to systematically search for planetary signatures in the presence of these secondary effects. We note, however, that none of the excluded light curves show signs of short-duration bumps, except MACHO 97-BLG-41, for which the deviation is explained naturally by binary rotation (Albrow et al. 2000a) rather than a planet orbiting a binary (Bennett et al. 1999).

To eliminate events of particularly poor quality for planet detection, we introduce event selection criteria:

1. All data must pass certain quality tests; only DoPHOT (Schechter, Mateo, & Saha 1993) types 11 and 13 are accepted.
2. There must be at least 20 data points from at least one observatory in one band.
3. Each observatory-band data set included must contain at least 10 data points.
4. The error in u_0 from a combined fit must be less than 50%. If u_0 is not well constrained, then the source's path through the Einstein ring is not well determined, and hence it is difficult to estimate the sensitivity of the event to planets. When available, we use OGLE and MACHO data to help constrain u_0 but not to search for planets. Our final sample includes a total of 43 events. A full list of these events along with the photometric data is presented in Albrow et al. (2001).

4. SYSTEMATIC SEARCH FOR PLANETARY SIGNATURES

The method of measuring the sensitivity of an event to the presence of planets, and at the same time searching for planetary signatures if they are present, is thoroughly described in Albrow et al. (2001). Very briefly, we obtain a PSPL fit using equation (3) and simultaneously renormalize the photometric errors at each observatory so that the total $\chi^2_{\rm PSPL}$ of this fit is equal to the number of degrees of freedom. Note that outliers are not included for error renormalization but are included when searching for planets. We also include in all model fits a term that accounts for the correlation of the photometry with the seeing that we observe in most of our light curves (both microlensed and constant stars). Although these procedures do bias us against binaries, the bias is serious only if all the points from one observatory are concentrated in a short span of the light curve and there are no contemporaneous data from other observatories. From direct inspection of the 43 light curves in our event sample, we find that such bunching affects O (1%) of our total light-curve coverage, which leads to an overestimate of our detection efficiency of a similar magnitude. Since this bias is an order of magnitude smaller than our statistical errors, we ignore it. On the other hand, Monte Carlo experiments with constant stars reveal that error renormalization and removal of systematic effects are essential in order to draw reliable inferences from the light curves and to avoid spurious detections. See Albrow et al. (2001) for details and a thorough discussion.

For each planet-star mass ratio q and each planet-star projected separation $\theta_{\rm E} d$, as well as each angle α of the source trajectory relative to the binary axis, we find the best fit to the remaining parameters (t_0, $t_{\rm E}$, u_0, F_s, and F_b). The corresponding χ^2 thus yields $\Delta\chi^2 \equiv \chi^2 - \chi^2_{\rm PSPL}$, for which we set a threshold value $\Delta\chi^2_{\rm min} = 60$. If $\Delta\chi^2 > \Delta\chi^2_{\rm min}$, then the geometry ($d$, q, α)

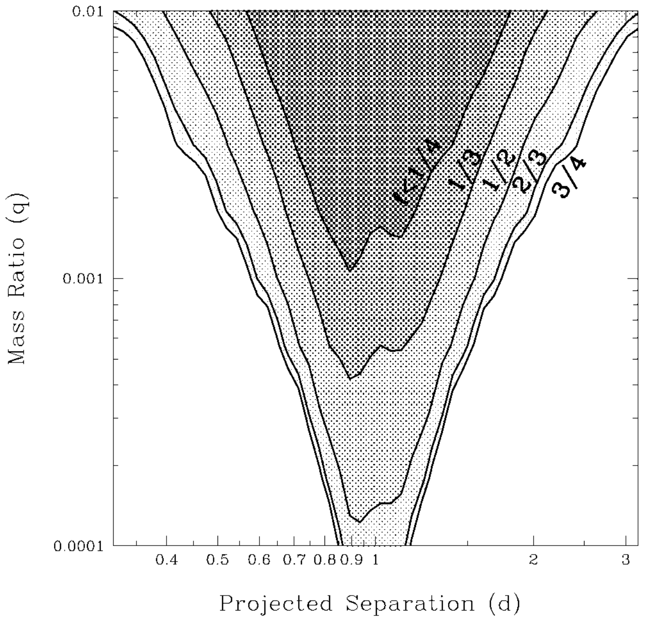

FIG. 1.—Exclusion diagram for pairs of planet parameters (d, q), where d is the projected separation in units of the Einstein ring and q is the planet-star mass ratio. The inner contour indicates the (d, q) for which the fraction of lenses with a planet is $f < \frac{1}{4}$ at 95% confidence. Other contours are for $f < \frac{1}{3}$, $\frac{1}{2}$, $\frac{2}{3}$, and $\frac{3}{4}$. A mass ratio $q = 0.001$ corresponds approximately to $m_p = 0.3\ M_{\rm Jup}$, and a projected separation of $d = 1$ corresponds to a physical projected separation $r_p = 2$ AU. We have assumed a detection threshold of $\Delta\chi^2_{\rm min} = 60$. [*See the electronic edition of the Journal for a color version of this figure.*]

is excluded. If $\Delta\chi^2 < -\Delta\chi^2_{\rm min}$, we tentatively conclude that we have detected a planet. The detection efficiency $\epsilon_i(d, q)$ for planets with this (d, q) in event i is then just the fraction of all angles α (out of 2π) that are excluded. We define a "planetary system" as a binary lens with mass ratio $q < 0.01$.

We set the threshold $\Delta\chi^2_{\rm min} = 60$ by first noting the continuous distribution of $\Delta\chi^2 \lesssim 50$ in our data. If a significant fraction of these were due to planets, the distribution would extend to much more extreme values, since a small random change in the impact parameter could easily increase $\Delta\chi^2$ to several hundred. Hence, the great majority of these deviations must be due to small unrecognized systematic errors. Monte Carlo tests performed with constant stars reveals that deviations of $\Delta\chi^2 \lesssim 60$ are easily explained by systematic and statistical noise. We therefore set the threshold high enough to exclude these nonplanetary sources of noise. We also show results for the more conservative threshold $\Delta\chi^2_{\rm min} = 100$.

This search procedure identifies two possible candidates, but these are also representatives of two classes of phenomena that must be excluded from our search: nearly equal mass binary lenses and global-asymmetry anomalies. MACHO 99-BLG-18 has an ~15 day anomaly of amplitude ~2%. Such an anomaly is longer than that expected from planets with $q \lesssim 0.01$, and we therefore systematically explored binary-lens fits with $q \geq 0.01$. This uncovered a fit with $q \sim 0.2$ that is favored over the best-fit planet ($q \leq 0.01$) by $\Delta\chi^2 = 22$. We therefore exclude MACHO 99-BLG-18 from the analysis. Although $\Delta\chi^2 = 22$ is below our normal threshold ($\Delta\chi^2 = 60$), we estimate that the probability that we have inadvertently thrown out a real planetary detection that is $\lesssim$10%, smaller than the statistical errors on our resultant limit on planetary companions (see Albrow et al. 2001 for a discussion). OGLE 99-BUL-36 displays an overall asymmetry that is consistent with a distortion caused by a $q \sim 0.003$ planet. Such parallax asymmetries are a general feature of parallax, which must be present at some level in all microlensing events (Gould, Miralda-Escudé, & Bahcall 1994). Indeed, this distortion is equally well fit by such a parallax asymmetry model. Given that OGLE 99-BUL-36 has a relatively short timescale ($t_{\rm E} \simeq 30$ days), one might naively expect the parallax interpretation to be unlikely. However, the magnitude of the parallax asymmetry is quite small and detectable only due to the high quality of the data. The resulting asymmetry implies reasonable values for the most probable mass and distance to the lens. We conclude that we cannot reliably detect planets from global asymmetries and should exclude from our analysis all events that display such anomalies and reduce our efficiency estimates accordingly. Although we do not explicitly do this, this results in detection efficiencies that are overestimated by a negligible amount, since a very special planetary geometry is required to produce a global asymmetry (rather than a short duration anomaly). This conclusion is borne out by explicit simulations (Albrow et al. 2001). Thus, there are no viable planet candidates out of our original sample of 43 events.

5. EXCLUSION DIAGRAM FOR GALACTIC PLANETS

From the above analysis of each event i, we obtain an efficiency $\epsilon_i(d, q)$ as a function of planetary geometry (d, q). Let $f(d, q)$ be the fraction of lenses having a planet at (d, q). Then, from binomial statistics, the probability of observing no planets is $P = 1 - \prod_i [1 - f(d, q)\epsilon_i(d, q)]$. Note that in the limit $f\epsilon \ll 1$ (approximately valid in the present study), this

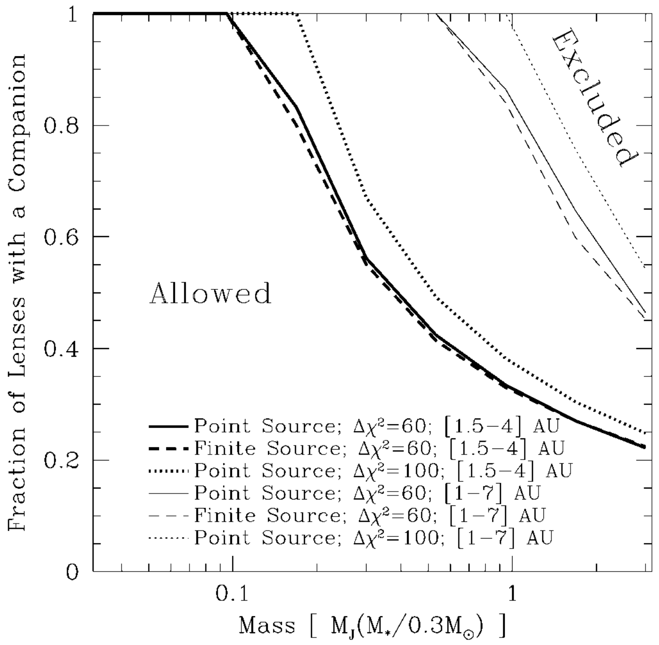

FIG. 2.—Exclusion diagram for planets anywhere in a continuous range of semimajor axes centered on the Einstein ring. Bold curves show the excluded fraction (at 95% confidence) anywhere in the range 1.5 AU $< a <$ 4 AU, while solid curves show the fraction for 1 AU $< a <$ 7 AU. We have assumed a detection threshold of $\Delta\chi^2_{\rm min} = 60$ and that the primary has an Einstein ring radius $r_{\rm E} = 2$ AU. For other Einstein ring radii, the separations scale as ($r_{\rm E}/2$ AU). The dashed curves show the negligible effect of including the finite size of the source in the modeling. The dotted lines are for $\Delta\chi^2_{\rm min} = 100$.

reduces to the Poisson formula $P = [1 - \exp(-N)]$, where $N(d, q) = f(d, q) \sum_i \epsilon_i(d, q)$ is the expected number of detections. Thus, to a good approximation, fractions $f(d, q) \geq 3/\sum_i \epsilon_i(d, q)$ can be rejected at 95% confidence.

Based on this analysis, we build an exclusion diagram (Fig. 1) based on the sample of 42 events (excluding MACHO 99-BLG-18) for planet parameters (d, q). To convert d and q into physical parameters of planet mass m_p and projected physical separation r_p, we must estimate the typical mass M and physical Einstein radius $D_L\theta_E$ for the events in our sample. The majority of detected microlensing events are almost certainly bulge stars lensing other bulge stars (Kiraga & Paczyński 1994). If the lenses were drawn randomly from the bulge mass function as measured by Zoccali et al. (2000), one would expect the typical mass to be $M \sim 0.3\ M_\odot$ and hence the typical timescale to be $t_E \sim 20$ days. However, the median timescale for our sample is 40 days. The difference is probably mainly due to a bias in our selection process. From equation (1), a bias toward large t_E will cause biases toward higher M, higher $\pi_{\rm rel}$, and lower $\mu_{\rm rel}$. Comparing Figures 1*a* and 1*b* from Gould (2000), we infer that most of the dispersion in observed timescales is due to $\mu_{\rm rel}$ and $\pi_{\rm rel}$, so the bias in terms of mass is likely to be modest. Hence, we adopt $M \sim 0.3\ M_\odot$ and $\pi_{\rm rel} \sim 40\ \mu$as, and thus $\theta_E \sim 320\ \mu$as. With our convention $D_L = 6$ kpc, $q = 0.001 \Rightarrow m_p = 0.3\ M_{\rm Jup}$, and $d = 1 \Rightarrow r_p = 2$ AU.

In Figure 2, we present upper limits for the fraction of lenses with planets over two ranges of semimajor axes a centered on the Einstein ring. To convert from projected separation (Fig. 1) to semimajor axis, we integrate over all orientations assuming circular orbits, $M = 0.3\ M_\odot$ and $D_L\theta_E = 2$ AU. We calculate efficiencies using both the point-source approximation and allowing for finite source size (Gaudi & Sackett 2000) but find that the difference is negligible. We find that less than one-third of lenses have Jupiter mass companions anywhere in the range of $1.5\ {\rm AU} < a < 4.0$ AU. These are the first significant limits on planetary companions of M dwarfs.

We thank the anonymous referee for helping to clarify a number of important points. We thank the EROS, MACHO, and OGLE collaborations for providing the original electronic microlensing event alerts that are the sine qua non of this work and the MACHO and OGLE collaborations for providing their original data for many of the events. We are especially grateful to the observatories that support our science (Canopus, CTIO, ESO, Perth, SAAO, Yale) via the generous allocations of time that make this work possible and to those who have donated their time to observe for this program. PLANET acknowledges financial support via award GBE 614-21-009 from the organization for Nederlands Wetenschappelijk Onderzoek (Dutch Scientific Research), the Marie Curie Fellowship ERBFMB-ICT972457 from the European Union, grant Deutsche Forschungsgemeinschaft Do 629/1-1, a "coup de pouce 1999" award from the Ministère de l'Éducation Nationale, de la Recherche et de la Technologie, Département Terre-Univers-Environnement, grants AST 97-27520 and AST 95-30619 from the NSF, NASA grant NAG5-7589, a Presidential Fellowship from Ohio State University, and NASA through a Hubble Fellowship grant from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555.

REFERENCES

Abe, F., et al. 1997, Variable Stars and the Astrophysical Returns of the Microlensing Surveys, ed. R. Ferlet, J.-P. Maillard, & B. Raban (Gif-sur-Yvette: Editions Frontières), 75
Albrow, M., et al. 1996, in IAU Symp. 173, Astrophysical Applications of Gravitational Lensing, ed. C. S. Kochanek & J. N. Hewitt (Dordrecht: Kluwer), 227
———. 1998, ApJ, 509, 687
———. 2000a, ApJ, 534, 894
———. 2000b, ApJ, 535, 176
———. 2001, ApJ, submitted (astro-ph/0104100)
Alcock, C., et al. 1997, ApJ, 479, 119
Bennett, D. P., et al. 1999, Nature, 402, 57
Charbonneau, D., Brown, T. M., Latham, D. W., & Mayor, M. 2000, ApJ, 529, L45
Gaudi, B. S., & Sackett, P. D. 2000, ApJ, 528, 56
Gilliland, R. L., et al. 2000, ApJ, 545, L47
Gould, A. 2000, ApJ, 532, 936
Gould, A., & Loeb, A. 1992, ApJ, 396, 104
Gould, A., Miralda-Escudé, J., & Bahcall, J. 1994, ApJ, 423, L105
Henry, G. W., Marcy, G. W., Butler, R. P., & Vogt, S. S. 2000, ApJ, 529, L41
Kiraga, M., & Paczyński, B. 1994, ApJ, 430, L101
Lattanzi, M. G., Spagna, A., Sozzetti, A., & Casertano, S. 2000, MNRAS, 317, 211
Mao, S., & Paczyński, B. 1991, ApJ, 374, L37
Marcy, G. W., Cochran, W. D., & Mayor, M. 2000, in Protostars and Planets IV, ed. V. Mannings, A. P. Boss, & S. S. Russell (Tucson: Univ. Arizona Press), 1285
Paczyński, B. 1986, ApJ, 304, 1
Refsdal, S. 1964, MNRAS, 128, 295
Schechter, P. L., Mateo, M., & Saha, A. 1993, PASP, 105, 1342
Udalski, A., Zebrun, K., Szymanski, M., Kubiak, M., Pietrzynski, G., Soszynski, I., & Wozniak, P. 2000, Acta Astron., 50, 1
Zoccali, M. S., Cassisi, S., Frogel, J. A., Gould, A., Ortolani, S., Renzini, A., Rich, R. M., & Stephens, A. 2000, ApJ, 530, 418