THE ASTROPHYSICAL JOURNAL, 374:L37–L40, 1991 June 20

GRAVITATIONAL MICROLENSING BY DOUBLE STARS AND PLANETARY SYSTEMS

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Received 1991 March 12; accepted 1991 April 2

ABSTRACT

Almost all stars are in binary systems. When the separation between the two components is comparable to the Einstein ring radius corresponding to the combined mass of the binary acting as a gravitational lens, then an extra pair of images can be created, and the light curve of a lensed source becomes complicated. We estimate that ~10% of all lensing episodes of the Galactic bulge stars will strongly display the binary nature of the lens. The effect is strong even if the companion is a planet. A massive search for microlensing of the Galactic bulge stars may lead to a discovery of the first extrasolar planetary systems.

Subject headings: galaxies: The Galaxy — gravitational lenses — planets: general — stars: brown dwarfs — stars: variables

1. INTRODUCTION

Gravitational lensing of a point source by a point mass creates two images with the combined brightness exceeding that of the source. If the separation between the two images is too small to be resolved, then the only observable consequence of the lensing is a change in the apparent brightness of the source, and the phenomenon is usually referred to as gravitational microlensing. It was discussed in many papers (Einstein 1936; Liebes 1964; Refsdal 1964; Chang & Refsdal 1979, 1984; Gott 1981; Canizares 1982; Vietri & Ostriker 1983; Nityananda & Ostriker 1984, and others). The possibility of using gravitational lensing to detect massive compact objects in the Galactic halo (MACHOs) was first pointed out by Paczyński (1986), and later discussed in more detail by Griest (1991), Nemiroff (1991), and De Rújula, Jetzer, & Massó (1991). Several groups have announced their intent to make an observational search for MACHOs (Alcock, Axelrod, & Park 1989; Bennett et al. 1990; Moniez 1990; Turner, Wardle, & Schneider 1990). Paczyński (1991) and Griest et al. (1991) discussed microlensing of the Galactic bulge stars by the Galactic disk stars, a phenomenon that could be used to detect brown dwarfs.

It is well established that the majority of the Galactic disk stars are binaries with periods in the range $1 < P_{\rm bin} < 10^9$ days, uniformly distributed in log $P_{\rm bin}$, with ~10% of all stars in every decade of $P_{\rm bin}$ (Abt 1983, and references therein). The distribution of mass ratios is subject to a variety of observational biases, but is reasonably well fitted by a power law near q^{-1} over the range $q = 0.1$–1.0 (Trimble 1990, and references therein). Therefore, a fair fraction of microlensing events of the Galactic bulge stars will be due to binaries. Microlensing by two point masses is a well-understood phenomenon (Nemiroff 1986; Schneider & Weiss 1986; Grieger et al. 1989, and references therein). However, the scenario considered so far was microlensing of a quasar at a large redshift by binary stars in a galaxy at a moderate redshift. Here, we propose to look for the effects of microlensing of the Galactic bulge stars by the Galactic disk binaries. Such microlensing events will produce light curves dramatically different from those due to single stars, and some of the events may be missed in a search, unless they will be specifically looked for.

The aim of this *Letter* is to present some examples of microlensing by double stars and by planetary systems, and to estimate the frequency of such events for the Galactic bulge stars as lensed by the Galactic disk objects.

2. MODEL

All computational details involved in microlensing by two point masses can be found in Schneider & Weiss (1986) and Witt (1990), while the specifics of microlensing of the Galactic bulge stars were provided by Paczyński (1991). The geometry of the phenomenon as projected onto the sky is shown in Figure 1. The circle representing the Einstein ring has a radius of 1.0 mas for a source located at a distance of 8 kpc, and a lensing star of 1 $M_\odot$ located at 4 kpc. This corresponds to the radius $R_0 = 6.0 \times 10^{13}$ cm = 4.0 AU at 4 kpc and to 1.2×10^{14} cm = 8.0 AU at 8 kpc. The characteristic time for microlensing induced light variations is $t_0 \equiv R_0/V$, where $V \sim 200$ km s^{-1} is the transverse velocity. For ordinary Galactic disk stars, with masses in the range 0.1–1.0 $M_\odot$, this time scale is in the range 1–4 weeks (Paczyński 1991).

The lens presented in Figure 1 consists of a 1 $M_\odot$ primary and a 0.1 $M_\odot$ secondary, i.e., $q = 0.1$. The separation between them is taken to be equal to the Einstein ring radius of the primary. The lensed source is modeled as a uniform disk of radius $R_{\rm star} = 10^{11}$ cm. The source moves along one of the six straight lines. The corresponding light curves are shown in Figure 2. Usually, three unresolved microimages combine to produce the apparent brightness of the source. However, when the source is projected onto the region surrounded by caustics formed by the binary, then an extra pair of microimages is formed. Whenever the source crosses a caustic, a pair of microimages appears or vanishes, producing spectacular spikes in the light curves shown in Figure 2. A spike may also be produced when a source moves close to a cusp, as shown by the light curve c. When the source trajectory is far from the caustics, the light curves are less interesting, but the binary lens makes them somewhat asymmetric, as also shown in Figure 2 (a, e, and f).

In the same Figure 2 there are two examples of light curves corresponding to the source trajectories c and d for the case

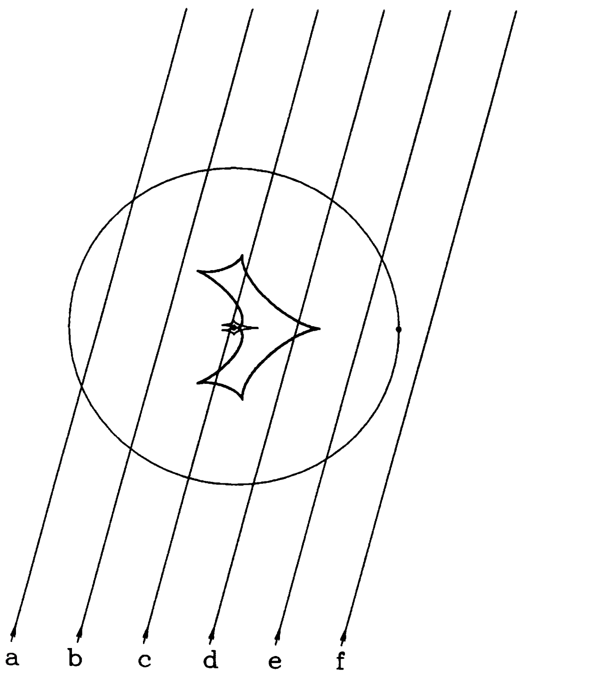

FIG. 1.—Geometry of microlensing by a binary, as seen in the sky. The primary star of 1 $M_\odot$ is located at the center of the figure, and the secondary of 0.1 $M_\odot$ or 0.001 $M_\odot$ is located on the right, on the Einstein ring of the primary. The radius of the ring is 1.0 mas for a source located at a distance of 8 kpc and the lens at 4 kpc. The two complicated shapes around the primary are the caustics: the larger and the smaller corresponding to the 0.1 $M_\odot$ and 0.001 $M_\odot$ companions, respectively. If a source is located outside these regions, then only three microimages are formed, while a source inside them forms five microimages. The parallel straight lines indicate the trajectories of sources for which the light variations are shown in Fig. 2.

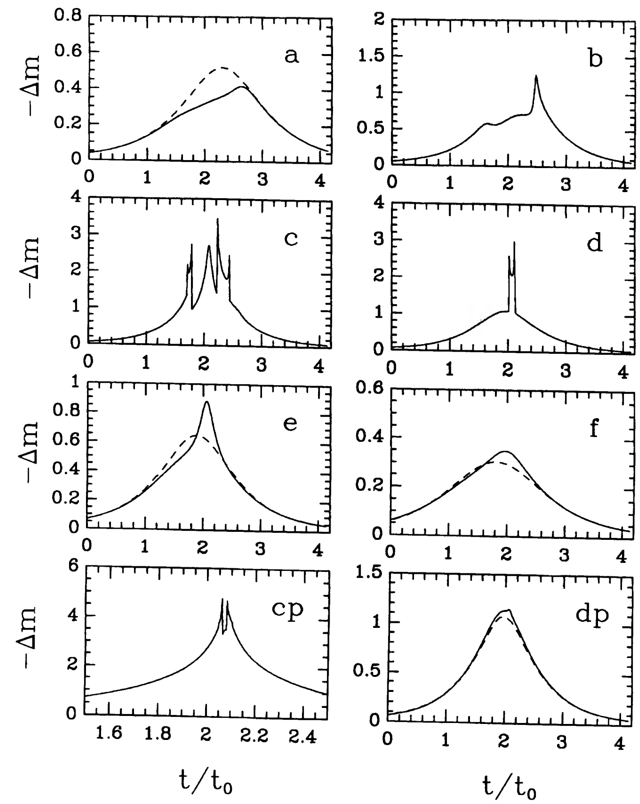

FIG. 2.—The light curves shown correspond to the six source trajectories in Fig. 1. The source is modeled as a uniform disk of radius $R_{\rm star} = 10^{11}$ cm. The first six light curves, a–f, correspond to the case with a 0.1 $M_\odot$ companion; the last two, cp and dp, correspond to the case with a 0.001 $M_\odot$ companion. Notice very high spikes when a source crosses a caustic, or approaches a cusp, as in the light curves c, d, and cp. The low-amplitude light curves a, e, f, and dp, are shown together with the dashed light curves expected for single-mass microlenses matching the wings.

that the secondary has a mass of only 0.001 of the primary, i.e., like that of Jupiter. They differ from the light curves corresponding to $q = 0.1$ in having a much shorter time interval during which the double nature of the lens is striking.

The most dramatic effect of a binary lens is the appearance of five microimages when the source is within the region surrounded by the caustics, and the corresponding spikes in the light curve. Therefore, it is convenient to define the cross section for *strong* binary lensing by the size of that region. We calculated three different measures of that size: the area S, the "width" Δp, and the "length" Δl. The area is the obvious quantity. The "width" is defined as the range of impact parameters for which the source enters the region (or regions) surrounded by the caustics, averaged over all angles between the source trajectory and the line joining the two lensing stars. The "length" is defined as the length of the segment of the source trajectory that is within that region (or regions), averaged over all angles and all impact parameters.

All three cross sections have a peak when the separation between the two components of a binary lens is approximately equal to the Einstein ring radius corresponding to the combined mass of the binary. We further notice that $\Delta S \sim (\Delta p)^2 \sim (\Delta l)^2 \sim a^4$ for $a \ll R_0$ and $\Delta S \sim (\Delta p)^2 \sim (\Delta l)^2 \sim a^{-4}$ for $a \gg R_0$; this can also be shown analytically.

Binary stars are known to have a large range of separations, and the same may be true for planetary systems. As the cross sections for strong binary lensing vary a lot with the ratio a/R_0, it is convenient to calculate the effective "width" and "length" of the caustic region defined as

$$w^* \equiv \int_{-\infty}^{+\infty} \Delta p \, d \log (a/R_0) , \tag{1a}$$

$$l^* \equiv \int_{-\infty}^{+\infty} \Delta l \, d \log (a/R_0) . \tag{1b}$$

Numerical integration gives the effective "width" $w^* = 1.2$, 0.54, 0.19, and 0.06 for the mass ratios $q = 1$, 0.1, 0.01, and 0.001, respectively. The corresponding numbers for the effective "length" are $l^* = 0.46$, 0.19, 0.054, and 0.016. It is interesting, that the cross sections are fairly large even for the extreme mass ratio of 0.001, which corresponds to the secondary being a planet rather than a star. This opens up a possibility of conducting a search for planetary systems associated with the Galactic disk stars by observing their gravitational lensing effects on the Galactic bulge stars.

3. DISCUSSION

We shall estimate the probabilities of two types of events: microlensing of the Galactic bulge stars by binaries and by planetary systems.

The cross section for binary events peaks near the separation corresponding to the Einstein ring radius corresponding to the combined mass of the binary, i.e., a separation of a few AU. This is comfortably in the range in which known binaries are uniformly distributed in log $P_{\rm bin}$ (Abt 1983), and therefore uniformly in log a, where a is the separation between the two components. Therefore, the average "width" of the region surrounded by the binary caustic is given as

$$w(q) = 0.15 \int_{\log a_{\min}}^{\log a_{\max}} \Delta p \, d \log a = 0.15 w^*(q) , \quad q \equiv M_1/M_2 , \tag{2}$$

where $a_{\min} \approx 10^{11}$ cm $\ll R_0$, $a_{\max} \approx 10^{17}$ cm $\gg R_0$, and the numerical coefficient 0.15 corresponds to 10% of all binaries having periods within any decade, and therefore 15% of all binaries having their separations within any decade.

The equation (2) gives $w(1.0) = 0.18$, $w(0.1) = 0.08$, $w(0.01) = 0.028$, and $w(0.001) = 0.009$. The meaning of these numbers is the following. If all binaries had the same mass ratio, say $q = 0.1$, then the average width for their binary cross section would have been $0.08R_0$, while a single star would have a cross section to microlensing equal to $2R_0$. Therefore, the fraction of microlensing events with *strong* binary characteristics would be $0.08R_0/2R_0 = 0.04$, i.e., 4%. However, binaries come with various mass ratios, and we have to average over q. The cross section averaged over the observed mass ratios (Trimble 1990) is

$$w_{\rm binary} = \frac{\int_{0.1}^{1.0} w(q) q^{-1} \, dq}{\int_{0.1}^{1.0} q^{-1} \, dq} = 0.13 . \tag{3}$$

Therefore, the probability that a given microlensing event will produce a *strong* signature of a binary lens is $w_{\rm binary}/2 = 0.07$, i.e., one has to observe ~ 15 microlensing events to find one with a strong binary characteristic, like the light curves c and d in Figure 2. However, this is a very conservative estimate, as the light curves b and e in Figure 2 are also distinctly different from those expected for a single point mass lens. Therefore, the probability that lensing by double stars will be recognized is likely to be larger by a factor of ~ 2.

According to Paczyński (1991) four microlensing events caused by single Galactic disk stars are expected per year per 10^6 Galactic bulge stars in "Baade's window." However, this window is so small that the search will have to be conducted at a higher Galactic latitude, such as $l \sim -6°$, where the probability is down by a factor of 2. The frequency of binary events is likely to be smaller by another factor 10. Therefore, we may expect there are about two binary events per year per 10^7 Galactic bulge stars. Notice, that binary stars with separations either much smaller or much larger than the Einstein ring radii act as single-star microlenses.

Virtually nothing is known about planetary systems, except for our own. Let us suppose that every star has a planet with a mass 10^3 times smaller than the star, and the planet is at a distance between $0.3R_0$ and $3.0R_0$ (note: Jupiter is $\sim 1.3R_0$ from the Sun). This distance range corresponds roughly to 1–10 AU. The average "width" of the region between the caustics due to such planetary systems can be calculated with an integral similar to that in equations (1) and (2). Adopting $q = 0.001$ and changing the range of integration:

$$w_{\rm planet} = \int_{-0.5}^{0.5} \Delta p \, d \log (a/R_0) = 0.06 . \tag{4}$$

In this model the probability of microlensing by a planetary system is $\sim w_{\rm planet} R_0/2R_0 \approx 0.03$, i.e., one out of 30 microlensing events of the Galactic bulge stars may be strongly modified by a planetary system, i.e., the appearance of an extra pair of microimages may produce sharp spikes in the light curve, as shown in Figure 2, light curve cp. However, a clearly noticeable distortion of the light curve is also seen in Figure 2, light curve dp and would likely be noticed in the observations. Therefore, within our model the presence of a planet could be detectable in up to 5% or 10% of all microlensing events, which means about two events per year per 10^7 Galactic bulge stars.

The proposed approach is difficult, but not hopeless. In fact, this may be an easier and more reliable way of determining the presence of planets around other stars than any other technique proposed so far.

A typical duration of a strong disturbance of a light curve by a binary or a planetary companion is just the "length" multiplied by t_0. The average "length" can be calculated in exact analogy with the calculation of the average "width" (cf. eqs. [1]–[3]). We find that $l_{\rm binary} \approx 0.06$ and $l_{\rm planet} \approx 0.015$. Therefore we expect the average duration to be $\approx 0.06t_0$ for binaries, and $\approx 0.015t_0$ for planetary systems. With t_0 in the range 1–4 weeks, we expect $\Delta t_{\rm binary} \sim 0.4$–$1.7$ days, and $\Delta t_{\rm planet} \sim 2.5$–$10$ hr. This is a short time interval, and it can be easily missed in a large-scale search. However, any strong lensing phenomenon, with prominent but short-lasting spikes (cf. Fig. 2) is preceded by a much longer and gradual rise in the luminosity. This points to the need for real time data processing in the search for microlensing, so that potentially interesting events could be identified ahead of time.

The diversity of light curves expected from binary lenses is very large. However, they are determined by only a few parameters: the mass ratio $q = M_1/M_2$, the dimensionless separation between the two components a/R_0, the dimensionless impact parameter p, and the impact angle. In addition there are the time scale of the event t_0, and the source radius. The expected amplitude of light variations is very large, so in most well-observed cases, it should be possible to find all six parameters. In particular, we expect no difficulty in the determination of the mass ratios. Therefore, planets will not be confused with stars.

Our model assumed that the relative positions of the two lensing masses remain constant. In fact, the two will have an orbital velocity $V_{\rm orb} \sim 10$–20 km s^{-1} for separations $a \sim R_0 \sim 4$ AU. This is much smaller than the characteristic transverse lens velocity $V \sim 200$ km s^{-1}. Therefore, the orbital motion will be just a small perturbation. Nevertheless, it may lead to some confusion in the determination of the mass ratio.

There is yet another interesting phenomenon. The spikes due to caustic crossings are infinitely high for a point source, but they have finite amplitude for an extended source. The time scale associated with the peaks can be estimated to be $2R_{\rm star}/V \approx 10^4$ s ≈ 3 hr, where a source radius of $\sim 10^{11}$ cm, and a transverse velocity of ~ 200 km s^{-1} are adopted. Therefore, given advance warning such events could be observed, and could be used to study the source structure. Similar phenomena were discussed by Miralda-Escudé (1991) and by Wambsganss & Paczyński (1991) in the context of sources at cosmological distances.

Presumably some Galactic bulge stars are also double, though their statistics are not known. The microlensing of a double point source by a single point mass is very simple: the combined light curve is a linear superposition of the light curves of the two components. The two amplitudes are determined by the two impact parameters (cf. Figs. 1 and 2 of Paczyński 1991), and the two elementary light curves are shifted in time by an amount that is proportional to the projected separation between the two components. The characteristic time scales t_0 are the same for both elementary light curves, if the binary orbital velocity is small. A difference in colors of the two components will make the apparent light curve color-dependent. A massive search for microlensing events in the Galactic bulge will provide information about the bulge binaries, and it will be most sensitive to binaries with separations comparable to the projected Einstein ring radius, i.e., a few AU.

It is a pleasure to acknowledge stimulating discussions with J. Wambsganss. This project was supported by NASA grant NAGW-765 and NSF grant AST87-18432.

REFERENCES

Abt, H. A. 1983, ARA&A, 21, 343
Alcock, C., Axelrod, T., & Park, H. S. 1989, Seminar at Center for Particle Astrophysics
Bennett, D. P., et al. 1990, preprint, UCRL-JC-105813, Lawrence Livermore National Laboratory
Canizares, C. R. 1982, ApJ, 263, 508
Chang, K., & Refsdal, S. 1979, Nature, 282, 561
———. 1984, A&A, 132, 168
DeRújula, A., Jetzer, Ph., & Massó, E. 1991, preprint, CERN-TH.5797/91
Einstein, A. 1936, Science, 84, 506
Gott, J. R. 1981, ApJ 243, 140
Grieger, B., Kayser, R., Refsdal, S., & Stabell, R. 1989, Abh. Hamburger Sternwarte, 10, 4
Griest, K. 1991, ApJ, 366, 412
Griest, K., et al. 1991, preprint
Liebes, S., Jr. 1964, Phys. Rev., 133, 835
Miralda-Escudé, J. 1991, ApJ, submitted
Moniez, M. 1990, preprint, LAL 90-20
Nemiroff, R. 1986, preprint
———. 1991, A&A, in press
Nityananda, R., & Ostriker, J. P. 1984, J. Ap. Astr., 5, 235
Paczyński, B. 1986, ApJ, 304, 1
———. 1991, ApJ, 371, L63
Refsdal, S. 1964, MNRAS, 128, 295
Schneider, P., & Weiss, A. 1986, A&A, 164, 237
Trimble, V. 1990, MNRAS, 242, 79
Turner, E. L., Wardle, M. J., & Schneider, D. P. 1990, AJ, 100, 146
Vietri, M., & Ostriker, J. P. 1983, ApJ, 267, 488
Wambsganss, J., & Paczyński, B. 1991, AJ submitted
Witt, H, J, 1990, A&A, 236, 311