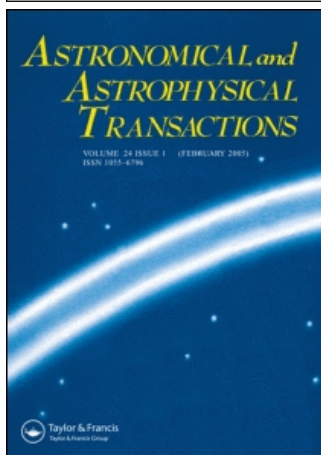


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GRAVITATIONAL LENSING AND LENS INTERFEROMETRY FROM DARK MATTER IN THE GALACTIC HALO

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The gravitational lensing effect and the interferometric effect occurred due to dark bodies of our Galaxy are considered.

KEY WORDS gravitational lensing, interferometry

The missing mass in galactic halos may consist of cold dark matter such as axions or black holes (Blumenthal *et al.*, 1984; Press and Spergel, 1985), or massive neutrinos or other particles (Blumenthal *et al.*, 1984), Jupiters or neutron star and black hole relics of population III stars (Bond *et al.*, 1984) which may have been sufficiently prolific in the early galaxy to account for the mass observed today. Some authors have suggested that observed elemental abundances in the galaxy preclude the latter possibility (M. J. Rees, private communication). However, the high velocity of some pulsars and their distribution at high galactic latitudes demonstrates already that relic neutron stars must be a component of the galactic halo. It is possible to set useful limits on, and possibly detect the populations of neutron stars, black holes, or Jupiters by observing microlensing of stars in background galaxies. By observing the light curve of lensing events, it is possible to determine the mass of the deflectors. The probability of observing microlensing is independent of the mass of the individual deflectors, and depends only on the total mass of deflectors in the halo. Under some circumstances interference fringes may be observed, and these can be used to measure stellar diameters in distance galaxies.

Assume a spherically symmetric distribution of dark halo stars of density n per cubic parsec; with a maximum radius $r_0 \sim 100$ kpc.

Imagine a high resolution field of view on a distant galaxy, at distance $d \gg r_0$, on which there is a surface density of stars σ per square radian. We will consider the probability that in a typical field of view of halo star gravitationally lenses a star in the background galaxy, and that time variable microlensing will occur due to the proper motion of halo object. The volume of the halo v sampled by one field of view ϕ is $v = \pi r_0^3 \phi^2$, and the number of lenses in this field N_e is given by $N_e = \pi n r_0^3 \phi^2$.

The background galaxy acts like a screen on which the lensing objects are revealed. Since we consider only compact halo objects or Jupiters, we can assume them to be point sources. Gravitational lensing is only significant, causing a) increased luminosity and b) double images, if the angular separation between the source and the lensing object is within the cone of inversion θ_0 given by

$$\theta_0^2 = \frac{4GM}{c^2} \frac{L_{SD}}{(L_{SD} + L_{OD})L_{OD}},$$

where L_{SD} is the source-deflector distance, L_{OD} is the observer-deflector distance, and M is the mass of the deflector.

For almost all relevant screen galaxies, $L_{SD} \gg L_{OD}$ and $\theta_0^2 \approx 4GM/c^2(1/L_{OD})$. For a one solar mass deflector between 10^4 and 10^5 pc, $\theta_0 \sim (5 - 1.4) \times 10^{-9}$ rad; for a Jupiter ($10^{-3} M_\odot$) we have $\theta_0 \sim (1.5 - 0.4) \times 10^{-10}$ rad.

First consider the duration of a lensing event. Rotation curve data show typical rotation velocities $V_r \sim 250 \text{ kms}^{-1}$. The duration of a lensing event τ is simply the time for proper motion $\sim \theta_0$: $\tau = L_{OD}\theta_0/V_r$,

$$\tau = \left[\frac{4GM}{c^2} \cdot \frac{L_{OD}}{V_r^2} \right]^{1/2}$$

For the solar mass lensing objects at 10^5 pc, $\tau \sim \frac{1}{2}$ year. To cover the distance range from a few kpc to 100 kpc, the time scale required for observations is from ~ 1 month to ~ 1 year. For Jupiters the time scale is reduced to days. The intensity variation depends on the angular impact parameter for the lensing event θ_1 and is best described by the amplification factor $A = \frac{1}{2} (\xi + \xi^{-1})$ where $\xi^2 = 1 + 4\theta_0^2/(V^2 t^2 + \theta_1^2)$.

Large amplifications are possible, up to $\sim 10^3$, but only in the improbable circumstances of very near alignment. Figure 1 shows a set of light curves for different impact parameters. Notable is the fact that the light curve is always symmetrical. This property can be used to distinguish lensing events from other transient phenomena such as novae.

Now we consider the probability of observing such a lensing process. The observation of an event requires the density of "screen stars" to be high enough that an alignment $< \theta_0$ happens sufficiently often. This can be estimated by considering the total inversion cone angular area α in a field of view ϕ , and comparing it with the inverse of the stellar surface density. (We assume a Poissonian distribution of stellar images, with negligible probability of overlap.) The angular area per star in the field galaxy is σ^{-1} and $\sigma = 2\pi N_s \theta_0^2 = 2\pi n r_0^3 \phi^2 \theta_0^2$. To observe one lens in the field ϕ , we require $\alpha \geq \sigma^{-1}$. This sets the following limit: $\sigma > (4\pi n r_0^3 \phi^2 \theta_0^2)^{-1}$.

If we assume that the total mass of halo objects is constant, M_t , and all are of the same population, with equal mass M , the number of deflectors is inversely proportional to M , but the mean angular area α is *independent* of M , given by:

$$\alpha = \frac{6GM_t}{c^2 r_0} \phi^2.$$

For a halo of $10^{12} M_\odot$, with $r_0 \sim 100$ kpc, we obtain $\alpha \sim 10^{-9} (\text{rad})^2$ per one degree field. To observe lensing events with high probability requires the survey

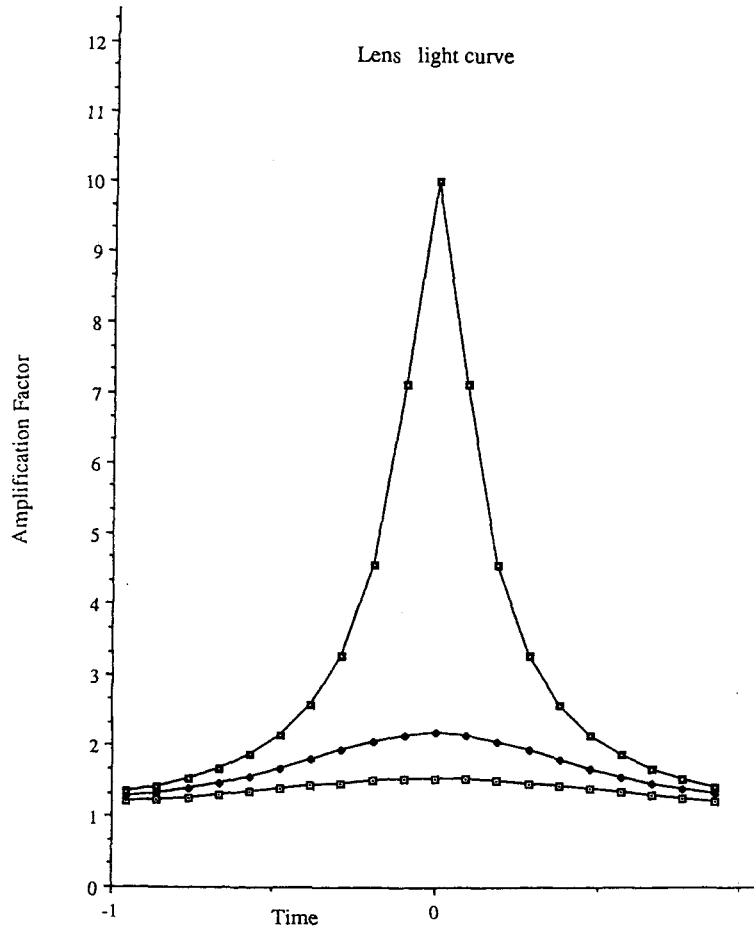


Figure 1 Typical curves for the intensity amplification in a lensing event, with amplification factors of 1.5, 2.2, and 10.

of a screen area of about $(1 \text{ deg})^2$ with a surface density of stars similar to that of a normal galaxy such as M31 or M33. For these, σ^{-1} is $\sim 10^{-11}$ and 2.5×10^{-11} , leading respectively to 1,200 and 400 lensing events at any one time.

The cone of inversion size is less than the diffraction limit for most telescopes, so lens double images will not be resolved. The dominant effect is a luminosity variation occurring over a time scale τ . We note that the detection of microlensing requires a non-homogeneous background screen. Thus stellar images need to be resolved, and it is important to use appropriate background galaxies in which this is possible.

In some circumstances it is possible to observe interference effects in the lensed system. The lens system acts like a very long baseline interferometer, and it may be possible to a) resolve the surfaces of distant stars and b) to detect phase fluctuations introduced by gravitational waves (Sazhin *et al.*, 1989). In rare ideal

circumstances strong “twinkling” would be observed, due to interference of the two beams.

The baseline is equal approximately to the product of the angular size of inversion cone and the distance between the observer and deflector. Numerically, it is $\sim L_{OD}\theta_0 \sim 10^{14}$ cm for a neutron star, and $\sim 10^{13}$ cm for a Jupiter. The resolving power of such an interferometer is of the order of 10^{-17} rad for visible light. The phase difference between the two paths is

$$\Delta\Psi = \frac{\pi L_{DO}}{\lambda_e} \left(\frac{L_{DO}}{L_{SD}} + 1 \right) \theta \sqrt{\theta^2 + 4\theta_0^2},$$

where θ is the angular separation between the source and deflector. If the path lengths are close enough, interference maxima and minima will occur due to the motion of the Earth-deflector system. The fringe spacing is determined by the condition $\Delta\Psi = \pi$. For values of $\theta \sim \theta_0$ (at the edge of the cone of inversion), the time interval between the maxima is

$$\delta\tau = \pi \frac{\lambda_e}{V_r} \frac{L_{SD}}{L_{SD} + L_{OD}} \frac{1}{\theta A(\theta_1)}.$$

Figure 2 shows a typical interference light curve.

At the edge of the inversion cone the time interval between fringes is ~ 2 ms for a neutron star and ≈ 40 ms for a Jupiter. At the point of closest encounter the fringe rate reaches a minimum value, given by

$$\delta\tau \approx \frac{100}{A^{1/2}} \text{ s}$$

independent of the deflector mass.

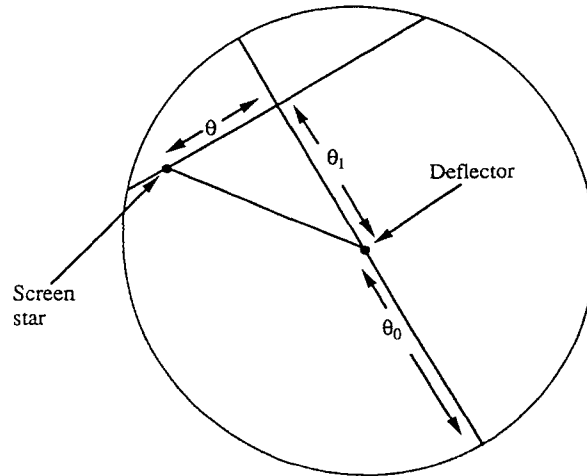


Figure 2 Geometrical diagram for a lensing event. The screen star is within the inversion cone of the deflector, θ_0 . The angular separation between position of the deflector and the point of closest encounter is θ_1 . The second image would emerge on the opposite side of the deflector, but since it is unresolvable, is not shown here.

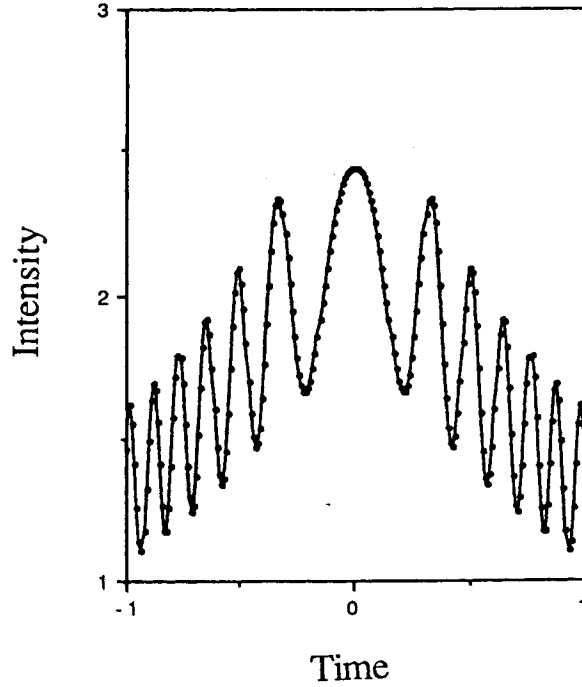


Figure 3 A toy model for the gravitational lens twinkling of a star. The ratio of deflector mass (GM/c^2) to the optical wavelength is 30, and the depth of modulation is $\sim 20\%$. The period of the twinkling increases from the edge of the inversion cone and the intensity passes through a characteristic maximum at the center.

These results are valid for an unresolved screen star. For the real screen star the brightness distribution over the disk is given by

$$I(\theta) = \frac{I_O}{\theta_s} \left[1 - \left(\frac{\theta}{\theta_s} \right)^2 \right],$$

where I_O is the total flux from the star, and θ_s is the characteristic angular scale of the brightness distribution. The modulation depth of the interference fringes is then given by

$$\frac{\delta I}{I} \approx \frac{1}{4\pi^2} \frac{\lambda_e^2}{r_g L_{DO}} \frac{L_{OS}^2}{R_*^2},$$

where R_* is the radius of the screen star, L_{OS} is the distance to the screen star and $R_*/L_{OS} = \theta_s$. To obtain a large intensity modulation we must have small deflector mass, and small radius R_* , and to detect the modulation we require a large enough telescope to give a reasonable photon count rate.

The effect of modulation is negligible for a neutron star deflector and a main sequence screen star. The situation becomes better with a deflector of the earth mass but still, in the case of Andromeda, $\delta I/I$ is only $\sim 10^{-5}$, for visible light, $R_* = R_\odot$ and $L_{OD} = 10$ kpc. In this situation, however, star spots of size

$\sim 10^{-2}R_{\odot}$ could give rise to a modulation depth $\sim 10\%$. The time interval between the maxima would be ~ 1 s and the total duration of the event would be $\sim 10^4$ s.

If the screen star was a white dwarf, with the deflector at 1 kpc, $\delta I/I$ increases to 100%. Unfortunately, present telescopes cannot detect white dwarfs at 1 Mpc, but by using a 40 m optical telescope the effect could be observed.

At optical wavelengths twinkling will be a rare phenomena to observe, due to the requirement that the path lengths are equal within the coherence length of the source. However, lensing light curves should be frequently observable if the missing mass is due to matter in macroscopic form. The frequency and duration of the lensing events will allow the mass and space density of lensing objects to be estimated. Modern image processing techniques should allow efficient detection of such events on 10^6 pixel CCD frames.

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