Polarization in binary microlensing events

G Ingrosso\textsuperscript{1,2}, F De Paolis\textsuperscript{1,2}, A A Nucita\textsuperscript{1,2}, F Strafella\textsuperscript{1,2}, S Calchi Novati\textsuperscript{3,4}, Ph Jetzer\textsuperscript{5}, G Liuzzi\textsuperscript{6} and A Zakharov\textsuperscript{7,8,9}

\textsuperscript{1} Dipartimento di Matematica e Fisica \textquoteleft E. De Giorgi\textquoteright, Università del Salento, Via per Arnesano, I-73100, Lecce, Italy
\textsuperscript{2} INFN, Sezione di Lecce, Via per Arnesano, I-73100, Lecce, Italy
\textsuperscript{3} Dipartimento di Fisica \textquoteleft E. R. Caianiello\textquoteright, Università di Salerno, I-84084 Fisciano (SA), Italy
\textsuperscript{4} Istituto Internazionale per gli Alti Studi Scientifici (IIASS), Vietri Sul Mare (SA), Italy
\textsuperscript{5} Institute für Theoretische Physik, Universität Zürich, Winterthurerstrasse 190, 8057 Zürich, Switzerland
\textsuperscript{6} Scuola di Ingegneria, Università degli Studi della Basilicata, via dell\’Ateneo Lucano 10, 85100, Potenza, Italy
\textsuperscript{7} Institute of Theoretical and Experimental Physics, B. Cheremushkinskaya 25, 117259 Moscow, Russia
\textsuperscript{8} Bogoliubov Laboratory of Theoretical Physics, Joint Institute for Nuclear Research, 141980 Dubna, Russia
\textsuperscript{9} North Carolina Central University, 1801 Fayetteville Street, NC 27707 Durham, USA

E-mail: ingrosso@le.infn.it

Received 24 June 2013, revised 9 October 2013
Accepted for publication 9 October 2013
Published 11 July 2014

Abstract

The light received by source stars in microlensing events may be significantly polarized if both an efficient photon-scattering mechanism is active in the source stellar atmosphere and a differential magnification is therein induced by the lensing system. The best candidate events for observing polarization are highly magnified events with source stars belonging to the class of cool, giant stars in which the stellar light is polarized by photon scattering on dust grains contained in their envelopes. The presence in the stellar atmosphere of an internal cavity devoid of dust produces polarization profiles with a two peaks structure. Hence, the time interval between them gives an important observable quantity directly related to the size of the internal cavity and to the model parameters of the lens system. We show that, during a microlensing event, the expected polarization variability can solve an ambiguity that arises in some cases, related to the binary or planetary lensing interpretation of the perturbations observed near the maximum of the event light-curve. We consider a specific event case for which the parameter values corresponding to the two solutions are given. Then, assuming a polarization model for the source star, we compute the two expected polarization profiles. The position of the two peaks appearing in the polarization curves and the characteristic time interval between them allow us to distinguish between the binary and planetary lens solutions.

Keywords: microlensing techniques, stellar atmospheres, polarization of starlight, mass loss and stellar winds

1. Introduction

Gravitational microlensing technique initially developed to search for massive astrophysical compact halo objects (MACHOs) in the Galactic halo by long observational campaigns towards several directions in the sky \cite{3, 5, 8, 29}, has become nowadays a powerful tool to investigate several astrophysical phenomena. Microlensing observations have been used:

\begin{itemize}
  \item to map the amount and distribution of luminous matter in the Galaxy, Magellanic Clouds and the M31 galaxy \cite{11, 14, 23};
  \item to carry out detailed studies of different classes of variable stars which actually do change their brightness due to changes in size and temperature \cite{26, 27};
  \item to test stellar atmosphere models via the detection of limb-darkening effects \cite{1, 13, 33};
\end{itemize}
Polarization of the stellar light is produced if some suitable asymmetry is present in the stellar disk due, e.g., to hot spots, tidal distortions, eclipses, fast rotation or magnetic fields.

In the microlensing context, an overall polarization of the stellar light is always present since different parts of the source star disk are differently magnified by the lens system. Moreover, due to the relative motion between source and lens, the gravitational lens scans the disk of the source star giving rise also to a time dependent polarization signal. The polarization signal will be relevant, and possibly observable, in events with high magnification (both single lens and binary), which also show large finite source effects, namely for events in which the source star radius is of the order or greater than the lens impact parameter.

In a recent work [19] we considered a specific set of highly magnified, single-lens events and a subset of exoplanetary events observed towards the Galactic bulge. As an illustration, we also considered the expected polarization signal for the PA-99-N2 exoplanetary event towards M31. We calculated the polarization profiles as a function of time taking into account the nature of the source stars. Given a band typical magnitude at maximum magnification of about 12 and a duration of the polarization signal up to 1 day, we showed that the currently available technology, in particular the polarimeter in FORS2 on the VLT, may potentially allow the detection of such signals.

Besides the interest related to stellar astrophysics, the analysis of a polarization profile (which is related to the underlying magnification light-curve) may in principle provide independent constraints on the lensing parameters in binary events. The aim of the present paper is to show that, given sufficient observational precision, polarization measurements are able to solve a specific type of ambiguity, namely the planet or binary interpretation of anomalies present in microlensing light curves. The general method is similar to that of [21] in which the presence in giant stars of resonant lines with intensity increasing from the center to the star limb (and a variable magnification across the stellar disk) leads to narrow band (centered on the resonance line) stellar fluxes with a two peaks structure. Similarly, we obtain polarization profiles with a double peak structure and the observable time interval between them becomes an important tool to investigate both the source and lens parameters.

High magnification microlensing events provide an important channel to detect planets, via the detection of perturbations near the peak of the events. It is known that these perturbations can be produced by a planet or a binary companion to the primary lens and that both types of solutions can be generally distinguished, due to different magnification patterns around caustics. However, there are cases (that are expected to be common), in which the degeneracy between the planet and binary solution cannot be resolved by the analysis of the light curves. We consider in particular the OGLE-2011-BLG-0905/MOA-2011-BLG-336 event case [9].
and we show that the expected polarization curves are different for the planet and binary case, potentially allowing us to solve the ambiguity. Of course, since accurate polarization measurements cannot be obtained with a survey telescope, alert systems are necessary, allowing large telescopes to take polarimetry measurements during a microlensing event.

2. Generalities

Following the approach outlined in [7] we define the intensities $I_\parallel (\mu)$ and $I_\perp (\mu)$ emitted by the scattering atmosphere in the direction making an angle $\chi$ with the normal to the star surface and polarized as follows: $I_\parallel (\mu)$ is the intensity in the plane containing the line of sight and the normal, $I_\perp (\mu)$ is the intensity in the direction perpendicular to this plane.

We choose a coordinate system in the lens plane with the origin at the center of mass of the binary system. The Ox axis is directed towards the observer, the Ox axis is oriented parallel to the binary component separation. The location of a point $(x, y)$ on the source star surface is determined by the angular distance $\rho$ from the projected position of the source star center $(x_0, y_0)$ and by the angle $\varphi$ with the Ox axis $(x = x_0 + \rho \cos \varphi$ and $y = y_0 + \rho \sin \varphi)$. In the above coordinate system $\mu = \sqrt{1 - \rho^2 / \rho_0^2}$, where $\rho_0$ is the angular source radius. Here and in the following all angular distances are given in units of the Einstein angular radius $\theta_E$ of the total lens mass.

To calculate the polarization of a star we integrate the unnormalized Stokes parameters and the flux over the star disk [2, 24]

$$F = F_0 \int_0^{2\pi} \int_0^{\rho_0} A(x, y) I_\perp (\mu) \rho d\rho d\varphi,$$

$$F_\parallel = F_0 \int_0^{2\pi} \int_0^{\rho_0} A(x, y) I_\parallel (\mu) \cos 2\varphi \rho d\rho d\varphi,$$

$$F_\perp = F_0 \int_0^{2\pi} \int_0^{\rho_0} A(x, y) I_\perp (\mu) \sin 2\varphi \rho d\rho d\varphi,$$

where $F_0$ is the unmaginified star flux, $A(x, y)$ is the point source magnification due to the lens system and $I_\parallel (\mu) = I_\parallel (\mu) + I_\perp (\mu)$ and $I_\perp (\mu) = I_\parallel (\mu) - I_\perp (\mu)$ are intensities related to the considered polarization model.

As usual [7], the polarization degree

$$P = \left( F_\perp^2 + F_\parallel^2 \right)^{1/2} / F,$$

and the polarization angle

$$\theta_p = (1/2) \tan^{-1} \left( F_\perp / F_\parallel \right).$$

Since we are dealing with binary events for which the source trajectory may intersect either fold caustics or cusps (where the lensing magnification of a point source becomes infinite), instead of directly solving the lens system [31], we evaluate the magnification $A(x, y)$ at any point in the source plane by using the inverse ray-shooting method [20, 30]. As it is well known, the magnification depends on the mass ratio $q$ between the binary components and on their projected separation $d$ (in units of the Einstein radius $R_E$).

Further parameters entering in the above equations are the coordinates $(x_0, y_0)$ of the source star center. These are given, at any time $t$, in terms of the other lens system parameters, that are: the maximum amplification time $t_{\text{E}}$, the impact parameter $u_0$ (which is the minimum distance between source star center and the center of mass of the lens system), the Einstein time $t_E$ and the angle $\alpha$ of the source trajectory with respect to the Ox axis connecting the binary components.

3. Polarization for cool giant stars

Polarization during microlensing of source stars with extended envelopes has been studied for single-lens events [25] and for binary lensing [15]. As emphasized in these works, the model is well suited to describe polarization in evolved, cool stars that exhibit stellar winds significantly stronger than that of the Sun.

The scattering opacity responsible for producing the polarization is the photon scattering on dust grains. However, since the presence of dust is only possible at radial distances at which the gas temperature is below the dust sublimation temperature $T_h \approx 1300$ K (depending on the grain composition), in our model a circumstellar cavity is considered between the photosphere radius and the condensation radius $R_c$, where the temperature drops to $T_c$.

The dust number density distribution is parametrized by a simple power law

$$n_{\text{dust}}(r) = n_0 \left( R_h / r \right)^{\beta} \text{for } r > R_h,$$

where $r = (\rho^2 + z^2)^{1/2}$ is the radial distance from the star center, $n_0$ is the dust number density at the radius $R_h$ of the central cavity and $\beta$ is a free parameter depending on the velocity structure of the wind: $\beta = 2$ holds for constant velocity winds while larger values correspond to accelerated winds.

We estimate $R_h$ according to simple energy balance criteria. We consider the balance between the energy absorbed and emitted by a typical dust grain as a function of the radial distance from the star

$$\int_0^r F_s^2 (r) \pi a^2 Q d\lambda = \int_0^r 4\pi a^2 B_{\nu} (T(r)) \lambda d\lambda,$$

where $F_s^2 (r)$ is the stellar flux, $Q$ is the grain absorption efficiency, $T(r)$ the dust temperature, $B_{\nu} (T(r))$ the black body emissivity and $a$ the dust grain size. This calculation assumes that the heating by non-radiative processes and by the diffuse radiation field is negligible so that we limited ourselves to compute $Q$, for a typical particle size distribution [22] with optical constants derived by Draine and Lee [10]. Specifically, the numerical value of $R_h$ is obtained by using equation (5) with $T(R_h) = T_c$. Assuming $T_c \approx 1300$ K, we
show in figure 1 the ratio $R_{\text{h}}/\sqrt{R_{\text{h}}}$ as a function of the stellar surface temperature $T_{\text{s}}$. The typical dust sublimation temperature $T_{\text{s}} \approx 1300$ K has been assumed.

The explicit form of the intensities $I_{\alpha}(\mu)$ and $I_{\beta}(\mu)$ is given in [15, 25]. It turns out that the polarization $P$ linearly depends on the total optical depth $\tau = n_{\text{e}} \sigma_{\text{h}} / (\mu - 1)$, where $\sigma$ is the scattering cross-section and the scatterers are taken to exist only for $r > R_{\text{h}}$. An estimate of the order of magnitude of $\tau$ is derived assuming a stationary, spherically symmetric stellar wind [16]

$$\tau \approx 2 \times 10^{-3} \eta K \left( \frac{M}{10^{-3} M_{\odot} \text{ yr}^{-1}} \right) \left( \frac{30 \text{ km s}^{-1}}{v_{\infty}} \right)^{2} \left( \frac{24 R_{\odot}}{R_{\text{h}}} \right),$$

(6)

where $\eta \approx 0.01$ is the dust-to-gas mass density ratio, $K \approx 200 \text{ cm}^{2} \text{ g}^{-1}$ is the dust opacity at $\lambda > 5500$ Å, $M$ is the mass-loss rate and $v_{\infty}$ the asymptotic wind velocity.

To estimate $\tau$ for cool giant stars, we relate $M$ to the stellar parameters of the magnified star. Indeed, it is well known that from main sequence to AGB phases, $M$ increases by 7 orders of magnitude [12]. By performing numerical simulations of the mass loss of intermediate and low-mass stars, it was shown that $M$ obeys to the relation

$$M = 2 \times 10^{-14} \left( \frac{L/L_{\odot}}{R/R_{\odot}} \right)^{2} \left( \frac{T/T_{\odot}}{M/M_{\odot}} \right)^{3} M_{\odot} \text{ yr}^{-1}.$$  

(7)

For the more common stars evolving from main sequence to red giant star phases, $M$ values in the range $\left(10^{-13} - 10^{-3}\right) M_{\odot} \text{ yr}^{-1}$ are expected. This corresponds, from equation (6) to values of $\tau$ in the range $4 \times 10^{-4} - 4 \times 10^{-2}$.

4. Results

In the following we focus in particular on the event OGLE-2011-BLG-0950/ MOA-2011-BLG-336 event, corresponding to the models A and B in table 1. The light curves of the two models are almost identical and thus indistinguishable and agree very well with the experimental points of the event [9].

Figure 1. The ratio $R_{\text{h}}/\sqrt{R_{\text{h}}}$ is shown as a function of the stellar surface temperature $T_{\text{s}}$. The typical dust sublimation temperature $T_{\text{s}} \approx 1300$ K has been assumed.

Figure 2. Simulated light-curves of the OGLE-2011-BLG-0950/ MOA-2011-BLG-336 event, corresponding to the models A and B in table 1. The light curves of the two models are almost identical and thus indistinguishable and agree very well with the experimental points of the event [9].

11 Negative perturbation means that the magnification of the perturbed part of the light curve is lower than the magnification of the corresponding single-lensing event. In the model A, the source trajectory passes the negative perturbation region behind an arrowhead-shaped central caustic, in the model B the analogous region is between two cusps of an asteroid-shaped caustic [9].
Figure 3. Polarization profiles in units of $\tau$ are given for different values of $\beta$ and $R_s$. In the upper panel, assuming $R_s = 6R_e$, the continuous, dotted and dashed curves correspond to $\beta = 2$, $3$, $4$, respectively. In the bottom panel with $\beta = 3$, we vary $R_e = 6R_s$ (continuous), $R_e = 10R_s$ (dotted) and $R_e = 14R_s$ (dashed line).

Figure 4. Polarization profiles in units of $\tau$ for the models A and B in table 1. The polarization parameters are $\beta = 3$ and $R_e = 10R_s$.

Table 1. Best-fit parameters of the event OGLE-2011-BLG-0950/ MOA-2011-BLG-336 for the binary (A) and planetary (B) lens models.

| model  | $t_0$ (days) | $u_0$ ($10^{-3}$) | $t_e$ (day) | $d$ | $q$ | $\alpha$ | $\rho_h$ ($10^{-3}$)
|--------|--------------|------------------|-------------|-----|-----|----------|----------------|
| A      | 5786.40      | 9.3              | 61.39       | 0.075 | 0.83 | 0.739    | 3.2            |
| B      | 5786.40      | 8.6              | 65.21       | 0.70  | 5.8  | $10^{-3}$ | 4.664          |

The polarization signal gets the maximum when the condensation radius $R_s$ (the radius of the central cavity in the stellar atmosphere) enters and exits the lensing region. Two peaks appear at symmetrical position with respect to $t_0$ and the characteristic time scale $\Delta t_o$ between them is related to the transit duration of the central cavity

$$\Delta t_o \approx 2t_E \times \sqrt{R_s^2 - u_0^2}. \quad (8)$$

In figure 3 (upper panel, where $R_s = 6R_e$), we explore the effect on the polarization signal of varying the parameter $\beta$. As one can see, the maximum polarization value increases for the model B. The polarization signal gets the maximum when the condensation radius $R_s$ (the radius of the central cavity in the stellar atmosphere) enters and exits the lensing region. Two peaks appear at symmetrical position with respect to $t_0$ and the characteristic time scale $\Delta t_o$ between them is related to the transit duration of the central cavity

$$\Delta t_o \approx 2t_E \times \sqrt{R_s^2 - u_0^2}. \quad (8)$$

In figure 4, by taking as an illustration $\beta = 3$ and $R_e = 10R_s$, we compare the expected polarization profiles for the best-fit models A and B in the OGLE-2011-BLG-0950/ MOA-2011-BLG-336 event. The position of the two maxima is different and such difference remains for any selected values of $\beta$ and $R_e$. Therefore, an independent determination of $R_s$, based (as shown in figure 1) on a direct observation of the source star temperature $T_s$ and the determination of the source radius $R_s$ (through the best-fit to the event light-curve), allows us to distinguish the two models A and B, namely the binary or planetary solution to the lens system.

Actually, in the case of the considered event OGLE-2011-BLG-0950/ MOA-2011-BLG-336, the radius and the surface temperature of the source are unconstrained by observations and therefore our analysis of the simulated polarization profiles remains an exercise that, anyhow, shows the potentiality of the method.

The polarization signal of varying the parameter $\beta$. This behavior is expected since the dust density gradient across $R_s$ (which is transiting the lensing region) increases with increasing $\beta$ and this has the effect to reinforce the asymmetry across the stellar atmosphere which, ultimately, is at the origin of the polarization signal for cool giant stars. The bottom panel of figure 3, where we fix $\beta = 3$, shows that for increasing $R_s$ values the distance between the two maxima increases. The effect is present in the polarization curves (not shown) evaluated for different $\beta$ values. From these results it is evident that the only relevant model parameter is $R_s$, which is directly related to the observable time interval $\Delta t_o$, as shown in equation (8). The parameter $\beta$, related to the wind acceleration mechanism, remains instead largely undetermined, since it does not exist an observable uniquely related to it.

We emphasize that the detection of the polarization signals in forthcoming microlensing events is technically reachable, as already noted in [19]. However, to that aim, it is necessary to select, among all microlensing events, the class of the highly magnified events that also show large finite size source effects, in particular events with source stars belonging to the class of cool, giant stars [32]. These evolved stars have both large radii (giving rise to relevant finite size source effects) and large stellar atmospheres, where the light get polarized by photon scattering on dust grains. For these events, hopefully, the dust optical dept $\tau$ could be $\leq 10^{-3}$ so that the polarization signals $P \geq 0.2\%$ could be detectable, due to both the high brightness at maximum and the large time duration of the polarization signal. This observational
programme may take advantage of the currently available surveys plus follow up strategy already routinely used for microlensing monitoring towards the Galactic bulge (aimed at the detection of exoplanets). In particular, this allows one to predict in advance for which events and at which exact time instant the observing resources may be focused to make intensive polarization measurements.

We conclude by noting that polarization measurements in a binary microlensing event (OGLE-2012-BLG-0798) have been performed recently. The data analysis, with the aim of distinguishing among the several models that give a good fit of the observed light curve, is at present in progress [6].

References

[1] Abe F, Bennett D P, Bond I A et al 2003 Astron. Astrophys. 411 L493
[2] Agol L 1996 Mon. Not. R. Astron. Soc. 279 571
[3] Alcock C, Akerloff C W, Allsman R A et al 1993 Nature 365 621
[4] An J H, Evans N W, Kerins E et al 2004 Astrophys. J. 601 845
[5] Aubourg E, Bareyre P, Brehin S et al 1993 Nature 365 623
[6] Bozza V et al 2013 personal communication
[7] Chandrasekhar S 1950 Radiative Transfer (Oxford: Clarendon)
[8] Cho J-Y, Shin I-G, Han C et al 2012 Astrophys. J. 756 48
[9] Draine B T and Lee H M 1984 Astrophys. J. 285 89
[10] Evans N W and Belokurov V 2002 Astrophys. J. 567 L119
[11] Ferguson J W, Alexander D R, Allard F et al 2005 Astrophys. J. 623 585
[12] Gaudi B S and Gould A 1999 Astrophys. J. 513 619
[13] Gyuk G 1999 Astrophys. J. 510 205
[14] Ignace R, Bjorkman E and Bryce H M 2006 Mon. Not. R. Astron. Soc. 366 92
[15] Ignace R, Bjorkman E and Bunker C 2008 Proc. Manchester Microlensing Conf.: 12th Int. Conf. ANGLES Microlensing Workshop ed E Kerins, S Mao, N Rattenbury and L Wyrzykowski Proc. Sci. (GMCS)002
[16] Ingrosso G, Calchi Novati S, De Paolis F et al 2009 Mon. Not. R. Astron. Soc. 399 219
[17] Ingrosso G, Calchi Novati S, De Paolis F et al 2011 Gen. Relativ. Gravit. 43 1047
[18] Ingrosso G, Calchi Novati S, De Paolis F et al 2012 Mon. Not. R. Astron. Soc. 426 1496
[19] Kayser R, Refsdal S and Stabell R 1986 Astron. Astrophys. 166 36
[20] Loeb A and Sasselov D 1995 Astrophys. J. L 449 33
[21] Mathis J S, Rumpl W and Nordsiek K H 1977 Astrophys. J. 217 425
[22] Moniez M 2010 Gen. Relativ. Gravit. 42 2047
[23] Simmons J F L, Newsam A M and Willis J P 1995 Mon. Not. R. Astron. Soc. 276 182
[24] Simmons J F L, Bjorkman J E, Ignace R and Coleman I J 2002 Mon. Not. R. Astron. Soc. 336 501
[25] Soszyński I, Udalski A, Szymański M et al 2011 Acta Astr. 61 217
[26] Soszyński I, Udalski A, Szymański M et al 2013 Acta Astr. 63 21
[27] Stenflo J O 2005 Astron. Astrophys. 429 713
[28] Udalski A, Szymański M, Katuszny J et al 1994 Astrophys. J. 426 L69
[29] Wambsganss J 1997 Mon. Not. R. Astron. Soc. 284 172
[30] Witt H J and Mao S 1994 Astrophys. J. 430 505
[31] Zub M, Cassan A, Heyrovsky D et al 2011 Astron. Astrophys. 525 A15
[32] Rattenbury N J et al 2005 Astron. Astrophys. 439 645