Observation of Microlensing towards the Galactic Spiral Arms. EROS II 2 year survey *

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Abstract. We present the analysis of the light curves of 8.5 million stars observed during two seasons by EROS (Expérience de Recherche d’Objets Sombres), in the Galactic plane away from the bulge. Three stars have been found that exhibit luminosity variations compatible with gravitational microlensing effects due to unseen objects. The corresponding optical depth, averaged over four directions, is \( \tau = 0.38^{+0.53}_{-0.15} \times 10^{-6} \). All three candidates have long Einstein radius crossing times (~ 70 to 100 days). For one of them, the lack of evidence for a parallax or a source size effect enabled us to constrain the lens-source configuration. Another candidate displays a modulation of the magnification, which is compatible with the lensing of a binary source.

The interpretation of the optical depths inferred from these observations is hindered by the imperfect knowledge of the distance to the target stars. Our measurements are compatible with expectations from simple galactic models under reasonable assumptions on the target distances.

Key words: Galaxy: halo – Galaxy: kinematics and dynamics – Galaxy: stellar content – Galaxy: structure – (Cosmology:) gravitational lensing

1. Introduction

Since the seminal paper of Bohdan Paczyński 1986, observations have demonstrated that gravitational microlensing is an efficient tool to investigate the Milky Way structure. After the first detections of microlensing effects towards the Large Magellanic Cloud (Alcock et al. 1993; Aubourg et al. 1993) and towards the Galactic bulge (Udalski et al. 1993; Alcock et al. 1995), searches for microlensing have entered an active era. The results of recent campaigns of observations are somewhat difficult to interpret. The negative search for short duration events and the rarity of long duration events found towards the Magellanic Clouds (Ansari et al. 1996; Alcock et al. 1997a; Palanque-Delabrouille et al. 1998 and Alcock et al. 1998) imply that only heavy dark compact objects \((M > 10^{-2} M_\odot)\) could account for a significant fraction \((\geq 25\%)\) of the halo mass required to explain the rotation curve of our galaxy. On the other hand, the optical depth measured in the Galactic bulge direction (Udalski et al. 1994;
equipped with a 2 passbands. Photons are collected by two cameras, each 0

2.1. Data taking

Since July 1996 the EROS team has been using at La Silla observatory the MARLY telescope (1 m, f/5) with a dichroic beam-splitter allowing simultaneous imaging of a 0.7′(α) × 1.4′(δ) field in EROS-visible and EROS-red wide passbands. Photons are collected by two cameras, each equipped with a 2 × 4 mosaic of 2K × 2K LORAL CCDs (Bauer et al. 1997). In this analysis, seven sub-fields are considered per image because one of our 16 CCDs is not operational. The pixel size is 0.6 arcsec, and the median global seeing is 2 arcsec. CCDs are read-out in parallel in approximately 50 s, during which the telescope moves towards the next field to be imaged. After acquisition by the VME system, raw data are reduced by DEC-Alpha workstations using flat-field images taken at the beginning of the night. The DLT tapes produced are shipped to the CCPN (IN2P3 computing centre, CNRS) in Lyons, France, for subsequent processing.

The two EROS passbands are nonstandard. EROS-red passband is centered on λ = 762 nm with a full width half maximum Δλ ≃ 200 nm, and EROS-visible passband is centered on λ = 600 nm with Δλ ≃ 200 nm. Our calibration studies show that the corresponding magnitudes REROS and VERSOS are close to Cousins I and Johnson R to ±0.3 magnitudes. These REROS and VERSOS magnitudes will be used all along this article.

2.2. The targets

Four different directions are monitored in the Galactic plane, away from the bulge, totaling 29 fields which have a high stellar density, and cover a wide range of Galactic longitude. We refer to them as β & γ Sct, γ Nor and θ Mus. Table 1 gives the coordinates and available data related to the monitored directions; Fig. 2 displays the positions of the fields in Galactic coordinates and Fig. 3 shows the observation periods and average time sampling. The exposure times of 2 and 3 minutes were chosen to optimize the global sensitivity of the photometric measurements taken during microlensing magnifications (a compromise between the number of measurements and their precision, see Mansoux 1997).

By contrast with the Magellanic Clouds, the distance distribution of the monitored stars is imperfectly known, and should a priori vary with the limiting magnitude. In our detection conditions, the populations of stars used to obtain the optical depths given in Sect. 4.1 below are those described by the colour-magnitude diagrams of Fig. 4. An analysis of these diagrams has shown that their content is dominated by a population of source stars located ~ 7 kpc away, undergoing an interstellar extinction of about 3 magnitudes (see Mansoux 1997 for more details). This distance estimate is in rough agreement with the distance to the spiral arms deduced from Georgelin et al. 1994 and Russell et al. 1998, and will be used in this paper.

3. The search for lensed stars

3.1. Data processing and analysis

Light curves have been produced from the sequences of images using the specific software PEIDA (Photométrie et Étude d’Images Destinées à l’Astrophysique), designed

![Graph](image-url)
Fig. 2. Map of the Galactic plane fields (Galactic coordinates) monitored by EROS for the microlensing search. The shaded area represents the shape of the Galaxy. We have indicated our Galactic Centre fields and the 4 directions towards the arms.

Fig. 4. Colour-magnitude diagrams ($R_{EROS}$ vs $V_{EROS} - R_{EROS}$) for the stars monitored by EROS in the directions of $\beta$ & $\gamma$ Sct, $\gamma$ Nor and $\theta$ Mus. The boxes drawn in the upper corners correspond to the zones excluded from the search. The positions of the 3 candidates are indicated.
Table 1. Description of the 29 fields monitored in the spiral arms program. This table gives the fields centres, the averaged number of measurements and the number of light curves analysed in this article. Field gn401 has not been studied yet.

| Field number | α (h:m:s) J2000 | δ (d:m:s) J2000 | # of meas. | stars (million) |
|--------------|-----------------|-----------------|------------|-----------------|
| Scutum (β Sct) |                 |                 |            |                 |
| bs300        | 18:43:22.0      | -07:40:53       | 55         | 0.33            |
| bs301        | 18:43:27.0      | -06:13:42       | 52         | 0.23            |
| bs302        | 18:46:16.0      | -07:22:45       | 50         | 0.32            |
| bs303        | 18:46:20.0      | -05:55:35       | 50         | 0.28            |
| bs304        | 18:49:21.0      | -06:45:51       | 54         | 0.43            |
| bs305        | 18:52:26.0      | -06:35:44       | 53         | 0.37            |
| Scutum (γ Sct) |                 |                 |            |                 |
| gs200        | 18:28:03.0      | -14:51:06       | 55         | 0.32            |
| gs201        | 18:31:15.0      | -14:14:38       | 52         | 0.30            |
| gs202        | 18:31:33.0      | -12:48:53       | 49         | 0.29            |
| gs203        | 18:34:22.0      | -14:31:39       | 50         | 0.34            |
| gs204        | 18:34:28.0      | -13:04:31       | 50         | 0.45            |
| Norma (γ Nor) |                 |                 |            |                 |
| gn400        | 16:09:45.0      | -53:07:03       | 100        | 3.01            |
| gn401        | 16:18:22.0      | -51:44:43       | -          | -               |
| gn402        | 16:14:57.0      | -53:04:35       | 101        | 0.25            |
| gn403        | 16:22:28.0      | -52:06:20       | 108        | 0.30            |
| gn404        | 16:19:09.0      | -53:26:38       | 106        | 0.29            |
| gn405        | 16:26:52.0      | -52:21:02       | 111        | 0.22            |
| gn406        | 16:23:54.0      | -53:43:53       | 106        | 0.33            |
| gn407        | 16:31:31.0      | -52:28:44       | 107        | 0.22            |
| gn408        | 16:28:42.0      | -53:51:58       | 92         | 0.22            |
| gn409        | 16:15:51.0      | -54:48:45       | 90         | 0.26            |
| gn410        | 16:20:30.0      | -55:04:18       | 82         | 0.23            |
| gn411        | 16:09:37.0      | -55:10:07       | 90         | 0.32            |
| Musca (θ Mus) |                 |                 |            |                 |
| tm500        | 13:27:04.0      | -63:02:18       | 65         | 0.31            |
| tm501        | 13:31:18.0      | -63:34:41       | 64         | 0.33            |
| tm502        | 13:34:52.0      | -64:10:30       | 68         | 0.33            |
| tm503        | 13:23:58.0      | -64:59:52       | 64         | 0.29            |
| tm504        | 13:12:12.0      | -64:06:49       | 70         | 0.23            |
| tm505        | 13:16:15.0      | -64:40:50       | 65         | 0.28            |
| Total        |                 |                 |            | 8.44            |

Fig. 3. Time sampling for each direction monitored towards the spiral arms, in number of measurements per week. γ Nor is monitored between January and October, θ Mus is observed between January and August, β & γ Sct are monitored between May and November.

The main difference from the SMC analysis is the rejection against variable stars from the instability strip and against red giant variables. Unlike the Magellanic Clouds case where the positions of these populations in the colour-magnitude diagrams mostly populated by variable stars, and requirement for the stability of the curve outside the peak). They are also tuned to be loose enough to avoid rejection of non-standard microlensing events, which have a different peak shape.

3.2. The efficiency of the analysis

To determine the efficiency of each selection criterion, we have applied them to Monte-Carlo generated light curves, obtained from a representative sample of the observed light curves, on which we superimpose randomly generated microlensing effects. The microlensing parameters are uniformly drawn in the following intervals: impact parameter $u_0 \in [0,2]$, maximum the observed light curves, on which we superimpose randomly generated microlensing effects. The microlensing parameters are uniformly drawn in the following intervals: impact parameter $u_0 \in [0,2]$. a known shape), and to reject variable stars (rejection of stars lying in regions of the colour-magnitude diagrams mostly populated by variable stars, and requirement for the stability of the curve outside the peak). They are also tuned to be loose enough to avoid rejection of non-standard microlensing events, which have a different peak shape.

The main difference from the SMC analysis is the rejection against variable stars from the instability strip and against red giant variables. Unlike the Magellanic Clouds case where the positions of these populations in the colour-magnitude diagram are known a priori, the scatter and imperfect knowledge of the distances and reddenings of our target stars make our colour-magnitude cut somewhat empirical. In particular, its acceptance is different from one field to another (see the excluded regions in Fig. 4).
Fig. 5. Relative frame to frame average dispersion of the luminosity measurements versus $R_{\text{EROS}}$ (upper panel) and $V_{\text{EROS}}$ (lower panel), for stars with at least 50 reliable measurements for each colour. This dispersion is taken as an estimator of the mean photometric precision. The superimposed hatched histograms show the magnitude distribution of the stars in EROS bands.

3.3. Results of the selection

Three light curves satisfy all the requirements and are hereafter named candidates and labelled GSA1 to 3. Figures 7, 8 and 9 show the light curves of each candidate and Table 2 contains their characteristics. Measurements taken after Jan 1st, 1998 (date 2922) are shown, although they were not used in the selection.

4. Optical depth and event timescales

4.1. Optical depth

The optical depth towards a pointlike source is defined as the fraction of time during which it undergoes a lensing magnification larger than 1.34. For a given target the measured optical depth $\tau$ is computed from:

$$\tau = \frac{1}{N_{\text{obs}}T_{\text{obs}}} \pi \sum_{\text{events}} \frac{\Delta t}{\epsilon(\Delta t)},$$

where $N_{\text{obs}}$ is the number of monitored stars in the target, $T_{\text{obs}}$ is the duration of the search period (650 days for this 2 year analysis) and $\epsilon(\Delta t)$ is the average detection efficiency normalized to the microlensing events with impact parameter $u_0 < 1$, whose maximum magnification takes place within the research period. The contribution of the candidates to the optical depth is given in Table 3.

We have modeled the Galaxy in two different ways using three components: a central bulge, a disc and a dark halo. The density distribution for the bulge - a barlike
Table 2. Characteristics of the 3 microlensing candidates

| Candidate | EROS2-GSA1 | EROS2-GSA2 | EROS2-GSA3 |
|-----------|------------|------------|------------|
| field     | γ Set      | γ Nor      | γ Nor      |
| Coordinates of star (J2000) | α = 18h29m09.0s | α = 16h11m50.2s | α = 16h16m26.7s |
| Galactic coordinates | b = −2°27 | b = −1°54 | b = −3°39 |
| l = 17°43 | l = 330°47 | l = 329°94 |
| R_{EROs} | 17.6 | 17.7 | 17.4 |
| V_{EROs} | 19.7 | 19.4 | 18.6 |
| Date of maximum magnification | Aug. 3rd, 1996 | Mar. 26th, 1997 | Oct. 7th, 1997 |
| Julian Day | -21447891.5 | 26429.0 ± 0.2 | 28062.2 ± 1.1 |
| Einstein radius crossing | 73.5 ± 1.4 | 98.3 ± 0.9 | 70.0 ± 2.0 |
| Max. magnification | 26.5 ± 0.6 | 3.05 ± 0.02 | 1.89 ± 0.01 |
| Impact parameter (in R_{EROs}) | 0.0378 ± 0.001 | 0.342 ± 0.002 | 0.593 ± 0.007 |
| χ² of best fit | 185.7/163 d.o.f. | 551/425 d.o.f. | 445/427 d.o.f. |
| Remarks | \( M_{tens} > 4.6 \times 10^{-3} M_\odot \) | binary source fit | at 95% C.L. (see text) |
|           | period 98 days (see text) |           |           |

Table 3. Contribution of the candidates to the optical depth \( \tau \) assuming the sources to be 7 kpc away. In the case of θ Mus we give a 95% C.L. upper limit on the optical depth contribution from events with \( \Delta t = 80 \) days (\( \epsilon (80 \text{ days}) = 18\% \)).

| Target | \( \beta \)       | \( \gamma \)       | \( \alpha \)       | \( \delta \)       |
|--------|-------------------|-------------------|-------------------|-------------------|
| Direction | Set    | Norn    | Musc    | Set    | Norn    | Musc    |
| <b>    | -2°5   | -2°6   | -2°7   | -1°8   |         |         |
| <l>    | 27°0   | 18°6   | 331°2  | 306°4  |         |         |
| Events detected | none | GSA1 & 2 |        | none |         |         |
| \( \Delta t \) (days) | -    | 73    | 98 & 70 | 27     | (80)    | (18)    |
| \( \epsilon (\Delta t) \) (%) | 10   | 1.02  | 0.29 & 0.21 | -     |         |         |
| \( \tau \) (target) \( \times 10^6 \) | 0.47 | 0.5   |         | <1.82 at 95\% C.L. |         |         |
| \( \bar{\tau} \) averaged over the 4 directions \( \times 10^6 \) | 0.38 ± 0.15 |         |         |         |         |

We compare our measurements with the predictions of two models with extreme disk contributions (here the main structure involved in microlensing). The first one has a “thin” disc and a standard isotropic and isothermal halo (Model 1) with a density distribution given in spherical coordinates by:

\[
\rho(r) = \rho_{\odot} \frac{R_{\odot}^2 + R_c^2}{r^2 + R_c^2},
\]

where \( \rho_{\odot} \) is the local halo density, \( R_{\odot} = 8.5 \) kpc is the distance between the Sun and the Galactic Centre, and \( R_c = 5 \) kpc is the Halo “core radius”. The matter distribution in the disc is modeled in cylindrical coordinates by a double exponential (see e.g Bienaymé et al. 1987 and Schaeffer et al. 1998):

\[
\rho_{\text{thin}}(R, z) = \frac{\Sigma_{\text{thin}}}{2H_{\text{thin}}} \exp \left( -\frac{(R - R_{\odot})}{R_{\text{thin}}} \right) \exp \left( -\frac{|z|}{H_{\text{thin}}} \right),
\]

where \( \Sigma_{\text{thin}} \) is the column density of the disc at the Sun position, \( H_{\text{thin}} \) is the height scale and \( R_{\text{thin}} \) is the length scale of the disc.

The second model (Model 2) has a “thin” and a “thick” disc, and a very light halo. Both models share the same bulge contribution. The model parameters are summarized in Table 4. Fig. 1 shows the expected optical depth up to 7 kpc as a function of longitude for both models, at the average latitude of our fields \( b = -2.5° \). As the main contribution comes from the thin disc (about 90%), variations of the optical depth from field to field due to the range of 2 to 3° in latitude can reach \( \approx 30\% \) in the case of \( \gamma \) Nor, and \( \approx 20\% \) for the other targets.

The expected optical depth, averaged over the four directions, is \( 0.55 \times 10^{-6} \) for model 1, and \( 0.65 \times 10^{-6} \) for model 2. These estimates vary by 50% if the average distance of the sources is changed by 2 kpc, or if the parameter \( \Sigma_{\text{thin}} \) is changed by \( 25M_\odot/\text{pc}^2 \). The measured optical depth, averaged over the four directions is:

\[
\bar{\tau} = 0.38^{+0.55}_{-0.15} \times 10^{-6}.
\]

The confidence interval reported here takes into account Poisson fluctuations and the possible event timescale variations inside the range [71, 98] days. The comparison of
Fig. 7. Magnification curves of the microlensing candidate GSA1 in the direction of $\gamma$ Scl. The fitted standard microlensing curve is superimposed (solid line).

Fig. 8. Magnification curves of the microlensing candidate GSA2 in the direction of $\gamma$ Nor. The solid line shows the fitted microlensing curve taking into account the modulation due to a dominant source orbiting in a binary system with period $P_0 = 98$ days. The dashed line corresponds to the best standard microlensing fit.

Fig. 1 with Table 3 also shows that the measured optical depths in the four directions are compatible with the predictions of both models.

4.2. Microlensing event timescales

The duration of the three events is long ($\sim 80$ days in average). Fig. 10 shows the expected event duration distribution towards $\gamma$ Nor within the framework of model 1. This distribution is obtained assuming the following mass functions and kinematical characteristics:

- We assume that lenses belonging to the (non-rotating) halo have the same mass ($0.5 M_\odot$); their velocities transverse to the line of sight of disc stars follow a Boltzmann distribution with a dispersion of $\sim 150$ km/s. Thus the expected duration of microlensing events is small (see Fig. 10).
- For lenses belonging to the bulge, the mass function is taken from Richer et al. 1992 and the velocities transverse to the line of sight of disc stars also follow a Boltzmann distribution with a dispersion of $\sim 110$ km/s. The expected rate of microlensing events due to this structure towards the direction considered in Fig. 10 ($\gamma$ Nor) is found to be negligible.
- The disc lenses mass function is taken from Gould 1997, which is derived from HST observations. Disc lenses are subject to a similar global rotation as the observer and the sources (Brand & Blitz 1993). We assume a negligible particular motion of the monitored sources with respect to the spiral arms, because they are probably young stars. Following Griest 1991, the motion of the Sun relative to the Local Standard of Rest is taken as $(v_{\odot R} = 9, v_{\odot \theta} = 11, v_{\odot z} = 16)$ (in km/s); the velocity dispersions of the lens population are expected to be $(\sigma(V_R) = 40, \sigma(V_\theta) = 30, \sigma(V_z) = 20)$ (in km/s). As the disc lenses have a low velocity relative to the line of sight, disc-disc events have longer timescales, as can be seen on Fig. 10.
Assuming that all three lenses belong to the halo leads to large probable masses (> 2\(M_\odot\)). As such high mass lenses would be visible stars that we do not observe (dismissing the unlikely possibility that the three could be neutron stars), the disc-disc lensing hypothesis is more probable. This hypothesis could also explain the fact that 4 events over the 45 found by the MACHO Collaboration towards the Galactic Centre (see Alcock et al. 1997b) have a timescale > 50 days, significantly larger than the mean for the whole sample (21 days). Indeed, the contribution of these 4 events to the total optical depth is about 0.6 \(\times\) 10\(^{-6}\), which is compatible with the expectation of the disc lensing contribution (~ 0.7 \(\times\) 10\(^{-6}\) for Model 1).

5. Detailed analyses of the candidates

Detailed analyses have been performed on GSA1 and GSA2 candidates, whose light curves are sufficiently sampled. For this purpose, we have used all available data on the candidates (i.e. three years of observations).

5.1. Candidate EROS2-GSA1

Candidate GSA1 exhibits a large magnification \(A_{\text{peak}} > 25\) at 95% C.L. with no detectable blending\(^2\) and no detectable parallax effect (Gould 1992). Despite the small impact parameter, no evidence for a distortion of the curve due to the non-zero size of the lensed source is found. A fitting procedure allows one to put an upper limit to the ratio of the angular stellar radius \(\theta_\star\) to the angular Einstein radius \(\theta_E\) of the lens:

\[
\frac{\theta_\star}{\theta_E} = \frac{\theta_\star}{\sqrt{\frac{4GM}{c^2}}} < 0.066 \text{ at 95\% C.L,}
\]

where \(M\) is the lens mass, \(D\) the distance of the observer to the source and \(xD\) its distance to the lens. From the position of the source in the colour-magnitude diagram we can assume that its temperature is comparable to or lower than that of the Sun. We then obtain:

\[
\frac{\theta_\star}{\theta_\odot} > 10^{(V_{\text{app, EROS}} - V_{\text{app, EROS}})/5},
\]

where the apparent magnitude \(V_{\text{app, EROS}}\) should be corrected for the interstellar extinction. Ignoring this correction leads to the conservative limit \(\theta_\star > 2.37 \times 10^{12}\) rad, implying that \(\theta_E > 3.6 \times 10^{-11}\) rad and that the angular proper motion of the deflector:

\[
\mu \text{ (km/s/kpc)} = 3.57 \times 10^{11} \frac{\theta_E(\text{rad})}{\Delta t \text{ (days)}} > 0.17 \text{ at 95\% C.L.}
\]

\(^2\) Fits including more than 10% blending are excluded at 95% C.L. Moreover, since the magnification curves are the same in both colours, the amplified star and an hypothetical blending star would have to have -by chance- the same colour.
We can then infer a lower limit on the parallax effect does not result in a significantly better fit. Taking into account the possibility of a bulge contribution, and the expected range of parameter space, Fig. 11 shows the excluded area for the tip of the 2-dim. vector $\bar{\nu}$ in the local transverse plane. The lower limit we find for the modulus $\bar{\nu}$ (and $\hat{r}_E$) is relatively small, because the best parallax fit, which is not significantly better than a standard fit (183.7/161 d.o.f. compared with 185.7/163 d.o.f.), is obtained for $\bar{\nu} = (-17.1, -31.1)$ km/s in the frame of Fig. 11. This special configuration produces a distorted light curve which diverges only marginally from the standard fitted curve, and only during periods where the measurements are not very precise.

From the definitions of $\theta_E$ and $\hat{r}_E$ one gets the relation:

$$M = \frac{c^2}{4G} \hat{r}_E \theta_E = \frac{c^2}{4G} \bar{\nu} \mu \Delta t^2,$$

from which we derive a lower limit on the lens mass by combining the two constraints from finite size and parallax analysis, i.e. at 95% C.L.:

$$M > 1.2 \times 10^{-3} M_\odot \quad \text{ignoring interstellar extinction,}$$

$$M > 4.6 \times 10^{-3} M_\odot \quad \text{with 3 magnitudes of extinction.}$$

Note that this limit is independent of the lens and source distances to the observer. The fact that this lower limit is so much smaller than the expected mass for such lenses follows immediately from the fact that each limit from which it is derived is not probing the expected range of kinematic parameters. Fig. 12 shows the excluded areas in the $M$ versus $x$ plane, from the finite size study and the parallax analysis, assuming the source to be located 7 kpc away. Exclusion curves for the two hypotheses on the interstellar absorption are shown. A better characterization of the lensed source should allow one to refine these preliminary studies.

Finally, a limit on the lens luminosity can be derived from the maximum blending limit allowed by the fit. At 95% C.L., the apparent magnitude of the lens is at least 2.5 magnitudes above the measured baseline magnitude, i.e. $R_{EROS} > 20.1$ and $V_{EROS} > 22.2$.

5.2. Candidate EROS2-GSA2

GSA2 has residuals to a standard microlensing fit which clearly exhibit a modulation; a period of $\sim 54$ days is found in the residuals of the standard fit during the magnification. On the other hand, taking into account a possible parallax effect does not significantly improve this fit. Furthermore, we know that the lensing of a periodic variable star would produce a modulation of the light curve whose amplitude should follow the magnification. As we do not detect a significant modulation in the non-magnified part of the light curve, the most probable origin of this modulation is that one dominant luminous source or two sources orbit around the centre of gravity of a binary system, inducing a wobbling of the line of sight with respect to the trajectory of the lens.

This type of configuration has been studied by Griest & Hu 1992, Sazhin & Cherepashchuk 1994 and Han & Gould 1997, and was already mentioned in our earlier article (Ansari et al. 1995).
Fig. 11. Excluded area for the tip of the 2-dim. vector $\vec{v}$ in the local transverse plane. The smallest speed compatible with the observations corresponds to a deflector with a velocity oriented towards the lower spike. The arrow shows the earth projected velocity at the maximum magnification time. The straight line is the intersection of the Galactic plane. The projection of the earth trajectory is indicated by the open circles, starting 60 days before maximum, ending 70 days after maximum, with 10 days spacing (right scale in AU). NEP is the North Ecliptic Pole direction, NGP is the North Galactic Pole direction.

The first class includes systems with a dominant source orbiting with a period $P_o \sim 51$ days, and with the projected semi-axis $\rho = ax/R_E \sim 0.04$ \(^4\). The second class corresponds to systems with two luminous stars orbiting with a period $P_o \sim 98$ days, with luminosity and mass ratios around 1/3-1/2, and a projected distance between the two components of about $\rho = ax/R_E \simeq 0.4$. Given the domain of values for $x$ and $R_E$, these parameters are compatible with physically acceptable masses of the binary satisfying Kepler’s third law. Many more configurations can fit the observations if we consider systems with elliptic orbits. A spectroscopic study of the source is under way in order to test its binarity. If the source proves to be a spectroscopic binary, then one can get a good estimate or constraint on the angular Einstein radius $\theta_E$ (and then on the angular proper motion of the lens $\mu$).

Expressing the Einstein radius and Kepler’s third law in the relation $\rho = ax/R_E$ leads to:

$$\frac{M_{\text{lens}}}{M_\odot} \frac{D}{7 \text{ kpc}} \sim 6.7 \times 10^{-6} \left[ \frac{P_o}{1 \text{ day}} \right]^{\frac{1}{2}} \left[ \frac{M_T}{M_\odot} \right]^{\frac{1}{2}} \rho^{-2} \frac{x}{1 - x} .$$

Fig. 13 illustrates this relation between $M_{\text{lens}} \times D$ and $x$ assuming the source to be a binary system with $P_o = 100$ days, with $\rho = 0.4$ and with two different hypotheses for the mass $M_T$ of the system.

\(^4\) Fits which are slightly less good can be obtained with larger periods, but in this case only the first shoulder (around date=2600) is correctly matched.
6. Conclusion

We have searched for microlensing events with durations ranging from a few days to a few months in four Galactic disc fields lying 18° to 55° from the Galactic Centre. We find three events that can be interpreted as microlensing effects due to massive compact objects. Their long duration favours the interpretation of lensing by objects belonging to the disc instead of the halo. The average optical depth measured towards the four directions is \( \bar{\tau} = 0.38^{+0.52}_{-0.15} \times 10^{-6} \). Assuming the sources to be 7 kpc away, the expected optical depths from two different galactic models vary from 0.55 to 0.65\times 10^{-6}, in agreement with our measurement.

One event displays a modulation of the magnification which is compatible with the lensing of a binary source. More information about the configuration of this possible binary source, and about the lens mass acting on the strongly amplified source, are expected from complementary observations. No evidence for parallax and blending effects has been found.

The observations continues towards the spiral arms. More accurate measurements should be obtained with the increase of statistics (Derue 1999), allowing one to estimate the disc contribution to the optical depth towards the bulge and the Magellanic Clouds.

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