Mon. Not. R. Astron. Soc. **278,** L46–L48 (1996)

Possible determination of isolated pulsar masses with gravitational microlensing

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Accepted 1995 November 28. Received 1995 November 20; in original form 1995 May 30

ABSTRACT

An extension of the ongoing gravitational microlensing programmes to the known pulsar population is shown to have the potential of determining isolated pulsar masses with a reasonable precision at a rate of ≥ 2 event century^{-1} within the existing sample. Amplification of stars below the detection limit may also occur and add to this rate. Positively detected events would be important for stellar evolution and high-density matter fields.

Key words: gravitation – pulsars: general – gravitational lensing.

1 MICROLENSING BY FIELD PULSARS

The recent reports of gravitational microlensing events (Udalski et al. 1993; Alcock et al. 1993; Aubourg et al. 1993) by three working groups not only have clearly demonstrated the feasibility of those observations, but also have provided valuable data which will help to understand the dark populations and the galactic dynamics itself. As extensively discussed in the literature (see, for example, Griest et al. 1991; Gould 1992), this method, proposed by Paczyński (1986), is based on the detection of the amplification $A(u)$ of a background star by the passage of a dark object (termed a MACHO, or MAssive Compact Halo Object; the main targets of the searches), which is in the simplest case a function of the dimensionless impact parameter $u = r_0/R_{\rm E}$:

$$A(u) = \frac{u^2+2}{u(u^2+4)^{1/2}}, \tag{1}$$

r_0 being the undeflected distance and $R_{\rm E}$ the so-called Einstein ring radius (Paczyński 1986), the basic quantity for the lensing phenomenon.

It is clear that, even though the observational strategies are directed to perform statistical searches of dark populations (see, for example, Blandford & Narayan 1992 and references therein), the microlensing phenomenon is in fact more general than that and can be observed in the case of *known* lensing objects. This observation forms the basis of Paczyński's (1995) proposal to conduct a programme to measure the masses of faint, high proper motion nearby stars with ~ 1 per cent accuracy. The final goal of that programme is to provide a determination of the local luminosity function at the faint end of the main sequence. The purpose of this Letter is to point out that a similar procedure may lead to another long-sought determination, namely the masses of *isolated* field pulsars which hold important clues about the nature of high-density matter.

Following Paczyński (1991, 1995), the angular radius of the pulsar Einstein ring can be written as

$$\phi_{\rm E} = 2.85 \times 10^{-3} \times (1\ {\rm arcsec}) \left(\frac{M}{{\rm M}_{\odot}} \frac{1\ {\rm kpc}}{D_{\rm p}}\right)^{1/2} \left(1 - \frac{D_{\rm p}}{D_{\rm s}}\right)^{1/2}, \tag{2}$$

where M is the pulsar mass, $D_{\rm p}$ its distance to the Earth and $D_{\rm s}$ the distance to the amplified background star. For a given proper motion of the pulsar $\dot{\phi}$, the area subtended in the sky by the Einstein ring in a time t is

$$S = 2\phi_{\rm E}\dot{\phi}t = 2.4 \times 10^{-4} \times (1\ {\rm arcsec})^2 \left(\frac{M}{{\rm M}_{\odot}} \frac{1\ {\rm kpc}}{D_{\rm p}}\right)^{1/2} \left(1 - \frac{D_{\rm p}}{D_{\rm s}}\right)^{1/2} \times \left(\frac{\dot{\phi}}{0.042\ {\rm arcsec\ yr}^{-1}}\right)\left(\frac{t}{1\ {\rm yr}}\right), \tag{3}$$

where the scaling is given for a 'typical' pulsar having $v_{\theta} \simeq 200\ {\rm km\ s}^{-1}$ at $D_{\rm p} = 1$ kpc.

The number of events per year, $\mathrm{d}N/\mathrm{d}t$, may be estimated by convolving the pulsar distribution (assumed to be isotropic for simplicity, see below) with the number of stars observed in the mean area covered by the pulsar motion, $\mathrm{d}N/\mathrm{d}t = 4\pi N_{\rm p} \langle S/t \rangle\ \mathrm{d}N_{\rm s}/\mathrm{d}\Omega\ {\rm yr}^{-1}$. To give a quantitative estimate, we have adopted the simple expression for $\mathrm{d}N_{\rm s}/\mathrm{d}\Omega$, valid for an exponential disc, of Bahcall et al. (1994), with $\Sigma = 48\ {\rm M}_{\odot}\ {\rm pc}^{-2}$ (Bahcall 1984). We have considered

$I_{\rm lim}=25$ and $M_I=15$ (expected for the hydrogen-burning limit: Burrows 1994), which seem reasonable for existing and forthcoming large telescopes. After integrating over the galactic latitude, we obtain

$$\frac{{\rm d}N}{{\rm d}t}=0.024\left(\frac{M}{{\rm M}_\odot}\frac{1\ {\rm kpc}}{D_{\rm p}}\right)^{1/2}\left(1-\frac{D_{\rm p}}{D_{\rm s}}\right)^{1/2}\left(\frac{\dot{\phi}}{0.042\ {\rm arcsec\ yr}^{-1}}\right){\rm yr}^{-1}. \tag{4}$$

In other words, there is a ~24 per cent probability of finding at least one event in the next decade. Several observational remarks are in order. First of all there is the question of the most convenient wavelength to maximize the probability of observing the events. To observe the densest background fields with the highest available spatial resolution, two near-infrared bands or an I, R combination will probably be the best alternatives. This strategy will exploit the pure geometric character of the microlensing, avoiding excessive dust extinction and also the fact that large telescopes will be optimized for the infrared region of the spectrum, where the image quality will be ≤ 0.2 arcsec near the diffraction limit (Barr 1995). On the other hand, the search for pulsars at low galactic latitudes is inherently difficult, so that it may not be important to observe fields around $b=0°$ after all. It should be noted that we have truncated the convolution at an angular latitude corresponding to one scaleheight of the disc dust distribution, crudely simulating these combined effects to arrive at the estimate given in equation (4). The important point raised by this crude estimate (valid only in a statistical sense) is that there may be a good chance of observing events, but only direct examination of the fields centred around each pulsar can prove useful to address this possibility.

Although faint background galaxies may also serve as potential targets in the pulsar fields, they will present additional complications. The size of the galaxies falls below 1 arcsec only for $I \geq 22$, so that there is no hope of finding pulsars for which $\phi_{\rm E}$ is larger than that (see equation 2). Therefore events in which a faint galaxy is lensed by a pulsar will present a flat-topped light curve (see, for example, Zylberajch 1995) which may be difficult to detect, and the mass determination will consequently be much less clear. This suggests that we should restrict our attention to stellar targets for which the phenomenon is better understood.

The above numbers suggest that the microlensing of a background star by a pulsar is, astronomically speaking, a conspicuous event, so that a careful evaluation of the ~100-pulsar subsample already available with measured proper motions (Taylor, Manchester & Lyne 1993) and an extension of this type of observational effort are in order. It is quite possible that favourable conditions for observing an event already exist in the rapidly growing pulsar inventory, especially if fainter, nearby pulsars like the recently discovered PSR J0108 – 1431 (Tauris et al. 1994) can be added to it. The calculations needed, unlike for the statistical MACHO searches, are much more similar to those for eclipses or stellar occultations by asteroids, with the obvious advantage that the events can be predicted, guided by accurate astrometry performed at radio frequencies. Progress in this field will also be stimulated because, for radio and optical–infrared positions to be combined as required for successful observations, the relative uncertainty between positions in these bands must not exceed $\sim\phi_{\rm E}$. Current interferometric techniques allow the location of radio sources to within 0.001 arcsec, and the accuracy of the *Hipparcos* data base is in principle even higher than this. However, the relative positions are not known to better than 0.01 arcsec, which is not enough for our purposes. The presence of several VLBI sources identified in the *Hipparcos* observations is essential to undertake the astrometric improvement necessary to conduct the programme.

When a predicted event can be effectively observed on a time-scale

$$t_0\equiv\phi_{\rm E}/\dot{\phi}=24\ {\rm d}\left(\frac{M}{{\rm M}_\odot}\frac{D_{\rm p}}{1\ {\rm kpc}}\right)^{1/2}\left(\frac{D_{\rm p}}{D_{\rm s}}\right)^{1/2}\left(\frac{200\ {\rm km\ s}^{-1}}{v_\theta}\right), \tag{5}$$

the pulsar mass can be calculated as

$$M={\rm M}_\odot\left(\frac{D_{\rm p}}{1\ {\rm kpc}}\right)\left(1-\frac{D_{\rm p}}{D_{\rm s}}\right)^{-1}\left(\frac{\dot{\phi}t_0}{0.0028\ {\rm arcsec}}\right)^2. \tag{6}$$

Note that, besides the technical difficulties of performing accurate photometry in the small fields, the main uncertainty will come from the factor $D_{\rm p}\,(1-D_{\rm p}/D_{\rm s})^{-1}$, which must be properly evaluated for a good determination of M, in addition to the accurately observable combination $\dot{\phi}t_0$. This task involves the determination of the spectral properties of the background star, which can provide $D_{\rm s}$ through modelling with ~10 per cent accuracy, plus knowledge of $D_{\rm p}$ throughout the measurement of the dispersion measure, or in some cases by parallax (e.g. Gwinn et al. 1986; Bailes et al. 1990). For the nearby pulsars ($D_{\rm p}\leq 1$ kpc) which have the largest proper motions and hence are the best candidates, the dispersion measure (DM) error is about ±25 per cent, which in turn indicates that M itself may be determined with 30–35 per cent precision in a typical event.

We finally stress that, even if no events are predicted for the next few years, it will still be very important to conduct a long-term photometric programme for a selected subsample of high-proper-motion pulsars to search for events in which a faint star *below* the sensitivity threshold becomes observable for some time because of pulsar lensing. To address this point, an estimate of the number of faint stars below the threshold per arcsecond, coupled with a statistical evaluation of the microlensing probability at a given time, must be carefully carried out to gather information about the pulsar mass.

The proposed studies have the potential impact of providing isolated pulsar masses, a quantity that is not directly known and is unlikely to be measured otherwise. An example of the potential value of microlensing observations for compact object astrophysics has recently been provided by the measurement of the parallax of the Earth via an event, with the consequent reconstruction of the kinematics and a dark mass determination of $M=1.3^{+1.3}_{-0.6}\,{\rm M}_\odot$ (Alcock et al. 1995). This is the first serious candidate neutron star measured in the existing sample. Microlensing could be crucial for an understanding of the stellar evolution endpoint (Burrows 1994).

ACKNOWLEDGMENTS

I acknowledge R. D. D. Costa, M. P. Allen, G. A. Medina-Tanco, E. M. Gouveia Dal Pino, M. Catelan, H. Cuevas, R. R. de Carvalho, J. Steiner, J. R. D. Lépine and J. S. Rego for useful discussions and advice about several aspects of this work. I also acknowledge an anonymous referee for useful criticisms that led to an improvement in the observational discussion given in the text and the correction of some typos in the first version. This work has been partially supported by the CNPq (Brazil) through a Research Fellowship, and by the FAPESP Agency (Brazil).

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