MICROLENSING AND HALO MASS IN FORM OF STARS

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Abstract

Paczyński (1986) suggested that “dark” objects in the halo of our Galaxy could enhance the luminosity of foreground stars, acting as gravitational microlenses. Such events has been recently reported by different collaborations. We assume that these microlensing events are produced by baryonic objects in the halo of our Galaxy. Rather than adopting a mean mass for the lensing objects we consider them distributed along a mass function similar to the disk one. Even if the number of microlensing events so far detected is not large, we show that it is possible to constrain the fraction of mass density in the halo of our Galaxy in form of stars. We estimate that this fraction varies between 0.1 and 0.8, if halo stars trace the total halo mass density; in the opposite case this range becomes narrower. If lensing objects have not been formed apart from the other halo stars, but in a more general context of star formation, neutron stars must also be present. We discuss these results in relation to galactic halo models for $\gamma$-ray bursts.

Keywords: dark matter – gamma-rays: bursts – gravitational lensing

1. Introduction

The nature of dark matter forming the halo of our Galaxy could be partially resolved by the ongoing experiments of gravitational microlensing. Paczyński (1986) proposed that compact remnants, such as black holes and neutron stars, or “Jupiters” and brown dwarfs (collectively named as Massive Astronomical Compact Halo Object, MA-CHO), could enhance the luminosity of foreground stars by gravitational microlensing. Three experiments are searching for these amplification events by monitoring millions of stars: the American-Australian MACHO collaboration at Mt. Stromlo Observatory, the French EROS collaboration at ESO, both monitoring stars in the Large Magellanic
Cloud (LMC), and the American-Polish OGLE collaboration at Las Campañas monitoring the galactic bulge. The first two collaborations have reported the detection of one (MACHO; Alcock et al. 1993) and two (EROS; Aubourg et al. 1993) events with the “canonical” features of microlensing amplification: symmetry of the light curve around its maximum and achromaticity (i.e. equal light curve for different colors; Paczyński 1986). A fourth event has been observed by OGLE collaboration (Udalski et al. 1993), but this experiment should not directly probe the halo of our Galaxy. All the lensed LMC stars have almost the same luminosity (\(\sim 19.5 \, m\)) and might also represent a new class of variable stars, mimicking microlensing events. Intense monitoring of these stars will prove if we are dealing with a new class of variable stars or with true microlensing events.

2. The fraction oh halo mass in form of stars

Turner (1993), assuming a characteristic mass for the lensing object of 0.1 \(M_\odot\), derived that the fraction of mass in the halo in form of stars, \(f\), must be between 0.1 – 0.5, in order to be consistent with the observed number of microlensing events. This value of \(f\) should provide a good approximation: from the duration of the events one can derive the most probable mass of the lensing object, which turns out to be a broad gaussian between 0.01 – 1 \(M_\odot\), peaked at \(\sim 0.1 \, M_\odot\) (Griest 1991). Detailed calculations on the mass of the lensing objects give 0.12\(^{+0.26}_{-0.08}\) \(M_\odot\) for the MACHO event, 0.31\(^{+0.64}_{-0.20}\) \(M_\odot\) and 0.38\(^{+0.82}_{-0.25}\) \(M_\odot\) for the EROS events; the average mass is estimated in 0.14 \(M_\odot\) (Jetzer & Massò 1994).

Here we calculate the fraction of halo mass in stars to be consistent with the observed number of microlensing events, taking into account a distribution of masses, rather than an unique value. We would have to use the halo mass function but it is unknown, therefore we adopt the disk Initial Mass Function (IMF) as a good approximation. (It can be shown that high mass stars \((M \gtrsim 1 \, M_\odot)\) practically do not contribute to the number of lensing events observed with current experiments, which is mainly determined by low mass objects). The disk IMF for masses greater than about one solar mass is known with good accuracy, problems arise for lower masses. Observational results on the stellar birthrate in the solar neighborhood require the presence of a “knee” in order to decrease the number of low mass stars (Miller & Scalo 1979). The most recent work (Tinney 1993) indicates the inflection point at \(\sim 0.25 \, M_\odot\); below this value the IMF could be either slowly rising or flat (Pound & Blitz 1993; Tinney 1993). We adopt the IMF proposed by Ferrini and co-workers (1990), which is slightly steeper
than the classical Salpeter’s at high masses; at the low mass end shows a “knee”, at about $0.3 M_\odot$, and is slowly rising below. We take two different low mass ends for the IMF, namely $M_L = 0.1 M_\odot$ and $M_L = 0.001 M_\odot$, in order to underline the importance of small mass objects to produce microlensing events. (We have also considered $M_L = 10^{-4} M_\odot$, but results are very similar to the case of $M_L = 0.001 M_\odot$.) A flat IMF below $0.25 M_\odot$ provides $\sim 15\%$ and $\sim 50\%$ less microlensing events than the adopted one, for $M_L = 0.1 M_\odot$ and $M_L = 0.001 M_\odot$ respectively.

The number of microlensing events depends also on the spatial distribution of lensing objects observed from the Sun. We do not know if stars in the halo trace the total halo mass density. We consider two contributions to the total density, one deriving from halo stars and the other from matter unable to produce microlensing events. For both these distributions we assume an isothermal profile characterized by a core radius: $r_c$ for halo stars and $R_c$ for non-lensing halo matter. The total halo density can be expressed as:

$$\rho(r) = \rho_0 \left[ f \frac{r_0^2 + r_c^2}{r^2 + r_c^2} + (1 - f) \frac{r_0^2 + R_c^2}{r^2 + R_c^2} \right]$$

where $\rho_0 = 7.9 \times 10^{-3} M_\odot \text{pc}^{-3}$ is the local dark matter density (Flores 1988), $r_0 = 8.5 \text{ kpc}$ is the distance between the sun and the galactic center, and $r$ measures distances from the Sun (LMC distance is $r_{LMC} = 50 \text{ kpc}$). We consider a halo extending, at least, up to the LMC: indications of large halo extensions come from the observational requirement of metal ejection from protogalaxies into the intergalactic medium (Hattori & Terasawa 1993) and by the interpretation of the Magellanic stream (Binney & Tremaine 1986). By assuming equation (1) we neglect a flattening of the halo at large distances (Sackett & Gould 1993) and contributions from a halo around the LMC (Gould 1993).

The first term in equation (1) refers to stars in the halo which are responsible for microlensing events, the other one takes into account the presence of matter which is not responsible for microlensing events and could be either baryonic or non baryonic. The halo core radius has been estimated in $2 - 8 \text{ kpc}$ (Caldwell & Ostriker 1981; Bachall, Schmidt & Soneira 1983), therefore for $f \ll 1$ the non-lensing matter is dominant and we take $R_c \sim 5 \text{ kpc}$ (and leave $r_c$ free); for $f \sim 1$ or if halo stars trace the total halo density we must require $r_c \sim 5 \text{ kpc}$.

Following Griest (1991) and taking into consideration the number of LMC stars monitored, the percentage of data effectively analysed, the time efficiency of the observations (see Table 1), we obtain the predicted number of events relative to MACHO and
EROS experiments, depending only on the fraction of the halo mass in stars and the core radius of the star distribution. By deriving fiducial intervals for the microlensing events by means of the Poisson statistics (90%), we report in Tables 2 and 3 the limits on the fraction of the halo mass in form of stars. These values refer to a stationary star and observer. Including a velocity distribution of halo objects and non-zero velocity of the Sun, star and Earth, results change very little (Griest 1991). We estimate also the most probable mass of the lensing stars in $0.13 \, M_\odot$.

In Table 2 we consider halo stars tracing the total distribution of halo mass. We obtain a large range for the fraction of halo mass in form of stars $0.1 \lesssim f \lesssim 0.8$, consistent with the one found by Turner (1993) using simplified arguments. In Table 3 we consider a contribution to the halo from non-lensing mass and leave open the possibility that halo stars do not trace the total distribution (i.e. $f \ll 1$). In this case constraints of $f$ are more stringent due to the lower mass available for producing microlensing events. We take $R_c = 5 \, \text{kpc}$ and derive limits on the fraction of halo mass in form of stars as a function of the star core radius $r_c$. We can allow much larger star core radii, but for small values of $r_c$ stars trace the total halo mass distribution and we obtain high values of $f$ (contrary to our assumption), instead for large star core radii we have $f \sim 0.3 - 0.4$.

3. CONCLUSIONS

The upper limit on $f$ indicates that the mass of our halo could be almost completely baryonic in form; at the same time the lower limit indicates that there must be some baryonic matter in form of stars to produce the observed microlensing events. If this mass has been repartee into stars by means of an “usual” IMF, we have that the most probable objects that have been formed are low mass stars, while high mass objects are rare. Therefore, it is not surprising that the mean lens mass is about $0.1 \, M_\odot$, moreover being microlensing experiments biased towards low masses because of the temporal coverage (Griest 1991). Following this line of reasoning we have, as a by product of the halo stellar evolution, a number of compact remnants which are too few to give microlensing effects in respect to low mass stars, but which should be responsible of $\gamma$-ray bursts.

BATSE results (Meegan et al. 1993), imply that the neutron star core radius is greater than $\sim 20 \, \text{kpc}$ in order to have an isotropic distribution of $\gamma$-ray bursts (Mao & Paczyński 1992; Brainerd 1992; Hakkila et al. 1994). Considering the observed number of microlensing events we have to face two different possibilities: stars in the halo of our Galaxy may or may not trace the total halo density. In the first case we can not
allow large star core radii because of the total halo core radius estimate (Caldwell & Ostriker 1981; Bachall et al. 1983) and therefore γ-ray bursts are likely cosmological. We expect $0.1 \lesssim f \lesssim 0.8$. In the opposite case we must require large halo star core radii in order to have an isotropic distribution of γ-ray bursts and we have $f \sim 0.3 - 0.4$. New microlensing events, as well as a larger sample of γ-ray bursts, will further constrain the value of $f$, providing indications on the nature of matter in the halo of our Galaxy and on the origin of γ-ray bursts.

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**TABLE 1:** MACHO and EROS parameters

| Parameters                                           | MACHO$^1$ | EROS$^{2,3}$ |
|------------------------------------------------------|-----------|--------------|
| Time of observations                                 | 1 yr      | 1.44 yr      |
| Minimum time between observations (mean)             | 1.5 d     | 1.7 d        |
| Number of monitored stars                            | $1.8 \times 10^6$ | $8 \times 10^6$ |
| Efficiency (binary, variable, sufficiently luminous stars) | 0.5      | 0.25         |
| Percentage of analyzed observations                  | 0.15      | 0.4          |

1 Alcock et al. 1993
2 Aubourg et al. 1992
3 Aubourg et al. 1993
**TABLE 2**

| Star Core radius ($r_c$) | MACHO $M_L = 0.1\ M_\odot$ | EROS $M_L = 0.1\ M_\odot$ | MACHO $M_L = 0.001\ M_\odot$ | EROS $M_L = 0.001\ M_\odot$ |
|--------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| 2 kpc                    | 0.32 – 1                    | 0.20 – 1                    | 0.19 – 1                    | 0.12 – 0.93                 |
| 5 kpc                    | 0.29 – 1                    | 0.18 – 1                    | 0.17 – 1                    | 0.11 – 0.82                 |
| 10 kpc                   | 0.22 – 1                    | 0.14 – 1                    | 0.13 – 1                    | 0.08 – 0.63                 |

Limits (90%) on the fraction of halo mass in form of stars consistent with the observed number of microlensing events, for a star distribution which traces the total halo mass.

**TABLE 3**

| Star Core radius ($r_c$) | MACHO $M_L = 0.1\ M_\odot$ | EROS $M_L = 0.1\ M_\odot$ | MACHO $M_L = 0.001\ M_\odot$ | EROS $M_L = 0.001\ M_\odot$ |
|--------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| 2 kpc                    | 0.68 – 1                    | 0.62 – 1                    | 0.62 – 1                    | 0.59 – 0.97                 |
| 5 kpc                    | 0.64 – 1                    | 0.59 – 1                    | 0.58 – 1                    | 0.55 – 0.91                 |
| 10 kpc                   | 0.56 – 1                    | 0.51 – 1                    | 0.51 – 1                    | 0.48 – 0.79                 |
| 20 kpc                   | 0.43 – 1                    | 0.40 – 0.81                 | 0.39 – 1                    | 0.37 – 0.61                 |
| 50 kpc                   | 0.32 – 1                    | 0.29 – 0.59                 | 0.29 – 1                    | 0.27 – 0.45                 |

Limits (90%) on the fraction of halo mass in form of stars which do not trace the total halo mass distribution. The core radius of the non-lensing matter distribution has been fixed to $R_c = 5\ kpc$. 