Gravitational Microlensing By Dark Clusters In the Galactic Halo

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The dark matter in Galactic halos, or some fraction of it, may be in the form of dark clusters which consist of small mass objects. Carr & Lacey (1987) have derived the permissible properties of such systems, and proposed the existence of dark clusters with mass of order $\sim 10^6 M_\odot$ to explain some of the observed dynamical properties of the stellar disk of the Galaxy. A population of bound systems with mass of $\sim 10^5$-$10^6 M_\odot$ is also an attractive possibility since it is close to the baryon Jeans mass at recombination, which may be the preferred mass scale for the first bound objects to form in the universe. At the present, the existence of dark clusters which consist of brown dwarfs, Jupiters, or black hole remnants of an early generation of stars, is not indicated, nor can be excluded on observational grounds.

We describe how dark clusters can be discovered in a sample of gravitational microlensing events in LMC stars. Alternatively, it could provide strict bounds on the fraction of halo mass which resides in such systems. If MACHOs are clustered, the implied degeneracy in their spatial and velocity distributions would result in a strong autocorrelation in the sky position of microlensing events on an angular scale $\lesssim 20$ arcsec, along with a correlation in the event duration.

We argue that a small number of events could be enough to indicate the existence of clusters, and demonstrate that a sample of $\simeq 10$ events would be sufficient to reject the proposal of Carr & Lacey (1987) at the 95% confidence level. If the mass of the hypothesized clusters is much lower than $10^6 M_\odot$, or the fraction of the dark matter which resides in clusters is small, then a much larger sample of events may be required.

Subject headings: The Galaxy - dark matter - gravitational lensing - Magellanic Clouds - galaxies: stellar content
1. INTRODUCTION

It has been proposed that the dark matter in galactic halos may consist of objects with mass of order $\sim 10^6 M_\odot$, either in the form of supermassive black holes (Lacy & Ostriker 1985; Ipser & Semenzato 1985, but see Moore 1993), or as dark stellar dynamical clusters of small mass objects (Carr & Lacey 1987). The main attraction in a population of such massive objects is that it could naturally explain some of the observed dynamical properties of the disk component of our Galaxy (Lacey & Ostriker 1985). This includes the observed amount of heating of the stellar disk and its dependence on time; the shape of the stellar velocity ellipsoid, and the observed tail of high velocity stars in the solar neighborhood. As pointed out by Carr & Lacey (1987), the hypothesized clusters have some advantages over the black holes scenario. They will not radiate with a considerable luminosity due to gas accretion when passing through the Galactic disk (Carr 1979; Lacey & Ostriker 1985), and will avoid a too rapid orbital decay and accumulation in the Galactic nucleus (cluster mass loss due to tidal disruption at small Galactocentric distances will reduce the dynamical friction).

Assuming that most of the halo mass resides in clusters, Carr and Lacey (1987) derived the permissible cluster properties which can lead to a dynamically consistent picture. They found that the typical cluster radius is constrained to be around $\approx 1 \text{pc}$ from collisional and tidal cluster disruption considerations, and that the clusters would have to be composed of objects with typical mass smaller than $10 M_\odot$ in order to avoid evaporating on a timescale shorter than the age of the Galaxy. Such clusters are unlikely to be predominantly composed of neutron stars or white dwarfs (Boughn, Saulson, & Seldner 1981; Gilmore & Hewett 1983, but see also Ryu, Olive, & Silk 1990; Eichler & Silk 1992), but they may consist of Jupiters, brown dwarfs, or small black hole remnants from an early generation of stars.

One must admit that, although shown to be a viable possibility, the idea that the entire galactic dark matter distribution resides in dense compact clusters may not be very appealing. However, there is absolutely no reason to exclude the possibility that some fraction of the halo dark mass is in the form of $10^5$-$10^6 M_\odot$ clusters. This is not an outrageous idea since we already know that (luminous) matter is clustered on various scales. Also, this mass range is close to the baryon Jeans mass at recombination, which may be the preferred mass scale for the first bound objects to form in the universe (Peebles & Dicke 1968; Carr & Rees 1984).

Recent detections of gravitational microlensing events (Alcock et al. 1993; Aubourg et al. 1993; Udalski et al. 1993, 1994) indeed suggest that at least some of the Galactic dark matter is in the form of Massive Compact Halo objects (MACHOs) with masses of order $\sim 0.1 M_\odot$ (see also Paczyński 1986,1991; Griest 1991; Griest et al. 1991). In this Letter we draw the attention to a simple test which can either reveal the existence of dark clusters in the Galactic halo, or place strict bounds on the fraction of dark matter which resides in
MACHO clusters. We describe the signature of clusters in a sample of microlensing events in the direction of the Large Magellanic Cloud (§2), and conclude in §3.

2. MICROLENSING BY CLUSTERS OF MACHOS

Let us assume that a fraction $f$ of the Galactic halo dark matter ($0 \leq f \leq 1$) consists of clusters with mass $M_C$ and radius $r_C$, each composed of objects with typical mass $m$. Carr & Lacey (1987) have demonstrated that the combination of $M_C \approx 10^6 M_\odot$, $r_C \approx 1\text{pc}$, $f = 1$, and $m = 0.1 M_\odot$ satisfies the conceivable dynamical constraints (but see Moore 1993), so we shall adopt these numbers as reference values. First we derive a few characteristics of the cluster population, and then discuss the observational implications on gravitational microlensing experiments.

The mass density profile of the Galactic halo in the range of Galactocentric distances $R_0 \leq R \leq R_{\text{LMC}}$ is well fit by $\rho(R) = V_\infty^2/(4\pi GR^2)$, where $V_\infty$ is the asymptotic rotational velocity of the disk, and $R_0(R_{\text{LMC}})$ are the distances of the Sun (LMC) to the Galaxy center, respectively. The number density of clusters as a function of distance from the Sun, $r$, in the LMC direction is

$$n(r) = \frac{f V_\infty^2}{4\pi G M_C (R_0^2 + r^2 - 2R_0 r \cos \theta_{\text{LMC}})} , \quad (1)$$

where $\theta_{\text{LMC}}$ is the angle between the LMC and the Galactic center. Denoting the total angular area of the LMC which is monitored for microlensing events by $\Delta \Omega (\approx 2\text{deg}^2)$, the number of foreground clusters with lines of sight which intersect that area is

$$N \approx \Delta \Omega \int_0^{d_{\text{LMC}}} n(r) r^2 dr = 22 f \left( \frac{M_C}{10^6 M_\odot} \right)^{-1} \left( \frac{\Delta \Omega}{2\text{deg}^2} \right) , \quad (2)$$

where we have substituted $R_0 = 8.5\text{kpc}$, $V_\infty = 220\text{km}\text{s}^{-1}$, $d_{\text{LMC}} = 55\text{kpc}$, and $\theta_{\text{LMC}} = 82^\circ$. The fraction of the LMC area which is behind dark clusters is

$$P_C \approx \Delta \Omega \int_0^{d_{\text{LMC}}} \frac{\pi r_C^2}{\Delta \Omega r^2} n(r) r^2 dr \approx 5 \times 10^{-4} f \left( \frac{M_C}{10^6 M_\odot} \right)^{-1} \left( \frac{r_C}{1\text{pc}} \right)^2 . \quad (3)$$

The optical depth for gravitational microlensing, averaged over all LMC lines of sight, is $\approx 5 \times 10^{-7}$ (Paczyński 1986), regardless of possible MACHO clustering. But, the probability for microlensing of an LMC star which is observed through a dark cluster is

$$\tau_C \approx \frac{M_C r_C^2}{m r_C^2} + 5 \times 10^{-7} (1 - f) \approx 1.5 \times 10^{-3} \left( \frac{M_C}{10^6 M_\odot} \right) \left( \frac{r_C}{1\text{pc}} \right)^{-2} . \quad (4)$$
where the r.h.s of equation (5) is an evaluation for a cluster at a distance of \( r = 10 \text{kpc} \), and the Einstein Radius, \( r_E \), is defined by

\[
r_E^2 = \frac{4Gm r(d_{LMC} - r)}{c^2 d_{LMC}}.
\]  

(5)

If a substantial fraction of the MACHO population resides in clusters then the angular distribution of microlensing events in LMC stars should be strongly correlated on very small angular scales. Equation (3) shows that \( P_C \ll 1 \) for a considerable range of parameters, which means that only a small fraction of the LMC area is observed through clusters. Therefore, in the limit \( f \to 1 \) the events will appear to be concentrated in \( \sim N \) isolated small regions (hereafter, “spots”), where \( N \) is given by equation (2). The typical angular size of each spot would be

\[
\theta_C \approx \frac{r_C}{10 \text{kpc}} = 20 \text{arcsec} \left( \frac{r_C}{1 \text{pc}} \right).
\]  

(6)

The number of spots would be effectively smaller then estimated by Eq. (2), and the reason for that is the following: the optical depth for microlensing is proportional to \( r_E^2 \), so the probability for lensing through a cluster at a distance \( r \) scales as \( r(d_{LMC} - r) \). This means that most events are likely to be produced by those clusters which are located within a (broad) range of distances around \( \approx 10 \text{kpc} \) where \( n(r)r(d_{LMC} - r) \) has a maximum. Thus, the effective number of spots is smaller than the number of clusters, \( N \).

Let us estimate the number of events which are required in order to confirm or rule out the population of \( 10^6 M_\odot \) dark clusters \( (f = 1) \) which has been proposed by Carr and Lacey (1987). Assuming that the monitored LMC stars are observed through a population of \( N \) clusters, the probability that no repetition from the same cluster will occur in a sample of \( k \) events (the “Birthday Problem”) is given by

\[
q_k \simeq \frac{N!}{(N-k)! \, N^k} \simeq e^{-k} \left( \frac{N}{N-k} \right)^{N-k+0.5},
\]  

(7)

where all clusters are assumed to have identical optical depth, and the rightmost approximation is due to Stirling’s formula. Substituting \( N = 22 \) as implied from Eq. (2) and using Eq. (7), we find that if no pair of events is observed at a separation \( \leq \theta_C \), then a sample of 10 events is sufficient for rejecting the proposal of Carr and Lacey (1987) at the \( \approx 90\% \) confidence level. Using Monte Carlo simulations which take into account the varying optical depth of clusters with distance, we found that the absence of a very close pair in a sample of 10 events enables rejecting the above hypothesis at the \( \approx 95\% \) confidence level (the higher confidence level reflects the fact that the effective number of spots is smaller than \( N \), as discussed earlier). Introducing Poisson noise in \( N \) into the simulations resulted in a negligible change in the number of required events (the contribution of realizations with \( N \gg 22 \) compensates almost entirely that of ones with \( N \ll 22 \)).
At the present, the closest pair among the 3 events observed towards the LMC (Alcock et al. 1993; Aubourg et al. 1993) is at a separation of 2.38$^\circ$ (this does not conflict with the fact that the total monitored LMC area in the MACHO experiment is 2 deg$^2$ since it is composed of four different fields). But, if a pair with angular separation $\leq \theta_c$ will be found in a sample of a few events, and the probability that this occurs by chance when there is no clustering is very small, then it may strongly suggest that dark clusters do exist.

In order to rule out a population of lower mass clusters (still with $f = 1$) the number of observed events should be of order $\approx 10(M_C/10^6 M_\odot)^{-1/2}$. This results from the scaling $k \propto N^{1/2}$ for a fixed value of $q_k$, normalized to 10 events for clusters with mass of $10^6 M_\odot$. One should bear in mind that a low value of $M_C$ implies a higher number of clusters, so a pair of events at angular separation $\leq \theta_c$ could appear by chance, in which case the above test would not be adequate. When a large sample of events is established, the only reliable way to evaluate the statistical significance for ruling out various portions of the $(f, M_C, r_C)$ parameter space would be using Monte Carlo simulations. These could also take the various observational biases, as well as the distribution of monitored LMC stars, into account.

A necessary condition for observing repeated events from the same cluster is that the average number of monitored LMC stars behind a cluster be more than one. Roughly 1.8 million LMC stars are currently being monitored in the MACHO project for brightness variations within a total area of $\approx 2$ deg$^2$ (K. Griest, private communication), so their average number behind each cluster is

$$\sim 1.8 \times 10^6 \left( \frac{\pi \theta_c^2}{\Delta \Omega} \right) \approx 10^2 \left( \frac{r_C}{1 \text{ pc}} \right)^2,$$

and the condition is satisfied.

An additional and independent test for the existence of dark clusters is provided by the distribution of event durations. The time scale for the intensity variation of a microlensed star depends on the lens’s mass and distance, and on the relative tangential velocity between the star and the lens. Since each of these three quantities may vary at least by an order of magnitude for Galactic halo objects, the distribution of event durations is expected to be quite broad. However, if events are produced by MACHOs within the same cluster, then the corresponding lenses are practically at identical distances, and have roughly the same velocity vector up to a correction of order $\sigma_C/V_\infty$, where $\sigma_C$ is the velocity dispersion of MACHOs within a cluster. In such case, the dispersion in the distribution of relative tangential velocities between a lens and a source will be reduced by a factor of $[(\sigma_C^2 + \sigma_{LMC}^2)/(V_\infty^2 + \sigma_{LMC}^2)]^{1/2} < 1$, where $\sigma_{LMC}$ is the velocity dispersion of the LMC stars. Therefore, the dispersion in event duration within each spot will be mainly due to the dispersion in the lenses’ masses, and events which are correlated in sky position should also be correlated in duration. When a sufficiently large sample of events is established, the dispersion in event duration within each “spot” should be significantly lower than the
dispersion in the entire sample.

Two important characteristics of a microlensing event are that it may occur (practically) only once for a given star, and that the light curve be symmetric around the maximum of brightness and have a characteristic shape (Paczyński 1991). An exception for the later is when either the lens or the source is a binary system or has a planet (Mao & Paczyński 1991; Gould & Loeb 1992). If the hypothesized clusters had been dense enough, the projected separation between MACHOs could have been comparable or smaller than the Einstein radius. In such case the light curve would not be symmetric, and stars would be observed to undergo repeated events. Equation (4) shows that this is unlikely to happen since the mean optical depth for microlensing through a cluster ($\sim 10^{-3}$) is considerably smaller than unity for a wide range of cluster properties (this is independent of the number of MACHOs per cluster). Nevertheless, assuming a typical MACHO mass of order $\sim 0.1 M_\odot$, and that the central projected density of a cluster may be an order of magnitude larger than the mean one, we may expect a few particular stars which happen to be aligned with a cluster center to exhibit repeated microlensing events (and more complex light curves) on a timescale of $\sim 10^2$ months.

In the future, if the existence of dark clusters is established, then a large sample of microlensing events could provide invaluable information on the projected structure of the clusters, their tangential velocities, and the mass distribution of MACHOs.

3. DISCUSSION

We described an observational test which can provide either an indication or constraints on the existence of dark clusters in the Galactic halo, using a sample of gravitational microlensing events in the direction of the LMC. We have shown that valuable information could be extracted already from a sample of a few events. For example, roughly 10 events in the LMC direction could be sufficient to rule out the population of $\sim 10^6 M_\odot$ clusters which has been proposed by Carr and Lacey (1987). On the other hand, if a comparable number of events exhibit clustering in sky position on scales $\lesssim 20$ arcsec, as well as the expected correlation in the event duration (§2), it would strongly suggest that clusters do exist.

Gould (1993) has shown that if the LMC acquires a halo of MACHOs, it would produce a variation of the optical depth to lensing as a function of sky position in the LMC by as much as $\sim 20\%$. This will not affect the correlation of events on very small angular separations, but it should be taken into account in the future when a large sample of events is established and confronted with Monte Carlo Simulations.

The test for MACHO clustering could in principle be applied also to microlensing of stars in the Galactic bulge where four events have already been observed (Udalski et al.
1993, 1994). However, although interesting by itself, it would not provide much valuable information on dark clusters since those are likely to be disrupted at small Galactocentric distances (i.e., \( \lesssim R_0/2 \), where the optical depth for lensing in that direction is the largest). On the other hand, if clustering is observed in that direction it may be explained, for example, by a small scale clustering of protostars in the Galactic disk.

We assumed that the observed microlensing events are produced by MACHOs in the Galactic halo. However, it is still possible that the observed events are due to MACHOs which are distributed in a thick disk rather than in the halo, in which case the test described in this Letter is inadequate. A larger sample of events will enable to discriminate among these two possibilities (Gould, Miralda-Escude, & Bahcall 1994; Gould 1993).

I wish to thank Rosanne Di Stefano, Chris Kochanek, Shude Mao, and Martin Rees for discussions and comments. This work was supported by the U.S. National Science Foundation, grant PHY-91-06678.
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This preprint was prepared with the AAS LATEX macros v3.0.