BROWN DWARFS, WHITE KNIGHTS, AND DEMONS

GEZA GYUK
Scuola Internazionale Superiore di Studi Avanzati, via Beirut 2-4, 34014 Trieste, Italy

N. WYN EVANS
Theoretical Physics, Department of Physics, 1 Keble Road, Oxford, England OX1 3NP, UK

AND

EVALYN I. GATES
Department of Astronomy and Astrophysics, University of Chicago, Chicago, IL 60637; Adler Planetarium, 1300 Lake Shore Drive, Chicago, IL 60605

Received 1998 February 4; accepted 1998 May 20; published 1998 July 1

ABSTRACT

This Letter investigates the hypothesis that the lensing objects toward the Large Magellanic Cloud are brown dwarfs by analyzing the effects of velocity anisotropy on the inferred microlensing masses. To reduce the masses, the transverse velocity of the lenses with respect to the microlensing tube must be minimized. In the outer halo, radial anisotropy is best for doing this; closer to the solar circle, azimuthal anisotropy is best. By using a constraint on the total kinetic energy of the tracer population from the Jeans equations, the microlensing mass is minimized over orientations of the velocity dispersion tensor. This minimum mass is \( \geq 0.1 M_\odot \), which lies above the hydrogen-burning limit. This demonstrates explicitly that populations of brown dwarfs with smoothly decreasing densities and dynamically mixed velocity distributions cannot be responsible for the microlensing events. Brown dwarfs are no white knights! There is one caveat. If there are demons sitting on the microlensing tube, they can drop brown dwarfs so as to reproduce the microlensing data set exactly. Such a distribution is not smooth and does not give well-mixed velocities in phase space. It is a permissible solution only if the outer halo is dynamically young and lumpy. In such a case, theorists cannot rule out brown dwarfs. Only exorcists can!

Subject headings: dark matter — Galaxy: halo — Galaxy: kinematics and dynamics — gravitational lensing

1. INTRODUCTION

The MACHO collaboration has interpreted its observations of microlensing events toward the Large Magellanic Cloud (LMC) as evidence that about one-third of the halo of our own Galaxy exists in the form of objects of around \( 0.5 M_\odot \) (Alcock et al. 1997). Unfortunately, there are seemingly insuperable objections to all of the obvious candidates for the lensing population. Normal stars would be visible (Alcock et al. 1997), white dwarfs are ruled out by current Population II abundance ratios (Fields, Mathews, & Schramm 1997; Gibson & Mould 1997), while the Hubble Deep Field gives stringent restrictions on the contribution of red dwarfs (Graff & Freese 1996). The microlensing events would be easier to understand if the characteristic mass of the lensing objects was below the hydrogen-burning limit (\( \approx 0.08 M_\odot \)). Of course, a lensing population of brown dwarfs would be much too dark to be visible, and there is no conflict either with the metallicity data or the Hubble Deep Field star counts. So, it is natural to ask the questions Can the deflectors be brown dwarfs? and Is it possible that the masses of the microlenses have hitherto been overestimated? The aim of this Letter is to answer these questions.

Uncertainties in estimates of the lens candidates arise from two fundamental sources: low number statistics and modeling error. Although the number of microlensing events observed toward the LMC is still low, a determination of the average mass for a given model. Of course, a lensing population of brown dwarfs would be much too dark to be visible, and there is no conflict either with the metallicity data or the Hubble Deep Field star counts. So, it is natural to ask the questions Can the deflectors be brown dwarfs? and Is it possible that the masses of the microlenses have hitherto been overestimated? The aim of this Letter is to answer these questions.

Low-mass lenses such as brown dwarfs are already ruled only for halo models with negligible rotation and isotropic velocity dispersions (e.g., Chabrier, Segretain, & Méra 1996). To rule out the hypothesis that the lenses are brown dwarfs requires a thorough investigation of halo models with very different kinematics—in particular with different streaming velocities and different random motions. Gyuk & Gates (1998) have already shown that rotating halos are unable to reduce
the microlensing mass estimates below about 0.25 $M_\odot$ (unless all of the lensing takes place very close to the Sun). This Letter will examine the effects of anisotropy and show that the associated modeling uncertainties cannot cause the high lens mass estimates.

2. VELOCITY ANISOTROPY AND THE MINIMUM MASS OF THE MICROLENSING OBJECTS

Let us start with a thought experiment. Suppose a stationary observer views a stationary source through a population of lenses with density $\rho$. The timescale of any lensing event is related to the Einstein radius $R_e$ and the transverse velocity $v_T$ by

$$ t_0 = \frac{R_e}{v_T} = \frac{1}{v_T} \sqrt{\frac{4GM\rho(D_s - D_l)}{c^2D_s}}, \tag{1} $$

where $M$ is the mass of the lens and $D_s$ and $D_l$ are the distances to deflector and source. Suppose now that the distribution of transverse velocities of the lenses is Gaussian with a dispersion $\sigma_T$. The microlensing optical depth $\tau$ is well known to be independent of the masses of the lenses (Press & Gunn 1973). The rate of microlensing $\Gamma$ is (e.g., Griest 1991)

$$ \Gamma = \langle 2\pi \rangle^{1/2} \frac{\sigma_T}{M^{1/2}} \int_0^{D_s} dD_s \rho(D_s) \sqrt{\frac{4GM\rho(D_s - D_l)}{c^2D_s}}, \tag{2} $$

and the timescale histogram is

$$ \frac{dT}{dt_0} = \frac{8\pi^2\sigma_T^2}{M} \int_0^{D_s} dD_s \rho(D_s)D_s^2(D_s - D_l)^2 \exp[-AD_s(D_s - D_l)], \tag{3} $$

with $A = 2GM(D_s c^2 t_0 \sigma_T^2)$. This demonstrates explicitly that all of the microlensing quantities $\langle \tau, \Gamma, d\Gamma/dt_0 \rangle$ depend only on the ratio $M/\sigma_T^2$. Given the microlensing data set alone, it is not possible to constrain the mass of the deflectors at all! Any mass estimate is solely a consequence of assumptions regarding the transverse velocity dispersions. The same data will be consistent with a smaller inferred mass if the transverse motions are reduced. This degeneracy between mass and velocity can be partially lifted if parallax effects (Refsdal 1966; Griest 1991; Gould 1994) or finite source size effects (Nemiroff 1997) can be detected in the light curve.

Of course, the analysis of the microlensing events toward the LMC is more complex than this thought experiment. Both the Sun and the LMC are moving, and therefore the expectation value of the transverse velocity of the lens with respect to the microlensing tube cannot be made arbitrarily small just by changing the velocity anisotropy of the lenses. Figure 1 shows a planform of the Sun and the LMC projected on the Galactic equatorial plane. The line of sight from the Sun to the LMC is shown as a dashed line. In the outer parts of the halo, this line of sight is aligned very nearly with the radial direction of the spherical polar coordinate systems. Radial anisotropy of the velocity dispersion tensor is the best option for reducing the mass estimates. Nearer the solar circle, the offset of the Sun from the Galactic center becomes important. The line of sight is aligned more nearly with the azimuthal direction. This means that radial anisotropy is now dangerous. The best recipe for the minimum microlensing mass is to allow the velocity dispersion tensor to be azimuthally distended near the Sun and to become radially distended in the outer halo.

As a simple model, let us assume that the density of the lensing population is smooth and falls off like a power of the distance ($\rho \propto r^{-1}$). We take the overall potential to be a power-law model, so that the circular velocity $v_{circ}$ falls like $r^{-1/2}$. Rich families of solutions to the Jeans equations for power-law density distributions in power-law potentials are known (Evans, Häfner, & de Zeeuw 1997). These are all aligned in the spherical polar coordinates but vary in the anisotropy of the principal components of the velocity dispersion tensor $\sigma$. The detailed Jeans solutions all satisfy the constraint (see eq. [3.8] of Evans et al. 1997)

$$ \sum_{i=1}^3 \sigma_i^2 \approx v_{circ}^2 \min\left(1, \frac{1}{\beta + \gamma - 2}\right). \tag{4} $$

From the standpoint of minimizing the microlensing mass estimates, the best of all possible worlds is to replace the inequality in the above expression with an equality. This means that the total kinetic energy required to support the lensing population against gravity is underestimated. The inferred microlensing mass will always be lower than the true mass. We allow the ratio of the principal components of the velocity dispersions to vary subject only to the condition that the sum of the components does not violate inequality (4). Thus, the Jeans equations are not satisfied spot-wise but only in a gross sense. The total kinetic energy cannot be reduced further without violating the rules of gravitational physics. If all of the deflectors are $1 M_\odot$ objects, the rate is (see e.g., Griest 1991;
constrained. The minimum mass estimate ranges from 0.1 always prefers to be as low as possible, while respond to the range. In such a situation, \( m \) to \( \bar{d} \) over their respective ranges. Different curves correspond to the range \( 1/16 \) to 16. For comparison, Freeman (1987) reports that the Population II stars in the spheroid have velocity dispersions at the solar position oriented on the cylindrical polar coordinate system such that \((140, 100, 75) \text{ km} \text{s}^{-1}\). The microlensing mass is to be minimized, while both the anisotropy parameters \( \lambda \) and \( \mu \) and the alignment of the velocity ellipsoid are varied.

After a little thought, it is obvious what the alignment is for the minimum mass estimate—the best of all possible worlds is when the velocity ellipsoid is aligned along the microlensing tube itself, with as much kinetic energy as possible put into motions along the tube and as little as possible put into transverse motions. Figure 2 shows the inferred mass as a function of \( \gamma \), where the mass has been minimized by allowing \( \lambda \) and \( \mu \) to float over their respective ranges. Different curves correspond to the range \(-0.25 \leq \beta \leq 0.25\). In such a situation, \( \lambda \) always prefers to be as low as possible, while \( \mu \) is only weakly constrained. The minimum mass estimate ranges from 0.1 \( M_\odot \) when \( \gamma = 2.0 \) to 0.25 \( M_\odot \) when \( \gamma = 4.0 \). The inferred mass is always larger than the hydrogen-burning limit. This leads us to the main result of the Letter: If the density of the microlensing population is smooth and monotonic decreasing (that is, reasonably well approximated by a power law), then the microlenses cannot be brown dwarfs, irrespective of the details of their kinematics. The strength of this statement is that it is based on the Jeans equations and is therefore robust.

3. A MODEST ESTIMATE

Let us emphasize that this algorithm for obtaining the minimum mass gives a value that is very much a lower limit. It uses a number of gratuitous approximations, all of which act to reduce the mass estimate. For example, the Jeans solutions of reasonable tracer populations may possess a kinetic energy greater than the minimum prescribed by equation (4). Again, almost certainly, the alignment along the microlensing tube that yields the minimum mass cannot be built—that is, there is no set of stellar orbits that can be superposed to yield a true dynamical model corresponding to the Jeans solution. Making the model more realistic will necessarily require more massive lenses. In this section, we provide an estimate of the more modest reduction in the microlensing masses expected from velocity anisotropy for one particular reasonably realistic model of the halo.

To do this, let us build Jeans solutions of tracer populations with the density of the Jaffe (1983) sphere,

\[
\rho = \frac{M}{4\pi r_1^3} \frac{r_1^4}{(r + r_1)^3},
\]

in a spherical isothermal halo potential. Here, \( r_1 \) is a scale length that describes when the density turns over. A typical estimate of its value might be \( r_1 \sim 50 \text{ kpc} \) (Kocharnek 1996; Wilkinson & Evans 1998). Let the anisotropy be defined as

\[
\frac{\sigma_\|^2}{\sigma_\perp^2} = \frac{\sigma_\perp^2}{\sigma_\|^2} = \lambda + \frac{r_1}{r}.
\]

This simple Ansatz allows the kinematics to change from azimuthal anisotropy to radial anisotropy or vice versa. Here, \( \lambda_* \) is the value of the anisotropy at infinity, whereas \( r_1 \) is a scale length on which the anisotropy changes. The solution of the spherical Jeans equation is readily found by the method of

\[
\Gamma = 2 \int_{a}^{b} dD_{\rho} R_{\rho}(D_{\rho}) \rho(D_{\rho}) [V(\|D_{\rho})].
\]

Here \( [V(\|D_{\rho})] \) is the average value of the transverse velocity of the lens with respect to the microlensing tube. The best estimator of the average event duration \( \langle t_e \rangle \) is 61 days (see Appendix A of Gyuk & Gates 1998). This uses the events and the efficiencies given in Alcock et al. (1997). So the microlensing mass estimate \( m_{\text{min}} \) is

\[
m_{\text{min}} \approx \left[ \langle t_e \rangle \frac{\Gamma}{\tau} \right].
\]
integrating factors as (see Binney & Tremaine 1987)

\[
\sigma^2 = r_{\text{circ}}^2 \exp \left(-2r_*/r \right)^{2\lambda \sigma^2} \left(r + r_* \right)^2 \\
\times \int_{r_*}^{\infty} dr \exp \left(2r_*/r \right)^{2\lambda \sigma^2} \left(r + r_* \right)^{-2}.
\]

The azimuthal dispersions now follow from equation (9). The isotropic model has \( \lambda_\sigma = 1 \) and \( r_* = 0 \) and a mass estimate (given by eq. [6]) of 0.348 \( M_\odot \). This can be reduced by anisotropy. The microlensing mass estimate in the plane of the asymptotic anisotropy \( \lambda_\sigma \) and the anisotropy scale \( r_* \) is shown in Figure 3. For this set of Jeans solutions—in which the anisotropy can change significantly but not dramatically—there is no hope of using anisotropy by itself to reduce the microlensing mass estimate below \( \approx 0.3 \ M_\odot \).

4. DISCUSSION AND CONCLUSIONS

If the density of the microlenses is smooth and decreasing, then they cannot be brown dwarfs. This holds irrespective of the details of their kinematics. This general result follows because the Jeans equations (or, equivalently, the virial theorem) imply the existence of an irreducible minimum kinetic energy to support the lensing population against gravity. Even in the optimum alignment of the velocity dispersion tensor of the lenses, this must yield sufficient transverse motion so that the minimum mass is \( \approx 0.1 \ M_\odot \) for halo models with flat rotation curves. This is above the hydrogen-burning limit.

There is a way to save brown dwarfs. Let us imagine a collection of demons sitting on the microlensing tube. One of the demons at a heliocentric distance of 20 kpc launches a brown dwarf of mass 0.06 \( M_\odot \) with a velocity of 106 km s\(^{-1}\) across our line of sight, and this causes event 4 with a blended timescale of 39.5 days. A second demon sitting on the microlensing tube at 30 kpc launches a brown dwarf with a velocity of just 75 km s\(^{-1}\), and this gives event 5 with a blended timescale of 55.5 days, and so on. Of course, demons can exactly reproduce the data set reported by Alcock et al. (1997) by dropping brown dwarfs from the microlensing tube. The density of brown dwarfs so produced is neither spherical nor axisymmetric nor in a steady state. The velocity distribution is not dynamically well mixed, and the time averages (Binney & Tremaine 1987, p. 171), which is the fundamental result underpinning steady state stellar dynamics, does not hold. If it did, we could infer the existence of further brown dwarfs at different phases of the same orbits and show that they produce microlensing events that are not seen. Such a model is possible if the halo is very blobby (e.g., Lynden-Bell 1994; Lynden-Bell & Lynden-Bell 1995). Then, in every direction that one looks (including \( \ell = 280^\circ, b = -33^\circ \)), there may be garbage heaps of brown dwarfs whose density and velocity distributions are lumpy. This possibility cannot be ruled out from the microlensing data set alone.

Most of this work was done during a visit to SISSA, Trieste. N. W. E. wishes to thank the astrophysics sector in general, and Dennis Sciama and John Miller in particular, for their kindness and their hospitality. N. W. E. thanks James Binney for numerous insightful remarks on this subject.

REFERENCES

Alard, C. 1997, A&A, 321, 424
Alcock, C., et al. 1997, ApJ, 486, 697
Binney, J., & Tremaine, S. 1987, Galactic Dynamics (Princeton: Princeton Univ. Press)
Chabrier, G., Ségr étain, L., & Méra, D. 1996, ApJ, 468, L21
Evans, N. W. 1994, MNRAS, 267, 333
Evans, N. W., Häfner, R., & de Zeeuw, P. T. 1997, MNRAS, 286, 315
Fields, B., Mathews, G. J., & Schramm, D. N. 1997, ApJ, 483, 625
Freeman, K. 1987, ARA&A, 25, 603
Gibson, B., & Mould, J. 1997, ApJ, 482, 98
Gould, A. 1994, ApJ, 421, L75
Graff, D., & Freese, K. 1996, ApJ, 456, L49
Griest, K. 1991, ApJ, 366, 412
Gyuk, G., & Gates, E. 1998, MNRAS, 294, 682
Jaffe, W. 1983, MNRAS, 202, 995
Kochanek, C. 1996, ApJ, 457, 228
Lynden-Bell, D. 1994, in Dwarf Galaxies, ed. G. Meylan & P. Prouglin (Garching: ESO), 548
Lynden-Bell, D., & Lynden-Bell, R. 1995, MNRAS, 275, 439
Mao, S., & Paczyński, B. 1996, ApJ, 473, 57
Marković, D., & Sommer-Larsen, J. 1997, MNRAS, 288, 733
Nemiroff, R. 1997, ApJ, 486, 693
Press, W., & Gunn, J. 1973, ApJ, 185, 397
Refsdal, S. 1966, MNRAS, 134, 315
Wilkinson, M., & Evans, N. W. 1998, in preparation