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THE MEANING OF EROS/MACHO

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ABSTRACT

Most of the mass density in the Universe—and in the halo of our own galaxy—exists in the form of dark matter. Overall, the contribution of luminous matter (in stars) to the mass density of the Universe is less than 1%; primordial nucleosynthesis indicates that baryons contribute between 1% and 10% of the critical density ($0.01h^{-2} \lesssim \Omega_B \lesssim 0.02h^{-2}$; h = the Hubble constant in units of $100\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$); and other evidence indicates that the total mass density is at least 10% of critical density, and likely much greater. If the universal density is as low as 10% of the critical density there may be but one kind of dark matter. More likely, the universal density is greater than 10%, and there are two kinds of dark matter, and thus two dark matter problems: In what form does the baryonic dark matter exist? and In what form does the nonbaryonic dark matter exist? The MACHO and EROS collaborations have presented evidence for the microlensing of stars in the LMC by $10^{-1\pm1}M_\odot$ dark objects in the halo of our own galaxy and may well have solved *one* of the dark matter puzzles by identifying the form of the baryonic dark matter. It is too early to make precise statements about the fraction of the mass density in the halo of our galaxy contributed by lensing objects ($= f_m$), though the EROS/MACHO data suggest that f_m is probably 0.1 or larger. Taking our galaxy to be typical and taking account a fraction f_m of the mass in the portion of the halo that contributes most significantly to microlensing (within 20 kpc of the galactic center), I estimate that lensing objects contribute a fraction $0.008f_m/h$ of the critical density, and clearly cannot account for the bulk of the dark matter if $\Omega_0 \gg 0.1$ (even

discarding the nucleosynthesis bound). (If the distribution of lensing objects extends throughout the galactic halo, out to about 100 kpc, their contribution is larger by a factor of five). If halo lensing objects contribute around 10% of the mass density in the halo, the EROS/MACHO results provide further evidence for a nonbaryonic component to the halo dark matter, consistent with the simplest prediction for the ratio of cold dark matter (e.g., axions or neutralinos) to baryons in the halo. In any case, the EROS/MACHO results in no way lessen the strong case that now exists for the mass density of the Universe being significantly larger than that which baryons can contribute: nor do they affect significantly the prospects for directly detecting particle dark matter in our vicinity. Discovering the nature of the baryonic dark matter should provide still further impetus for solving the more weighty dark matter problem, the nature of the nonbaryonic dark matter.

1 Introduction

1.1 The events

Two collaborations searching for massive, dark objects in the halo of our galaxy through gravitational microlensing reported candidate events this week. The French EROS collaboration has monitored the brightnesses of 3 million stars in the Large Magellanic Cloud (LMC) over a three-year period and reported two events: a star that brightened by a factor of about 2.5 over a characteristic time interval of about 54 days and a star that brightened by a factor of about 3.3 over a time interval of about 60 days [1]. (EROS measure the brightnesses of stars on 5° × 5° Schmidt plates taken with two filters, bleu and rouge, with a machine known as "MAMA.") The American-Australian MACHO collaboration has monitored the brightnesses of about 1.8 million stars in the LMC for one year and reported one event: a star that brightened by about a factor of about 6.8 over a characteristic time interval of about 34 days [2].[1] (MACHO use two CCD cameras and a dichroic beamsplitter to measure the brightnesses of stars in two colors, red and blue, and observed each star about 250 times during the year period.)

1.2 Microlensing

The basic idea of detecting massive, nonluminous objects in the halo by microlensing was suggested by Paczynski [3]; the discussion that follows is based upon the very nice paper by Griest [4]. The actual deflection of light from a star in the LMC (distance 50 kpc) by an object in our halo is far too small to measure, of order $\delta\phi \sim 2 \times 10^{-4}(m/M_\odot)^{1/2}$ arcseconds, where m is the mass of the halo object and the impact parameter (distance between the lensing object and the line of sight to the star) is taken to be the Einstein radius (see below). However, due to gravitational focussing the total brightness of the two unresolved images is greater than that of the unlensed star, by a factor equal to 1.34 for an impact parameter equal to the Einstein radius (and larger for smaller impact parameters). Since the a priori brightness of a given star is not known, Paczynski's idea was to look for time variation of the brightness of the star due to the motion of the lensing object across the line of sight.

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[1] The definitions of event duration used by MACHO and EROS differ by about a factor of two: I have used the MACHO definition for all three events.

The brightness amplification A depends upon the impact parameter l in units of the Einstein radius R_E:

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

where $l = uR_E$ and

$$R_E = \sqrt{\frac{4Gmx(L-x)}{c^2 L}}. \tag{2}$$

Here x is the distance to the lensing object and L is the distance to the star. A plot of $A(u)$ is shown in Fig. 1 (Fig. 2 of Ref. [4]); large A corresponds to small u.

Because the lensing object is moving (the *rms* halo velocity is around $300\,\mathrm{km\,s^{-1}}$) the impact parameter changes with time, and hence the amplification does too (in principle, one also must take into account the velocity of the star and the solar system, though it is a small correction [4]). The time profile of the amplification, or light curve $A(t)$, depends upon $u(t)$ alone.

To be specific, the impact parameter u is given by

$$u(t)^2 = u^2_{\rm min} + (v_T t/R_E)^2, \tag{3}$$

where $u_{\rm min}$ is the minimum value of the impact parameter, v_T is the velocity of the lensing transverse to the light of sight, and the epoch of maximum amplification defines time zero. Note that the light curves are a two-parameter family of curves. By the measuring the light curve for a microlensing event one can infer $u_{\rm min}$ $[= u(A_{\rm max})]$ and R_E/v_T. Recall, $R_E \sim GmL/c^2$, which implies that the event duration $t \sim \sqrt{GmL}/cv_T \sim 100\,{\rm da}\sqrt{m/M_\odot}$ (more later).

EROS define the duration of the event to be the characteristic time $t_{\rm EROS} = R_E/v_T$, which corresponds to impact parameter $u(\pm t_{\rm EROS}) = \sqrt{1+u^2_{\rm min}}$; MACHO define the duration of the event to be the total time the amplification is above threshold for detection of amplification, $t_{\rm MACHO} = 2\sqrt{u_T^2 - u^2_{\rm min}}R_E/v_T$. For maximum amplification $A_{\rm max} \gg 1$ and a threshold amplification $A_T \sim 1.34$ $(u_T \sim 1)$, which seems to apply to the data of both collaborations, $t_{\rm MACHO} \simeq 2t_{\rm EROS}$.

Now the formulas relating event rate to the abundance of halo objects; to begin, assume that the lensing objects have mass m, are distributed like the halo material, and contribute a fraction f_m of the halo density,

$$\rho_m = f_m \frac{r_0^2 + a^2}{r^2 + a^2} \rho_{\rm local}. \tag{4}$$

Here r = distance from the center of galaxy, $a = 5 \pm 5$ kpc is the core radius of halo, $r_0 \simeq 8.5$ kpc is the distance of the Solar System from the galactic center, and $\rho_{\rm local} \simeq 5 \times 10^{-25}\,{\rm g\,cm^{-3}}$ is the local halo density. (The mass density in the halo is determined by measurements of the rotation curve of our galaxy and the amount and distribution of light in the galaxy; the full extent of the halo—and its total mass—are not known, though there is evidence that the halo extends at least as far as the LMC and probably out to 100 kpc [5].) Further, let us assume that the threshold for detection is amplification A_T, corresponding to impact parameter u_T, and that the efficiency for the detection of a microlensing event above the amplification threshold is ε. (The latter is clearly an oversimplification as ε will be a function of A, the duration of the event, and perhaps other things.)

The probability that a given star in the LMC is being microlensed with amplification greater than A_T by a halo object is referred to as the optical depth for microlensing, and was calculated by Griest [4], cf. Eq. (4),

$$\tau \simeq 4 \times 10^{-7} f_m u_T^2; \tag{5}$$

where the halo is assumed to extend out at least as far as the LMC, the core radius is taken to be 5 kpc, u_T is the impact parameter corresponding to A_T ($u_T = 1$ for $A_T = 1.34$). The value of τ is not very sensitive to the first two assumptions.

Another interesting quantity is $\tau(y)$, the probability that a star in the LMC is microlensed by a halo object between the galactic center and distance y from it: $\tau(y)$ is shown in Fig. 2. (Said another way, $\tau(y)$ is the probability for microlensing under the assumption that the halo only extends out to radius y.) Figure 2 illustrates that most of the optical depth for microlensing is due to halo objects within $10-20$ kpc or so of the center of the galaxy.[2] *That is, microlensing only probes the inner portion of the halo, and further, not much of the lensing probability is due to objects near the solar*

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[2] The reason is simple: the Einstein radius, which the sets the radius of the tube within which halo objects lead to amplification above threshold, is proportional to the product of the distance to the lens and the distance from the lens to the LMC, and further, $d\tau/dy \propto \rho_m/m$, which falls off as r^{-2}.

neighborhood. This is an important fact to keep in mind when interpreting the EROS/MACHO events.

What makes microlensing observable is the time variation of the amplification. So even more important than the lensing probability is the rate of microlensing events (roughly τ divided by the typical event duration); integrating over the distribution of velocities and positions of halo lensing objects Griest obtains the microlensing rate (per star observed) with amplification greater than A_T, cf. Eqs. (7-14),

$$\Gamma \simeq 1.7 \times 10^{-6} f_m u_T/(m/M_\odot)^{1/2}\,\mathrm{yr}^{-1}. \qquad (6)$$

Note, Γ, unlike τ, depends upon the mass of the halo objects: for fixed f_m, the smaller the mass, the higher the event rate.

The duration and amplification of a microlensing event depends upon the impact parameter and the velocity, mass, and distance of the halo microlens. However, the velocity and distance of the halo lensing object can only be specified statistically, and thus the mass of the lensing objects can only be inferred from a measured light curve in a statistical way. Griest has constructed the likelihood function for the lensing mass, given the event duration and threshold for detection. The distribution is very broad, about a order of magnitude in mass at full-width, half maximum (Fig. 9 in Ref. [4]). The peak of that likelihood function occurs at a mass

$$\langle m\rangle \simeq 1.5 M_\odot (t/100\,\mathrm{da})^2/u_T^2. \qquad (7)$$

Note that this mass depends upon the threshold of the experiment; for EROS and MACHO $u_T \sim 1$.

The distribution of maximum amplification of microlensing events is basically geometric: The fraction of events with maximum amplification greater than A corresponds to events with minimum impact parameter less than $u_{\min} = u(A)$, which is simply equal to $u(A)/u_T$. This fraction $\epsilon(A)$ can also be expressed in terms of A and A_T,

$$\epsilon(A) = \sqrt{\frac{(1-A^{-2})^{-1/2}-1}{(1-A_T^{-2})^{-1/2}-1}}, \qquad (8)$$

and is show in Fig. 3; cf. Fig. 10 of Ref. [4].

To conclude this section: microlensing has many clear signatures: it is achromatic; the light curve is defined uniquely in terms of two parameters, maximum amplification and duration: the distribution of event amplifications is predicted; microlensing shows no preference for the type of lensed star; and so on. The most significant background for microlensing searches are variable stars; already, MACHO has compiled the largest catalogue of variable stars in the LMC. Because of its many signatures, microlensing should be a relatively easy hypothesis to test; indeed, EROS and MACHO have already mastered the difficult tasks of monitoring the brightnesses of millions of stars and discriminating against known types of variable stars. In the next year or so both collaborations should increase their data sets by a factor of ten or so and thus should clarify the few questions that have been raised about their events (large χ^2 for two of the three events and large amplification for the MACHO event despite their low threshold, cf. Fig. 3). The case for (or possibly against) the existence of halo lensing objects should be firmly established soon.

2 Overinterpreting the Events

What can one learn from the very preliminary MACHO and EROS results? Definitely not as much as one would like! But let's risk going out on a limb with some shaky interpretations.

First, the number of events seen. Based upon their stated exposures the number of expected events is

$$
\begin{aligned}
N_{\rm MACHO} &= 9.1 f_m \varepsilon u_T/(m/0.1M_\odot)^{1/2}, && (9)\\
N_{\rm EROS} &= 47 f_m \varepsilon u_T/(m/0.1M_\odot)^{1/2} && (10)
\end{aligned}
$$

where of course the detection efficiencies and thresholds for the two experiments are not necessarily the same. In order to infer the fraction of the mass density of the halo in lensing objects, f_m, one must know not only the efficiencies, but also something about the mass of the lensing objects (see below).[3]

MACHO has made no statement about f_m. From the duration of their event they infer a most likely mass of about $0.1M_\odot$; from their paper and

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[3] What one wants to do, and what both collaborations are certainly doing, is constructing the likelihood function for their events as a function of all the relevant parameters (lens mass or distribution of lens masses, spatial density of lenses, and so on) and taking account of acceptance, etc. From this, the most likely values for m and f_m and estimates for their variances can be inferred.

conversations with collaboration members I conclude that both u_T and ε are of order unity. Climbing out to the very end of the limb, this suggests that f_m is about 0.1 or larger (with great uncertainty).

EROS state in their paper that "the number of events is consistent with the hypothesis that the halo of our galaxy is made essentially of dark objects in the mass range of a few 10^{-2} to a few $M_\odot$." Taking $m = 0.1M_\odot$, this implies an efficiency $\varepsilon u_T \sim 0.04$. My interpretation of a talk given by EROS member Luciano Moscoso is that, based upon Monte Carlo simulations, the detection efficiency for events with $u_{\rm min} \lesssim 1$ is about 80% and for events with $u_{\rm min} \gtrsim 1$ it is much, much smaller. Their exposure seems to be much lower than 3 million stars times 3 years: only about half the stars were used and the time coverage of a typical star was about 600 days. Putting this together, I guess that $u_T \sim 1$ and $\varepsilon \sim 0.1$, suggesting that $f_m \sim 0.2$ or so.

Next, event duration; as mentioned earlier, the likelihood function computed by Griest peaks at a mass of $1.5M_\odot(t/100\,{\rm da})^2/u_T^2$. For MACHO, this implies a lensing mass of about $0.1M_\odot$, which is the central value stated in their paper. For EROS, the event durations are about twice as long; this implies a most likely mass of about $0.4M_\odot$. While the estimates for the lensing mass seem to be different, recall that the likelihood function is an order of magnitude in mass at FWHM and that the detection efficiencies will certainly depend upon the event duration and can influence the likelihood function.

As noted above, both the event rate and event duration are needed to infer the fraction of critical density contributed by halo lensing objects. Moreover, some a priori information may help in this regard. For example, stars made of hydrogen and helium more massive than about $0.1M_\odot$ are nuclear burning; previous unsuccessful searches for low-mass stars (M dwarfs) place severe limits to f_m for $m \gtrsim 0.1M_\odot$, perhaps even ruling out this possibility [6, 7]. Dark halo objects heavier than around a solar mass would have to be neutron stars, black holes, or white dwarfs, otherwise they would be easily visible; however, this possibility too is severely constrained by their contribution to the heavy-element abundance in our galaxy [7]. For these reasons it has been argued very convincingly that the mass of baryonic halo objects must be less than about $0.1M_\odot$; note, this makes my previous shaky estimates for f_m shaky *upper limits* since $\Gamma \propto m^{-1/2}$ and $f_m \propto m^{1/2}$.

Let's go on and estimate the fraction of critical density contributed by halo lensing objects, Ω_m. The strategy is as follows: (1) construct the ratio of mass in halo lenses to light for the Milky Way, M_m/L; (2) assume that this ratio is universal; (3) Divide this ratio by the critical mass to light ratio to find Ω_m.[4]

Much is known about the halo mass interior to about 20 kpc [5], and recall, most of the microlensing is due to objects within 20 kpc of the galactic center. The halo mass interior to 20 kpc is about $2.3 \times 10^{11} M_\odot$. The luminosity of the Milky Way galaxy is about $2.3 \times 10^{10} L_{B\odot}$. Assigning a fraction f_m of the halo mass within 20 kpc of the galactic center to lensing objects, I find

$$\begin{aligned} \frac{M_m}{L} &\simeq 10 f_m \frac{M_\odot}{L_{B\odot}} & (11) \\ \Omega_m &\simeq 8 \times 10^{-3} f_m / h. & (12) \end{aligned}$$

This is not much mass, though, to be sure, at least one of our assumptions was very conservative. Although microlensing searches are most sensitive to halo lensing objects within 20 kpc of the galactic center, it would be surprising if f_m suddenly dropped to zero at this point. If we assume that halo lensing objects populate the halo at the same fractional abundance out to 100 kpc, the known extent of the halo, the previous estimate increases by a factor of five:

$$\Omega_m \simeq 0.04 f_m / h, \qquad (13)$$

though still far from closure density.

To conclude this discussion, the MACHO and EROS collaborations may well have solved *one* of the dark matter riddles, namely, what form the dark baryons take. If so, their searches were spectacularly successful. However, the weightier dark matter problem is the nature of the nonbaryonic dark matter, as evidence indicates that Ω_0 exceeds 0.1, the maximum contribution permitted for baryons. (Nucleosynthesis bound aside, the contribution of halo lensing objects to the universal density cannot account for the total mass density if Ω_0 is significantly greater than 0.1.)

3 Implications for Particle Dark Matter

There is mounting evidence that Ω_0 is significantly greater than 0.1, the maximum contribution of baryons, and perhaps close to unity. The evidence

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[4] Astronomers measure the mass density of the Universe by multiplying the luminosity density, $\mathcal{L} \simeq 2.4h \times 10^8 L_{B\odot}\,\mathrm{Mpc}^{-3}$, times a characteristic mass to light ratio: the mass to light ratio (in the B_T system) that corresponds to critical density is $1200 h M_\odot / L_{B\odot}$.

that Ω_0 is close to unity includes several studies relating the peculiar velocities of galaxies within a few 100 Mpc of the Milky Way (and the Milky Way itself) to the distribution of galaxies determined from red-shift surveys based upon the IRAS Point Source Catalogue[5] and the fact that the only models for the formation of structure in the Universe that are consistent with measurements of Cosmic Background Radiation (CBR) anisotropy (e.g., COBE and experiments on smaller angular scales) and large-scale structure require nonbaryonic dark matter. A number of measurements of Ω_0, e.g., cluster virial masses and the infall of nearby galaxies into the Virgo Cluster, strongly suggest that Ω_0 is greater than 0.1, though perhaps not as large as unity. And finally, there are theoretical reasons in favor of $\Omega_0 = 1$ and nonbaryonic dark matter: a flat Universe is an unambiguous prediction of the inflationary paradigm, and there are several particles whose postulated existence is motivated by compelling particle-physics considerations and whose relic abundance is close to the critical density (e.g., neutralino and axion) [10].

In a flat, critical Universe particle dark matter is obligatory. For the discussion that follows I assume that $\Omega_0 = 1$ and that $\Omega_B \sim 0.05 - 0.10$. The universal ratio of exotic dark matter to baryonic dark matter is then

$$\frac{\Omega_X}{\Omega_B} = \frac{1 - \Omega_B}{\Omega_B} \simeq 10 - 20. \tag{14}$$

Of greater interest for the interpretation of the MACHO/EROS events is the local ratio of particle dark matter to baryonic dark matter. In order to fully answer this question we must know how galaxies and other structures formed. In the simplest circumstance, where only gravity is important and the initial velocities of baryons and particle dark matter are similar (or negligible), the answer is dictated by the equivalence principle: Baryons and particle dark matter must follow the same trajectories so that the ratio remains constant and equal to $10 - 20$.

When nongravitational forces become important then the two forms of dark matter will certainly become differentiated as particle dark matter does not interact electromagnetically, the most important nongravitational force that operates in the Universe. In general, the interactions of baryonic matter

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[5] The peculiar velocities of galaxies arise due to gravitational forces resulting from the inhomogeneous distribution of matter and depend upon the distribution of galaxies and the mean mass density; by determining the distribution of galaxies one can infer the mean mass density; see e.g., Refs. [8].

with itself (and the CBR) allow baryons to "cool" (i.e., dissipate their energy) and become more condensed, thereby decreasing the ratio of particle dark matter to baryonic dark matter.

For hot dark matter, relic particles that move fast (e.g., 20 eV neutrinos), the velocity distribution of the particle dark matter is very important: Neutrinos move too fast to become trapped in galaxies (at least until very recently) and so one expects the local ratio of hot dark matter to baryonic matter to be much, much lower than the universal ratio of $10 - 20$.

For cold dark matter (e.g., axions or neutralinos), relic particles that move very slowly, the velocity distribution is unimportant and one would expect that in objects whose formation only involves gravity the local density would reflect the universal value of $10 - 20$. There is no doubt that the formation of the disk of our galaxy involved dissipation (the disk-like structure traces to the dissipation of essentially all the energy not associated with angular momentum). While the halos of galaxies are not fully understood, they show no obvious signs of dissipation having been involved in their formation. Thus, the simplest assumption is that the ratio of cold dark matter to baryonic dark matter in the halo should reflect the universal value of $10 - 20$.[6]

The fraction of the halo mass density in lensing objects is crucial to understanding the implications of MACHO and EROS for particle dark matter. Let us consider two possibilities consistent with the data at hand: $f_m \sim 0.1$ and $f_m \sim 0.5$.

Suppose f_m turns out to be of order 0.1, as is suggested by a naive over-interpretation of the data. In this case the MACHO/EROS results are consistent with the simplest expectation for cold dark matter and inconsistent with hot dark matter. Moreover, the fact that 90% of the mass density in the halo remains unexplained would provide even further impetus for searching for cold particle dark matter in our own halo.

On the other hand, suppose that two or three years from now EROS and MACHO convincingly establish that f_m is 0.5. This is consistent with hot dark matter and inconsistent with the simplest expectation for cold dark matter. With regard to the latter I mention:

1. It could be that the inner part of the halo (which is what is probed by MACHO and EROS) has a smaller ratio of cold dark matter to baryons

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[6] The ratio of cold dark matter to baryonic dark matter expected for the mixed dark matter model ($\Omega_B \sim 0.05$, $\Omega_{\rm cold} \sim 0.65$, $\Omega_{\rm hot} \sim 0.3$) is only slightly smaller, around $7 - 13$. This is one of the models that best accounts for the observed large-scale structure.

because the baryons underwent some dissipation (after all they cannot have formed into astrophysical objects without dissipation). At present there are no compelling scenarios for the formation of these objects, so it is certainly possible that the baryons in the inner halo have undergone some dissipation.

2. It could be that the universal ratio of cold dark matter to baryons is only a few. One of the models that best accounts for the observed large-scale structure is cold dark matter + cosmological constant ($\Omega_\Lambda = 0.8$; $\Omega_{\rm cold} \sim 0.15$; and $\Omega_B \sim 0.05$). While it is certainly not the best motivated model, if the Hubble constant is close to $80\,{\rm km\,s^{-1}\,Mpc^{-1}}$, as many now believe [9], a cosmological constant will be mandatory to solve the cosmological age crisis.

3. A halo ratio of cold dark matter to baryonic dark matter of order unity, rather than $10-20$, has only a minor impact on experimental searches for the cold dark matter in our vicinity, as these experiments already take into account a factor of two uncertainty in the local density of halo material.[7]

4 Concluding Remarks

Luminous matter (in stars) contributes less than 1% of the critical density, and primordial nucleosynthesis makes a strong case that ordinary matter contributes between 1% and 10% of the critical density, establishing the existence of the first dark matter puzzle, the form of the baryonic matter. There is compelling evidence that the mass density of the Universe is much greater than 10% of the critical density and perhaps close to the critical density, establishing the existence of a second dark matter puzzle, the form of the nonbaryonic dark matter.

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[7] Given the uncertainties about the halo mass, even within 20 kpc of the galactic center, and the insensitivity of microlensing to the density of lensing objects nearby, it seems unlikely that microlensing experiments could ever establish with confidence that lensing objects contribute more than about 50% or so of the local dark matter density. Moreover, because there is nothing to prevent cold dark matter from falling into the halo of our galaxy, even if baryonic matter has been concentrated by dissipation, it is difficult to imagine that the local density of cold dark matter could be significantly less than the local halo density.

The EROS/MACHO collaborations may well have solved the first dark matter problem by providing evidence for dark baryons in the form of astrophysical mass objects in the halo of our own galaxy.[8] However, their discovery, as important as it is, has little to say about the second dark matter problem: The mass density contributed by halo lensing objects cannot significantly exceed 10% of the critical density (even discarding the constraint to Ω_B based upon primordial nucleosynthesis).

A critical Universe is well motivated, supported by mounting evidence, and must involve particle dark matter. The detection of dark stars in the halo of our own galaxy changes none of this; nor does it lessen significantly the prospects for the direct detection of the cold dark matter in our vicinity (e.g., in laboratory experiments designed to detect halo axions or neutralinos). The scientific stakes in testing the particle dark matter hypothesis are extremely high: identifying the primary constituent of the Universe, discovering a new particle of nature, and probing the earliest moments of the Universe. The pioneering searches for particle dark matter [11] must continue at full speed; if anything, solving part of the dark matter puzzle should provide still further impetus for solving the rest of the puzzle!

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[8] Dark baryons may well exist in more than one form. While only about 5% of galaxies are found in rich clusters of galaxies, in clusters most of the baryons exist in the form of hot, x-ray emitting gas (that is dark only in the context of "visible radiation."

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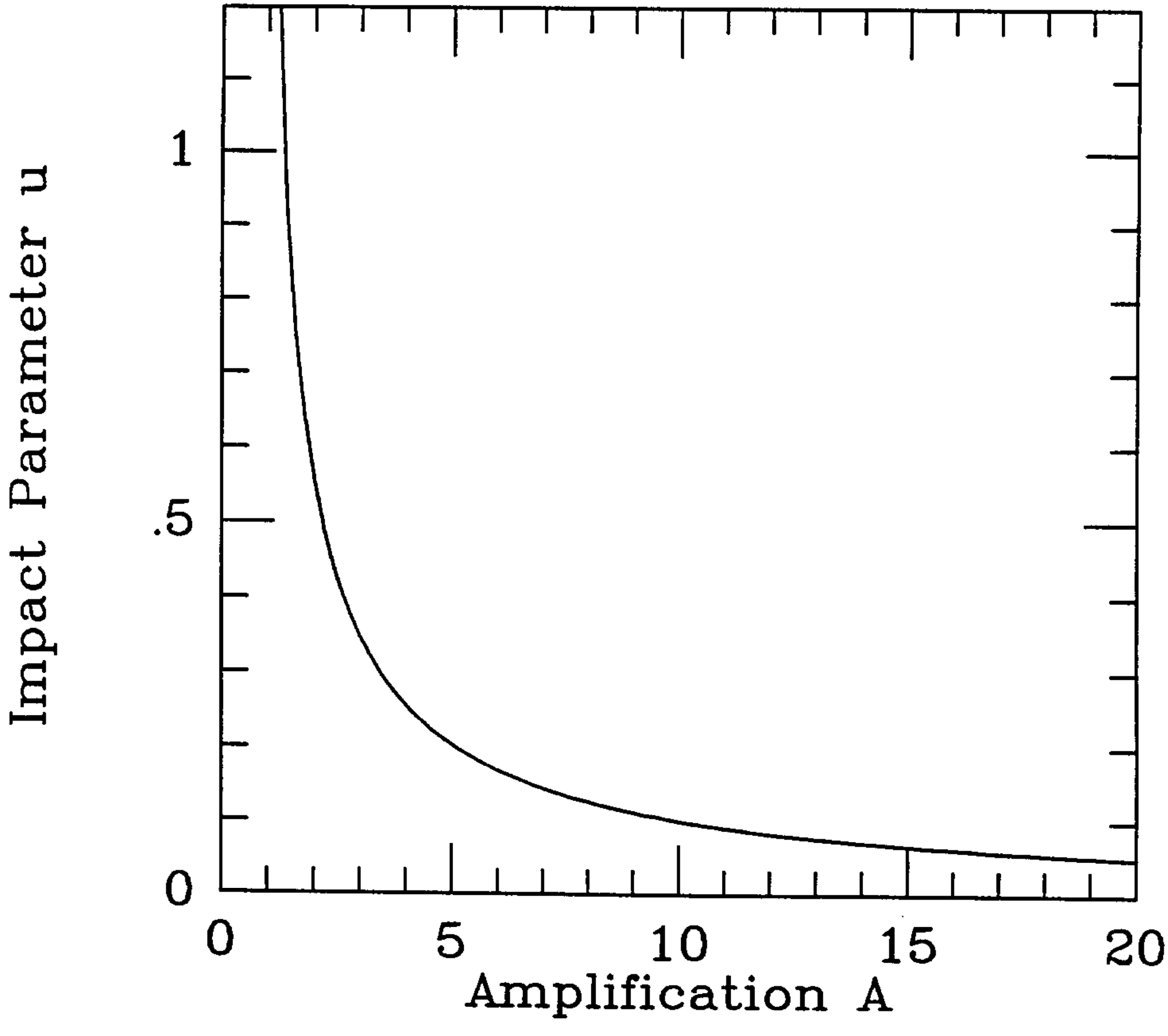
5 Figure Captions

Figure 1: Impact parameter u (in units of the Einstein radius, $u = l/R_E$) as a function of the amplification.

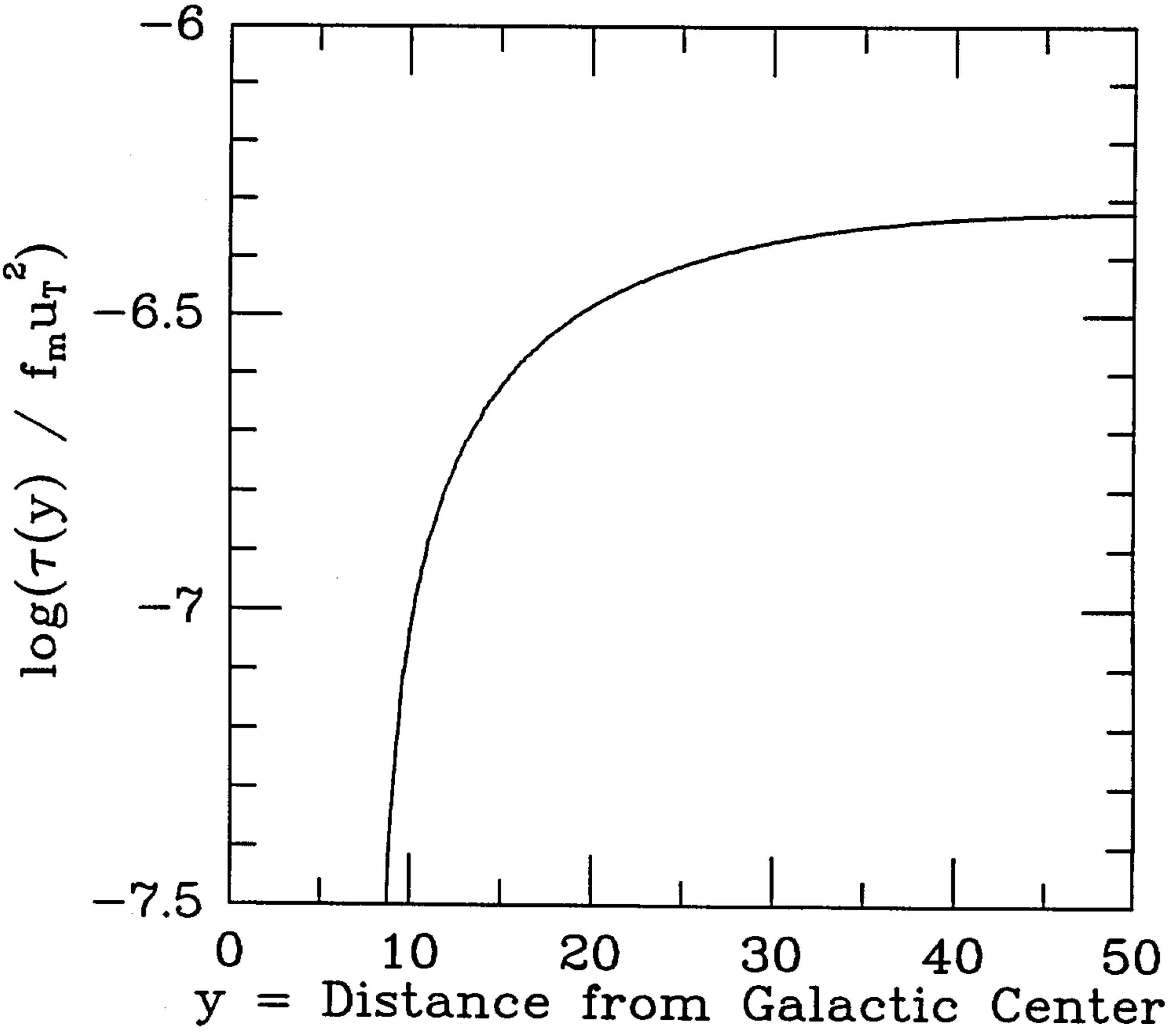
Figure 2: The optical depth for gravitational lensing due to halo objects within a distance y of the galactic center, $\tau(y)$, as a function of y. Note that most of the optical depth for microlensing is due to objects within $10-20$ kpc of the galactic center. Thus, microlensing experiments only probe this part of the halo and are insensitive to the extent of the halo as well as the local halo density.

Figure 3: The fraction of microlensing events expected with amplification greater than A for amplification thresholds of $A_T = 1.1, 1.34, 1.5, 2, 3$, and 5.

- FIG 1 -

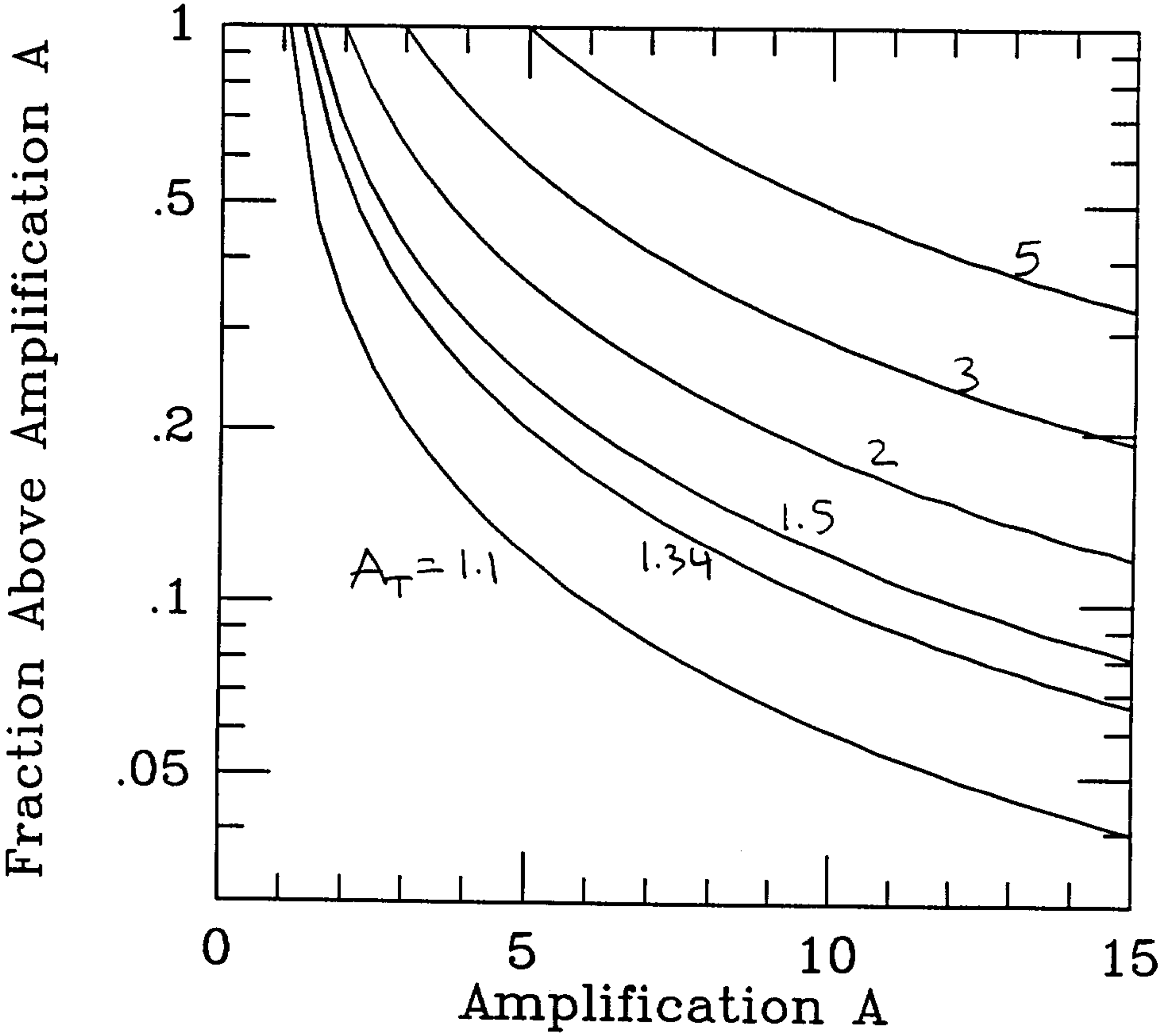


- FIG 2 -



−6
−6.5
−7
−7.5
0
10
20
30
40
50
$\log(\tau(y) / f_m u_T^2)$
y = Distance from Galactic Center

- FIG 3 -



1
.5
.2
.1
.05
Fraction Above Amplification A
0
5
10
15
Amplification A
5
3
2
1.5
1.34
A_T=1.1