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The Effect of Central Baryonic Cores in Dark Halos on the Evaluation of Strong Lensing Probabilities *

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Abstract We present an estimate of the strong lensing probability by dark halos, with emphasis on the role of the baryonic matter arising purely from radiative cooling. We treat the contribution of the cooled baryons optimistically with all the cooled baryons confined within a central core, and including no feedback process from stellar evolution. Our two-component model provides a strong lensing probability that is in good agreement with the observed distribution of multiple images of quasars, provided that the cooled baryons are deposited within a spherical region of radius of 0.1 times the virial radius and follow an isothermal profile. It is pointed out that strong lensing may be used as an additional probe of baryon physics in dark halos though this may meanwhile complicate the test of the inner density profiles of dark matter in halos using the observed strong lensing probability.

Key words: cosmology: theory — galaxies: halos — gravitational lensing

1 INTRODUCTION

Strong gravitational lensing serves as a sensitive probe of the central mass distributions of various dark halos ranging from very massive clusters (e.g., Wu & Hammer 1993) to galaxies (e.g., Keeton & Madau 2001; Li & Ostriker 2002). Based on a comparison of theoretically predicted and observationally determined probabilities of strong lensing, it has been shown that there should exist a steep inner density profile or a compact core in the central regions of dark halos. The required central cusps must be steeper than r^{-1}, the typical central density distribution of dark matter suggested by numerical simulations in the context of Cold Dark Matter (CDM) paradigm (e.g., Navarro, Frenk & White 1996; hereafter NFW). Indeed, in galaxies, if only the dark matter component acts as the lens and follows the so-called universal NFW profile, the predicted lensing probability is several orders of magnitude smaller than the observed ones such as those revealed by CLASS and JVAS (e.g., Li & Ostriker 2002; Oguri et al. 2001). Essentially, a single isothermal sphere (SIS) model of r^{-2} in the central cores of dark halos seems to provide a better explanation of the observed lensing probability.

Observationally, the absence of wide-separation ($> 10''$) multiple images of quasars places a stringent limit on the universality of a unique dark matter profile from galaxies to rich clusters.

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There are two aspects here: on one hand, the dominant mass component in the central regions may vary from galaxies to rich clusters; on the other hand, the mass distribution in dark halos may be oversimplified and an additional mass component may be properly added. A phenomenological approach to the issue is to adopt two different density profiles at different mass scales separated roughly at $M \sim 10^{13}\ M_\odot$ (e.g., Sarbu, Rusin & Ma 2002; Ma 2003; Li & Ostriker 2002): an SIS model for lower mass halos (galaxies) and an NFW profile for clusters. A more physically motivated model is to include the contribution of baryonic matter in the calculation of lensing probability, which arises from radiative cooling of the hot baryons duing the process of galaxy formation (Keeton 1998; Porciani & Madau 2000; Kochanek & White 2001). The total cooled baryonic mass in dark halos depends strongly on the cooling time. Adding such a scale-dependent baryonic matter component to the dark halos would suppress the lensing probability at large separations because of the longer cooling time in clusters and hence less cooled material deposited in their central regions. Indeed, strong lensing by a combined model of dark matter and cooled baryons in dark halos can essentially account for the observed distribution of image separations of quasars (Kochanek & White 2001).

In this paper, we will demonstrate the effect of baryons resulting from radiative cooling in dark halos on the estimate of strong lensing probability in the extreme case in which all the cooled baryons are confined within the central region of the dark halo and no feedback is involved. Moreover, we use a simple SIS model for the cooled baryon component instead of the more sophisticated model composed of a disk and a bulge (Kochanek & White 2001). We focus on the role of the cooled baryons in the evaluation of strong lensing probability rather than the detailed galactic structures. This simple model may, moreover, allow us to highlight the key parameters at various mass scales that dominate the strong lensing distribution.

Throughout this paper, we adopt a ΛCDM cosmological model with present-day matter and energy density parameters $\Omega_{\rm m} = 0.35$ and $\Omega_\Lambda = 0.65$, and a Hubble constant $H_0 = 65$ km s^{-1} Mpc^{-1}. The baryon fraction is $f_b = \Omega_{\rm b}/\Omega_{\rm m}$, with $\Omega_{\rm b} = 0.044$ (Burles et al. 2000).

2 MODELS OF DARK HALO AND COOLED BARYONS

We adopt the NFW profile for the dark matter component as suggested by numerical simulations

$$\rho_{\rm dm}(r) = \frac{\delta_{\rm ch}\rho_{\rm crit}}{(r/r_{\rm s})(1+r/r_{\rm s})^2}, \tag{1}$$

where $\rho_{\rm crit}$ is the critical density of the universe at redshift z, $\delta_{\rm ch}$ and $r_{\rm s}$ are the characteristic density and length, respectively. In combination of the virial theorem, we have

$$\delta_{\rm ch} = \frac{\Delta_{\rm c}}{3}\frac{c^3}{\ln(1+c) - c/(1+c)}, \tag{2}$$

and

$$r_s = \frac{1.626\times 10^{-5}}{c}\left(\frac{M}{M_\odot}\right)^{1/3}\left(\frac{\delta_{\rm c}}{200}\right)^{-1/3} h^{-2/3}(z){\rm Mpc}, \tag{3}$$

in which $\Delta_{\rm c}$ is the overdensity parameter with respect to the critical value, $h(z)$ is the Hubble constant in units of 100 km s^{-1} Mpc^{-1} at redshift z, and $c = r_{\rm vir}/r_s$ is the so-called concentration parameter which is given by the following empirical formula (Bullock et al. 2001):

$$c = 9\left[\frac{M}{1.5\times 10^{13} h^{-1} M_\odot}\right]^{-0.13}(1+z)^{-1}. \tag{4}$$

We assume that the baryons without radiative cooling follow simply the dark matter distribution and have the virial temperature $T_{\rm vir}$. The material after cooling becomes more centrally concentrated. For simplicity we assume that the cooled baryons have an SIS profile. In the framework of bremsstrahlung emission, the cooling time $t_{\rm cool}$ is uniquely determined by the conservation of energy

$$\frac{3}{2}n_{\rm t}kT_{\rm vir} = n_{\rm e}n_{\rm H}\Lambda(T)t_{\rm cool}, \tag{5}$$

where $n_{\rm t}$, $n_{\rm e}$ and $n_{\rm H}$ are the number densities of the baryons, electrons and hydrogen atoms, respectively, and $\Lambda(T)$ is the cooling function which can be determined using the Raymond & Smith (1977) code for a fixed constant metallicity of $Z = 0.3Z_{\odot}$. Setting $t_{\rm cool}$ equal to the cosmic age yields the cooling radius $r_{\rm cool}$. Furthermore, the total cooled baryonic mass within $r_{\rm cool}$ is

$$M_{\rm cool} = 4\pi f_{\rm b}\delta_{\rm crit}r_{\rm s}^3\left[\ln(1 + r_{\rm cool}/r_{\rm s}) - \frac{r_{\rm cool}/r_{\rm s}}{1 + r_{\rm cool}/r_{\rm s}}\right]. \tag{6}$$

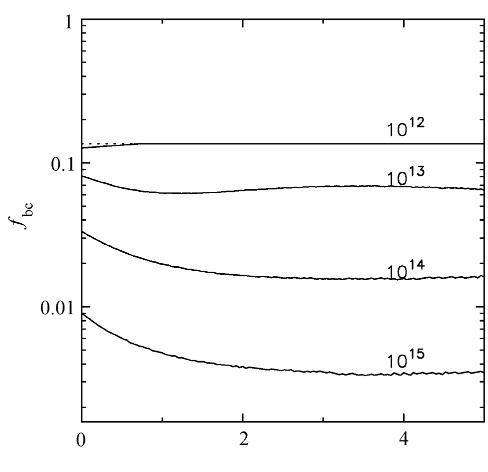

Fig. 1 Variations of the cooled baryon fractions $f_{\rm bc}$ in different halos with respect to redshift. The universal baryon fraction is shown by the dotted line.

In Fig. 1 we illustrate the growth of the cooled baryon fractions defined as $f_{\rm bc} = M_{\rm cool}/M_{\rm vir}$ with redshift for a set of systems $M_{\rm vir} = 10^{12}$, 10^{13}, 10^{14} and 10^{15} $M_{\odot}$. Since here we are not tracing individual halos, the undulations of the fractions is reasonable though the cooled baryonic mass is always increasing in a given individual halo.

Once the baryons are removed from the hot phase, they would flow inward because of the loss of pressure support. We treat the outer radius ($r_{\rm outer}$) of the redistributed cooled baryons as a free parameter. A conservative constraint is simply $r_{\rm outer} \leq r_{\rm cool}$, while a more practical estimate of $r_{\rm outer}$ based on current observations is $r_{\rm outer} \sim 0.1r_{\rm vir}$. By requiring mass conservation within $r_{\rm outer}$, we can fix the free parameter, the velocity dispersion σ_v, in the SIS model such that

$$\rho_{\rm b}(r) = \frac{\sigma_v^2}{2\pi G}\frac{1}{r^2} = \frac{M_{\rm cool}}{4\pi r_{\rm outer}}\frac{1}{r^2}. \tag{7}$$

3 LENSING PROBABILITY

For a distant source at redshift $z_{\rm s}$, the probability for lensing with an image separation greater than $\Delta\theta$ is given by Schneider, Ehlers & Falco (1992)

$$P(>\theta) = \int_0^{z_{\rm s}} dz\frac{dD_{\rm l}}{dz}\int_{M_{\rm min}}^{\infty}\frac{dn(M,z)}{dM}(1+z)^3\sigma_{\rm lens}(M,z)B(M,z)\,dM, \tag{8}$$

where $n(M,z)$ is the comoving number density of dark halos of mass M at redshift z, $\sigma_{\rm lens}(M,z)$ is the lensing cross section of the dark halos, $B(M,z)$ is the magnification bias, and $D_{\rm l}$ is the proper cosmological distance of the lens, $M_{\rm min}$ is the mass threshold above which multiple images with splitting angle greater than $\Delta\theta$ will occur.

We use the Press-Schechter formalism (Press & Schechter 1974) to describe the halo number density $n(M, z)$

$$\frac{dn}{dM} = -\sqrt{\frac{2}{\pi}}\frac{\bar{\rho}}{M}\frac{\delta_{\rm crit}(z)}{\sigma^2}\frac{d\sigma}{dM}\exp\left(-\frac{\delta_{\rm crit}^2(z)}{2\sigma^2}\right)dM, \tag{9}$$

where $\bar{\rho}$ is the present mean mass density of the universe, $\delta_{\rm crit}(z)$ is the redshift-dependent density threshold, which is related to the linear growth factor $D(z)$ through $\delta_{\rm crit}(z) = \delta_{\rm crit}(0)/D(z)$, and $\delta_{\rm crit}(0) = 1.68$. We adopt the approximate formula given by Carroll, Press & Turner (1992) for $D(z)$

$$D(z) = [g(z)/g(0)]/(1+z)\,, \tag{10}$$

$$g(z) = \frac{(5/2)\Omega_{\rm m}(z)}{[\Omega_{\rm m}(z)^{4/7} - \Omega_\Lambda(z) + (1+\Omega_{\rm m}(z)/2)(1+\Omega_\Lambda(z))/70]}. \tag{11}$$

Finally, the linear variance of the mass density fluctuation within a sphere of mass $M = 4\pi\bar{\rho}R^3/3$ is

$$\sigma^2(M) = \frac{1}{2\pi^2}\int_0^\infty k^2 P(k) W^2(k) dk, \tag{12}$$

where $W(x) = 3(\sin x - x\cos x)/x^3$ is the Fourier transform of the top-hat window function. We parameterize the power spectrum of the density fluctuation with $p(k) \propto k^n T^2(k)$ and $n = 1$ for the Harrison-Zel'dovich case. The best fit of the transfer function $T(k)$ of the adiabatic CDM model was provided by Bardeen et al. (1986). The amplitude of the power spectrum can be determined by the normalization parameter σ_8, for which we adopt a value of $\sigma_8 = 0.9$ in the present study.

The lensing cross section $\sigma_{\rm lens}$ in Eq. (8) can be evaluated by the lensing equation

$$y = x - \frac{m(x)}{x}, \tag{13}$$

where

$$m(x) = 2\int_0^x \frac{\Sigma(x')}{\Sigma_{\rm cr}} x'\,dx', \tag{14}$$

and the critical surface density $\Sigma_{\rm cr}$ is

$$\Sigma_{\rm cr} = \frac{c^2}{4\pi G}\frac{D_{\rm s}^A}{D_{\rm l}^A D_{\rm ls}^A}, \tag{15}$$

where x and y are the dimensionless distance parameters defined as $x = \boldsymbol{\zeta}/r_s$ and $y = |\boldsymbol{y}|$, respectively, $\boldsymbol{\zeta}$ is the position vector on the lens plane, and $\boldsymbol{\eta} = \boldsymbol{y} r_s D_s^A/D_l^A$ is the position vector on the source plane, $D_{\rm s}^A$, $D_{\rm l}^A$ and $D_{\rm ls}^A$ are the angular diameter distances to the source, to the lens, and from the lens to the source, respectively. For our two-component model of dark halos, the projected mass density along the line of sight is the sum of dark matter and cooled baryons: $\Sigma = \Sigma_{\rm dm} + \Sigma_{\rm cb}$, in which

$$\Sigma_{\rm dm}(x) = 2\rho_{\rm s} r_{\rm s}\int_0^\infty (x^2+t^2)^{-1/2}[(x^2+t^2)^{1/2}+1]^{-2}\,dt, \tag{16}$$

and

$$\Sigma_{\rm cb}(x) = \frac{\sigma_{\rm v}^2}{2\pi G}\frac{1}{x}\frac{\pi}{2}. \tag{17}$$

Multiple images should occur if $|y| \leq y_{\rm cr}$, where $y_{\rm cr} \equiv -y(x_{\rm cr})$, and $x_{\rm cr}$ is determined by $dy/dx = 0$. The cross section in Equation (8) for multiple images with $\Delta\theta > \Delta\theta_0$ is thus:

$$\sigma(\Delta\theta > \Delta\theta_0, M, z)_{\rm lens} \approx \pi y_{\rm cr}^2 r_s^2. \tag{18}$$

The lensing equations for the cooled baryons (SIS model), dark matter (NFW model), and baryons + dark matter model are shown in Fig. 2. It appears that the cooled baryons can indeed lead to a significant change of the lensing behavior even though the total mass fraction of the baryons is actually small.

Since the splitting angle $\Delta\theta$ is insensitive to the source position (e.g., Li & Ostriker 2002), the image separation can be calculated at the position $y = 0$,

$$\Delta\theta = \frac{r_{\rm s}}{D_{\rm l}^A}\Delta x(y) \approx \frac{r_{\rm s}}{D_{\rm l}^A}\Delta x(y=0) = \frac{2x_0 r_{\rm s}}{D_{\rm l}^A} \qquad \text{for } |y| < y_{\rm cr}, \tag{19}$$

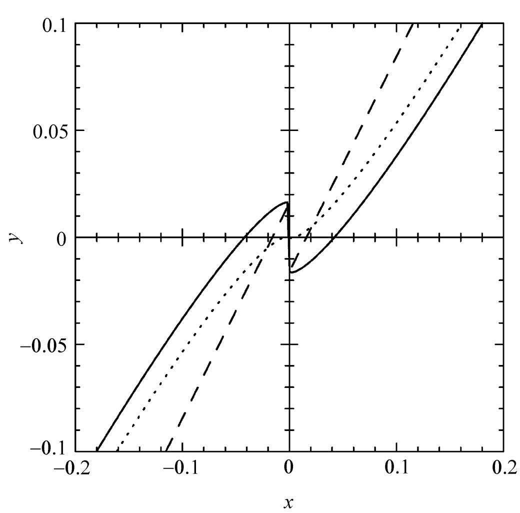

Fig. 2 Lensing equations for different density profiles: dashed, dotted and solid lines represent the SIS, NFW and the combined model, respectively.

where x_0 is the positive root of $y(x) = 0$. The brightness of the multiply-lensed images is simultaneously magnified by dark halos, which is reflected by the magnification bias, B. If the background sources have a power-law flux distribution, $f^{-\beta}(\beta < 3)$, we may estimate the magnification bias by

$$B = \frac{2}{3-\beta} A_m^{\beta-1}, \tag{20}$$

where $A_{\rm m}$ is the minimum total flux amplification for the multiply-imaged images, which can be estimated through (Li & Ostriker 2002)

$$A_{\rm m} \approx \frac{2x_0}{y_{\rm cr}}\,. \tag{21}$$

For the CLASS sample, $\beta \approx 2.1$ (Rusin & Tegmark 2001), and thus $B \approx 2.22 A_{\rm m}^{1.1}$.

4 RESULTS AND DISCUSSION

The largest uniformly selected sample of gravitational lensing systems is provided by JVAS and CLASS (Browne & Myers 2001; Helbig 2000; Browne et al. 2002; Myers et al. 2002). Among a statistically well-defined subsample of $\simeq 8,958$ flat-spectrum radio sources, 13 multiple images have been discovered, with image separations $\Delta\theta < 3''$. The mean redshift of a subsample of 42 sources is $\langle z_s \rangle = 1.27$ (Marlow et al. 2000). Here we assume that all sources are at the same redshift $z_{\rm s} = 1.27$. A more sophisticated way is to include the distribution function of background quasars. An explicit search for lenses with image separations $6'' \leq \Delta\theta \leq 15''$ has returned a negative result (Phillips et al. 2001), which can be used as an upper limit for large splitting angle events.

In Fig. 3 we compare the theoretically predicted distribution of multiple images with the JVAS/CLASS data. The NFW model alone predicts a probability too low to reconcile with the observations, a well-known fact as shown in the literature (e.g., Li & Ostriker 2002; Oguri et al. 2001). In contrast, an SIS model is able to reproduce the observed lensing probability at small angular scales but exhibits a tail at large angular separations that exceeds the upper limit set by Phillips et al. (2001). A combination of an NFW dark halo and an SIS baryonic core leads to the following conclusions: First, if the cooled baryons are distributed over the whole cooling regions characterized by the cooling radius $r_{\rm cool}$, then the expected lensing probability is insufficient to explain the observations, thus arguing for a more compact baryonic core in the central regions of dark halos. Secondly, reducing the core size of the baryonic matter leads to an increase of the lensing probability. A core size of $0.08 - 0.1R_{\rm vir}$ seems to provide the best fit to the observed data at small angular separations, and the resulting tail at large angular separations is also below the upper limit. If we further reduce the core size, we may over-predict the small separation events.

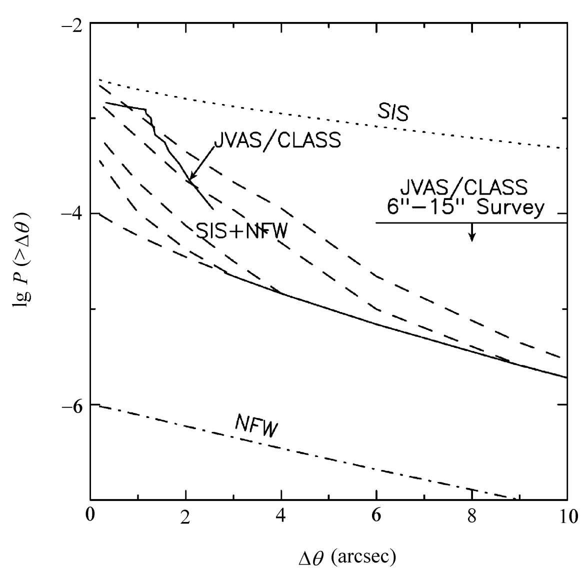

Fig. 3 Comparison of the predicted lensing probabilities by different models (SIS, NFW and SIS+NFW) with observations. Dashed lines from top to bottom represent the results of the combined model for $r_{\rm outer} = 0.08R_{\rm vir}, 0.1R_{\rm vir}, 0.15R_{\rm vir}, 0.2R_{\rm vir}$ and $r_{\rm cool}$ respectively. The JVAS/CLASS data at small scales and the upper limit at large separations are explicitly shown.

While our simple analytical model provides a satisfactory explanation of the observed distribution of the multiply-lensed images of quasars, emphasizing again the importance of the baryons in the central regions of intermediate dark halos such as galaxies, the model has an apparent shortcoming: All the cooled baryons are confined within the central cores, which leads to an overestimate of the lensing probability by the baryons. Because of the shallower potential wells of galaxies, the feedback process by stellar evolution may expel the gas from the host galaxies, which in turn reduces the total baryonic matter in dark halos. The effect should be more significant in low-mass halos, and may be only minor for massive halos like clusters. If the cooled baryons are partially expelled from the host galaxies, it is expected that the central baryonic cores should be even more compact in order to act as effective lenses. For a typical galaxy of $M = 10^{12} M_{\odot}$, its virial radius is roughly 100 kpc. Our requirement that the core size of the baryonic matter distribution in the central region of dark halos should be smaller than $0.1R_{\rm vir}$ is not drastic, but comparable with the size of luminous stellar disks and bulges. Finally, it is unlikely that the supermassive black holes at galactic centers could have a significant contribution to the lensing probability.

To summarize, baryons play a dominant role in the central matter distribution of dark halos. Without this baryonic matter component in addition to dark matter, it would be impossible to explain the observed distribution of strong lenses on $1''$–$10''$ scales. Consequently, strong gravitational lensing may be used as a probe of baryons in dark halos. On the other hand, we have an additional difficulty if we use strong lensing for tracing the inner density profile of dark matter in halos.

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