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GRAVITATIONAL LENSING AND THE LYMAN-ALPHA FOREST

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ABSTRACT

Possible connections between the inhomogeneities responsible for the Lyman-α forest in quasar spectra and gravitational lensing effects are investigated. For most models of the Lyman-α forest, no significant lensing is expected. For some versions of the CDM model-based minihalo hypothesis, gravitational lensings on scales $\lesssim 0''.1$ would occur with a frequency approaching that with which ordinary galaxies cause arcsecond scale lensing.

Subject headings: gravitational lenses — quasars

1. INTRODUCTION

As the radiation emitted by observed high-redshift quasars traverses the intervening cosmological distances, it interacts with material along the line of sight resulting in two well-known detectable phenomena: First, atomic line absorption in discrete gas clouds produces a complex signature of absorption lines in quasar spectra (Blades 1988). Second, deflection of photon trajectories by the gravitational potential wells of intervening objects produces a variety of gravitational lensing effects including multiple images, image distortions, flux "amplifications," and so forth (Turner 1989; Blandford 1990). These two effects are both very different in empirical character and are due to quite distinct physical causes; however, both are fundamentally the result of inhomogeneities in the material between observers and the quasars. Thus, it is natural to ask whether any connection should be expected between quasar absorption-line systems and gravitational lensing phenomena. Previously, Krolik & Kwan (1979) considered a possible correlation between certain rare, low-ionization state metal lines, notably C II lines, and gravitational lensing by galaxies in whose inner regions the absorbing gas was presumed to lie. Attempts to detect such a connection have so far been unsuccessful (Vietri 1986, private communication). In this paper we examine possible connections between the most common class of quasar absorption lines, Lyman-α due to H I, and gravitational lensing phenomena.

Numerous sharp absorption lines are detected on the short-wavelength sides of the Lyman-α emission lines of quasars. They are taken to be Lyman-α lines as was proposed by Lynds (1971), and are referred to as the Lyman-α forest. The observed number of lines per unit redshift is $(d\mathcal{N}/dz) \sim 6(1+z)^{2.2 \pm 0.7}$ (Murdoch et al. 1986), which indicates two important properties of absorbers. One is that their comoving number is more than 100 times that of galaxies, and the other is that their evolution is rapid.

Several models have been proposed for this Lyman-α forest. They are roughly divided into two classes: highly ionized, intergalactic clouds irradiated by diffuse UV flux, and neutral sheets formed at the caustics of collapsing pancakes. In the former model, several possibilities for the dynamical state of the clouds have been examined. These include pressure-confined expanding clouds (Sargent et al. 1980; Ostriker & Ikeuchi 1983), freely expanding clouds (Bond, Szaly, & Silk 1988), and equilibrium clouds confined by CDM gravity (Rees 1986; Ikeuchi 1986). The main physical properties of clouds are common to all such models: the mass 10^7–$10^9\ M_\odot$, the radius 10–50 kpc, and the gas temperature $\sim 3 \times 10^4$ K. These clouds are taken to be spherical. In the latter model, the gas temperature is less than 10^2 K because the diffuse UV flux is absorbed in the outer layer of a pancake (Barcons & Fabian 1987; Hogan 1987; McGill 1990). Common lines in the spectra of the gravitational lens pair 2345+007 A, B (Foltz et al. 1984) indicate that the absorbers are greater than 10 kpc in extent while having thickness less than 10^{15} cm to account for the H I column density. Therefore, this neutral gas model predicts a thin sheet with extraordinary large aspect ratio.

Even though these inferred absorbers are small in mass and surface mass density, their large number may give rise to gravitational lens effects on the quasars. The possible lensing effects are estimated by calculating effective optical depths, the image splittings, and making an estimate of collective lensing action.

The object of this paper is to investigate how the Lyman-α forest might contribute to the gravitational lensing of quasars. In §§ 2 and 3, we examine the model of highly ionized, intergalactic clouds and of neutral sheets, respectively. In § 4, the conclusions are summarized and discussed.

2. HIGHLY IONIZED INTERGALACTIC CLOUDS

2.1. *Basic Model*

For all models in which the clouds are heated and ionized by diffuse UV flux of the intensity, $\sim 10^{-21}$ ergs cm^{-2} s^{-1} Hz^{-1} sr^{-1} at $z \sim 2.5$, the gas temperature is around $T \sim 3 \times 10^4$ K. If we take the size estimate from the gravitational lens quasar 2345+007 A, B as $R \sim 10$ kpc, the mass of a cloud is $M \sim 10^7$–$10^9\ M_\odot$ from the observed H I column density. Depending upon the dynamical state, the structure inside the cloud is different; $n(r) \sim$ constant for pressure-confined clouds, $n(r) \sim r^\alpha (\alpha \sim 0.1$–$1)$ for freely expanding clouds, and $n(r) \sim r^{-2}$ for minihalos.

Hereafter, we will consider the minihalo model because the mass and lensing effect of clouds are biggest in this model. The mass of CDM is about 10 times larger than the baryon mass, $M_{\rm CDM} \sim 10^{8-10}\ M_\odot$. The number of minihalos per unit proper volume per unit mass is estimated from the observed number density evolution of the Lyman-α forest as

$$N(z, M) \simeq N(0)(1+z)^3(M/M_*)^{-\delta}, \qquad (1)$$

with $M_* = 10^7\ M_\odot$, $N(0) = 6$ Mpc^{-3} M_*^{-1} and $\delta = 1.5$–2.0

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(Ikeuchi, Murakami, & Rees 1989) for H_0 of 100 km s^{-1} Mpc^{-1}. When the diffuse UV flux increases with decreasing redshift at $z = 4$–2, which most naturally reproduces the number density evolution (Ikeuchi 1990), the minihalos are expanding like $R(z) \propto (1 + z)^{-5/3}$. However, the CDM does not follow the gas expansion.

From the mass function in equation (1), the number density of absorbers with galaxy-size mass, $M = M_g \simeq 10^{11}\ M_\odot$, is estimated to be one-hundredth of that of normal galaxies. From this reason, it may be expected that the lensing effect of the Lyman-α forest is roughly one-hundredth that of normal galaxies. This is only partially right, because the lensing effect sensitively depends upon the lens mass distribution, not just the total mass. A similar fact has been indicated by Turner, Ostriker, & Gott (1984), who showed that early-type galaxies provide the dominant contribution to galaxy lensing even though they are a minority of galaxies at a fixed mass. Therefore, it is necessary to present detailed calculations of the probable lensing effects by the Lyman-α forest.

2.2. *Gravitational Lensing Probabilities*

The lensing effects of the CDM minihalo model for the Lyman-α clouds will be greater than that for any other model because substantial additional mass (typically nonbaryonic) is postulated and because a sharply peaked density profile $[n(r) \sim r^{-2}]$ is implied. Both effects produce additional lensing cross section. In keeping with the attempt to calculate a maximum effect, we will also assume that

1. the mass distribution is singular (i.e., that the power-law extends to zero radius),
2. more massive clouds correspond to deeper potential wells and not merely larger objects.

We shall also adopt the most favorable parameters ($R = 10$ kpc, $\delta = 1.5$) which have been derived from the observations (Ikeuchi et al. 1989).

Turner et al. (1984, hereafter TOG) developed a formalism for calculating statistical quantities associated with a population of singular isothermal sphere (SIS) gravitational lenses. This formalism has been extended recently to include a variety of cosmological models (Gott, Park, & Lee 1989; Turner 1990), and its validity has been confirmed by Monte Carlo numerical calculations (Katz & Paczynski 1987). In this formalism, the lensing effectiveness of a population of SIS is given by a parameter

$$F = 16\pi^3 n_0 \left(\frac{c}{H_0}\right)^3 \left(\frac{\sigma_\parallel}{c}\right)^4 , \tag{2}$$

where n_0 is their current (comoving, the population is assumed to be unevolving) space density, $\sigma_\parallel$ is their one-dimensional velocity dispersion, and the other symbols have their usual meanings. Now, for an SIS, we have

$$\sigma_\parallel = \left[\frac{GM(<R)}{2R}\right]^{1/2} , \tag{3}$$

where $M(<R)$ is the mass within radius R. Using this relation, the gas mass distribution given by equation (1) is easily transformed into a distribution of velocity dispersions

$$N(z, \sigma_\parallel) = 2N(0)(1 + z)^3 \left(\frac{\sigma_\parallel}{\sigma_\parallel^*}\right)^{1-2\delta} \frac{1}{\sigma_\parallel^*} , \tag{4}$$

where

$$\sigma_\parallel^* = D^{1/2} \sigma_{\rm gas}^* , \tag{5}$$

D being the logarithmic ratio of baryon density to CDM density, and $1 \leq D \leq 3$ (Ikeuchi, Murakami, & Rees 1988). The value of $\sigma_{\rm gas}^*$ may be taken from the observations (Pettini et al. 1990) and is ≈ 10 km s^{-1}. By integration of $\sigma_\parallel^4 N(0, \sigma_\parallel)$ between 0 and σ^+ (valid for $\delta < 3$), we then obtain

$$F = \frac{16\pi^3}{3 - \delta} N(0) \left(\frac{c}{H_0}\right)^3 D^2 \left(\frac{\sigma_{\rm gas}^*}{c}\right)^4 \left(\frac{\sigma_{\rm gas}^+}{\sigma_{\rm gas}^*}\right)^{6-2\delta} , \tag{6}$$

or

$$F = \frac{16\pi^3}{3 - \delta} N(0) \left(\frac{c}{H_0}\right)^3 D^2 \left(\frac{\sigma_{\rm gas}^*}{c}\right)^4 \left(\frac{M^+}{M_*}\right)^{3-\delta} . \tag{7}$$

It should be noted that the value of $N(0)(c/H_0)^3$ is determined directly from the observed number of Lyman-α clouds per unit redshift, independent of the true value of H_0.

Inserting the above indicated numerical values of various parameters into equation (6) gives

$$F = 6.6 \times 10^{-5} D^2 \left(\frac{\sigma_{\rm gas}^+}{10\ {\rm km\ s^{-1}}}\right)^3 . \tag{8}$$

For comparison, an SIS model of the galaxy population (TOG) gives $F_{\rm gal} \approx 0.15$ although this figure is uncertain (Turner 1990) by a factor of ≥ 2.

Observations (Hunstead & Pettini 1989) give $\sigma_{\rm gas}^+ \approx 30$–40 km s^{-1} $z \simeq 3.5$ and fits to the Lyman-α column density distribution give $D \approx 2$ (Murakami & Ikeuchi 1990), so

$$F_{\rm MINIHALO} \lesssim 0.01 , \tag{9}$$

an upper limit somewhat smaller than $F_{\rm gal}$.

2.3. *Image Splittings*

Again following the approach of TOG, it is easy to derive the distribution of image separations in an $\Omega_0 = 1$ filled beam model (relevant to CDM) from equation (4). We find

$$P(\Delta\theta)d\Delta\theta \approx \left(\frac{\Delta\theta}{\Delta\theta^*}\right)^{2-\delta} d\Delta\theta , \tag{10}$$

where $\Delta\theta^* \approx 3D$ mas (milliarcseconds) and this distribution would extend up to about $48D$ mas, corresponding to Lyman-α line widths of ~ 40 km s^{-1}. For $\delta \approx 1.5$, the distribution would then be peaked at large values. Thus, direct search for minihalo multiple image lens systems may be feasible with VLBI or other high-resolution techniques. The best candidates will be just those which show high column densities indicating a small impact parameter and broad lines indicating a high-mass minihalo.

2.4. *Single Image Lensing*

As pointed out by Hinshaw & Krauss (1987), inclusion of finite core radii effects can dramaticly reduce isothermal sphere, multiple image, lensing cross sections. In particular, multiple image lensing will be suppressed for core radii

$$r_c \gtrsim \pi(\sigma_\parallel/c)^2 d_{\rm A} , \tag{11}$$

where $d_{\rm A}$ is the lens angular diameter radius. For typical lens redshifts, this means that core radii greater than about $3(\sigma_\parallel/10\ {\rm km\ s^{-1}})^2$ pc will suppress multiple image lensing. Little is known of the likely state and evolution of the extreme central regions of minihalos; however, it may easily be the case that these high central densities are not achieved and, thus, that minihalos are ineffective multiple image lenses.

Nevertheless, even without the production of multiple image, lensing flux amplification of single quasar images may have significant effects. As also shown by Hinshaw & Krauss (1987), the cross section for flux amplification by a factor of $\gtrsim 2$ by a finite core radius isothermal sphere is roughly equal to that for multiple image lensing by an SIS of the same velocity dispersion even for values of r_c several times larger than the equation (11) limit.

2.5. *Collective Lensing Effects*

Katz & Paczynski (1987) have carried out numerical studies of collective (i.e., involving more than one lensing object) gravitational lensing by a population of SIS lenses. Naturally, the importance of this effect depends upon the lensing optical depth τ_{GL}. For $\tau_{GL} \sim 0.2$, they find good agreement with the total lensing probabilities indicated by the TOG analytic treatment of the single lens case. Since $\Omega_0 = 1$ "filled beam" cosmology gives $(\tau_{GL}/F) \leq 0.06$ for $z_Q \leq 5$ and given the equation (9) value of $F_{\rm MINIHALO}$, we are clearly in the small τ_{GL} limit and can neglect collective effects. Even $k = 0$ but $\Lambda \neq 0$ models (Turner 1990) give $(\tau_{GL}/F) \lesssim 3$ for $z_Q \leq 5$ and still fall into the low optical depth range.

2.6. *Biased Minihalo Model*

The minihalo population considered in the above calculations has properties inferred from observations of the Lyman-α forest. Its total mass density corresponds to only about one-tenth of the critical density however the usual CDM model (Bond & Efstathiou 1984) assumes $\Omega_0 = 1$. Thus the question arises, just as in the CDM model of galaxies, of where the remaining mass might be located. By simple analogy to the biased galaxy formation scenario, one could postulate that the minihalos observed via Lyman-α absorption are a biased subset of the total population.

Of course, these undetected minihalos could still act as gravitational lenses. Since the properties of the undetected minihalo population are likely to differ systematically from those of the detected ones (in order to account for the difference in H I column density), it is difficult to evaluate their lensing properties. An optimistic upper limit is probably given by simply multiplying the equation (9) F value by a factor of 10.

3. NEUTRAL SHEETS

3.1. *Basic Model*

Several authors have discussed the neutral sheet model for the Lyman-α forest (Barcons & Fabian 1987; Hogan 1987; McGill 1990), but the differences among the models do not affect the following gravitational lensing considerations. We take the model by Barcons & Fabian (1987) for calculation of lensing effects.

According to this model, the physical nature of a typical sheet (spheroid) is as follows: spheroid radius $a \sim 10$ pc, thickness $b \sim 10^{-3}$ pc, gas density $n \sim 1$ cm^{-3}, mass $M \sim 10^{-2}\, M_\odot$ number density $N(z) = 2 \times 10^7 h_{100}^{-1}(1+z)^{4.7}$ Mpc^{-3}. For simplicity we assume these spheroidal sheets do not show any evolution.

3.2. *Gravitational Lensing*

The face-on surface densities of these neutral sheets are more than seven orders of magnitude too small to produce either multiple imaging or even significant single imaging flux amplification (TOG; Paczynski & Wambganss 1989). Even if seen exactly edge-on, the surface density falls at least three orders of magnitude short of interesting surface densities for lensing effects. Individually such clouds have no lensing effects.

Neither does it appear that collective "thick lens" effects can play any important role. Equation (1) indicates that the total number of such sheets at relevant (for lensing) redshifts is no more than about 10^2. Even if all acted coherently and additively (very unlikely), no significant lensing results.

Since the neutral sheet model explains the observed Lyman-α forest with a minimal mass (no H II nor nonbaryonic matter), it is unsurprising that it predicts negligible lensing effects.

4. DISCUSSION AND CONCLUSIONS

Our primary conclusion is that the inhomogeneities along the line of sight which produce the Lyman-α forest are unlikely to cause any significant gravitational lensing effects. The directly observed material (H I) is insignificant by very large factors even in models in which its density is taken to be quite large (i.e., the neutral sheet model discussed in § 3). In models which take the H I to be contained in a highly ionized plasma (see § 2), the lensing effects are still negligible unless a still more massive nonbaryonic mass distribution, such as a CDM minihalo, is postulated to accompany the observed H I and inferred H II. Finally, even in the most extreme and optimistic minihalo models, the predicted lensing effects are no greater than those of observed galaxies (i.e., still reasonably rare); in such models, most of the lensing action comes from the highest mass (corresponding to high column densities and large line widths) systems and not typical ones.

The primary observational implication of these calculations is that quasars showing Lyman-α forest lines with large column densities and velocity widths in the appropriate redshift range ($0.2 \lesssim z \lesssim 1$, thus requiring spacecraft observations) should be examined carefully for indications of lensing. If such a correlation were established empirically, it would provide important information on the nature of the Lyman-α forest and probably on larger issues in the theory of cosmic structure formation.

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