TIME DELAY EFFECT ON THE COSMIC BACKGROUND RADIATION FROM STATIC
GRAVITATIONAL POTENTIAL OF CLUSTERS

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ABSTRACT

We present a quantitative analysis of the time delay effect of the static gravitational potential of galaxy clusters on the cosmic background radiation (CBR). This is primarily motivated by growing observational evidence that clusters have essentially experienced no evolution since redshift \( z \approx 1 \), indicating that the contribution of a time-dependent potential to the CBR anisotropy discussed in the literature could be rather small for dynamically relaxed clusters. Using the softened isothermal sphere model and the universal density profile for the mass distribution of rich clusters, we calculate the CBR anisotropy by the time delay effect and compare it with those generated by the thermal and kinematic Sunyaev-Zeldovich (S-Z) effects, as well as by the transverse motion of clusters. While it is unlikely that the time delay effect is detectable in the current S-Z measurement, because of its small amplitude of \( 10^{-6} \)–\( 10^{-7} \) and its achromaticity, it nevertheless leads to an uncertainty of \( \sim 10\% \) in the measurement of the kinematic S-Z effect of clusters. Future cosmological application of the peculiar velocity of clusters to be measured through the S-Z effect should therefore take this uncertainty into account.

Subject headings: cosmic microwave background — cosmology: theory — galaxies: clusters: general — gravitation

1. INTRODUCTION

The microwave sky behind a cluster of galaxies should be primarily distorted through the so-called Sunyaev-Zeldovich (S-Z) effect—the inverse Compton scattering of the radiation by electrons in hot intracluster gas, which leads to a temperature decrement of typically \( \Delta T/T \sim 10^{-4} \) in the Rayleigh-Jeans part of the spectrum for a cluster as rich as Coma. The original goal of conducting the S-Z measurement is to estimate the Hubble constant, \( H_0 \), while recent attempts have also been made to determine the cluster baryonic (gas) mass in combination with X-ray observations (Myers et al. 1997; Mason & Myers 2000). However, the S-Z effect can only probe the distributions of intracluster gas, and provides no direct information about the underlying gravitational potential of the clusters; yet the latter plays a much more important role in cosmological study. This motivates us to address the following question: Can we simultaneously detect the gravitational imprint of the cluster potential on the microwave sky during the measurement of the S-Z effect?

Essentially, the gravitational potential of a cluster exerts an influence on the cosmic background radiation (CBR) through the gravitational lensing effect and the Rees-Sciama effect (Rees & Sciama 1968), which consist primarily of three components. The first arises from gravitational lensing, which alters the trajectories of the CBR photons, resulting in a reduction of the small-scale intrinsic fluctuations in the CBR. However, this component does not cause additional temperature variations in the CBR, because of the conservation of the CBR surface brightness. The second component arises from the Rees-Sciama effect, which accounts for the changing gravitational potential during the radiation cross time, giving rise to a decrement of CBR temperature. The third component corresponds to the purely relativistic time delay effect due to the deep gravitational potential, which enables us to receive the CBR photons emitted at an earlier time and thus makes a positive contribution to \( \Delta T/T \). This last component is predicted by both gravitational lensing and the Rees-Sciama effect.

In their pioneering work, Rees & Sciama (1968) concluded that the time-dependent potential could make more significant contributions to the CBR than the time delay effect. This has led many authors to direct their interest to the CBR anisotropies caused by the evolving gravitational potential of various nonlinear perturbations (e.g., Seljak 1996, and reference therein). Unfortunately, these results can hardly be applicable to galaxy clusters, because of the unrealistic models for cluster matter distributions, such as the Swiss-cheese model (Dyer 1976) and the “two-step vacuole” model (Rees & Sciama 1968; Nottale 1984), while numerical simulations are limited by the dynamical resolutions on cluster scales, especially inside core radii (Tuluie & Laguna 1995; Seljak 1996). So far, the only plausible constraint on the CBR temperature fluctuations from the time-dependent potential of a rich cluster may be that proposed by Chodorowski (1991). He studied the effect using a linear potential approximation and a pure spherical infall model for cluster, and found that \( \Delta T/T \leq 6.5 \times 10^{-7} \). In some sense, such an estimate can be regarded as an upper limit on the CBR temperature fluctuations caused by the time-dependent potential of a cluster.

On the other hand, numerous observations have claimed a “settled” configuration of cluster matter evolution since \( z \sim 1 \). It was shown more than a decade ago that optical counts of clusters are consistent with a no-evolution scenario for redshift out to at least \( z \approx 0.5 \) (Gunn, Hoesell, & Oke 1986). The same conclusion holds true for the X-ray–selected clusters since \( z \sim 0.8 \) (e.g., Fan, Bahcall, & Cen 1997; Rosati et al. 1998). Moreover, no significant differences in the dynamical properties have been detected between high- and low-redshift clusters, which include the

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X-ray luminosity, the X-ray temperature, the velocity dispersion of cluster galaxies, the mass-to-light ratio, the baryon fraction, etc. (Carlberg et al. 1996; Mushotzky & Scharf 1997; Wu, Xue, & Fang 1999, and references therein). In particular, the distribution of core radii of the intracluster gas in nearby clusters is identical to that of distant ones (z > 0.4; Vikhlinin et al. 1998). Taking these observational facts as a whole, we feel that, in addition to the claim for a low mass density universe, the gravitational potential of clusters is unlikely to have experienced a violent change since z ∼ 1. Therefore, the CBR fluctuation due to the changing or time-dependent gravitational potential of clusters at z < 1 could be rather small, and we should probably concentrate on the third component and explore how large the time delay effect on the CBR fluctuations from the static gravitational well of a rich cluster would be.

The gravitational time delay can be roughly estimated by Δt_0 = (2GM/c^2)ln(4D_c/D_0/r_0^2) for a pointlike mass M, where D_c is the distance to M, D_0 is the separation between M and the background source, and r_0 is the impact parameter. For a rich cluster with mass of 10^{15} M☉ at cosmological distance and CBR as the background source, Δt_0 ∼ 10^{-3}–10^4 yr. Recall that the time delay between the images of the gravitationally doubled quasar caused by a galactic lens of 10^{12} M☉ is ∼ 1 yr. A time delay of Δt_0 = 10^{3}–10^4 yr in the observer’s frame corresponds to a CBR temperature increment of ΔT/T ∼ Δt_0/t_0 ∼ 10^{-7}–10^{-6}. Indeed, such an amount of temperature variation is about 2 orders of magnitude smaller than the thermal S-Z effect. However, this value should be detectable with the future CBR detectors, such as the Microwave Anisotropy Probe (MAP) and Planck. Unlike the thermal S-Z effect and the kinematic S-Z effect due to the peculiar motion of galaxy clusters, ΔT/T arising from the time delay effect is insensitive to the impact distance, and therefore may be the dominant contributor to the CBR temperature fluctuations at large radii from the cluster centers. Alternatively, the presence of the time delay component may complicate the measurement of the kinematic S-Z effect. It has been suggested that the thermal and kinematic S-Z effects can be separated using their different spectra, especially at the frequency near 218 GHz, where the thermal effect is zero (see Birkinshaw 1999). One may also need to properly subtract the contribution of the time delay effect in order to extract the kinematic effect, although the latter is still the dominant component. In particular, the time delay effect due to clusters may be comparable to the CBR perturbation caused by the transverse motion of the clusters as lenses (Birkinshaw & Gull 1983; Gurvits & Mitrofanov 1986). This will add further difficulty in distinguishing between the two effects, even if the CBR measurements can reach a sensitivity of ∼10^{-6}–10^{-7}. On the other hand, a quantitative analysis of the time delay effect of clusters will be helpful for our estimate of various uncertainties in the CBR measurements around clusters.

2. TIME-DELAY EFFECT OF CLUSTERS OF GALAXIES

CBR anisotropy from the Rees-Sciama effect is mainly associated with nonlinear and strongly evolving potentials, which can be well described by the formalism (Martinez-Gonzalez, Sanz, & Silk 1990)

$$\Delta T \over T = \frac{5}{3c^2} (\phi_v - \phi_o) - \frac{2}{c^2} \int dx \cdot \nabla \phi + n \cdot \left( \frac{v_o - v_x}{c} \right),$$  \hspace{1cm} (1)

or equivalently,

$$\Delta T \over T = \frac{1}{3c^2} (\phi_v - \phi_o) + \frac{2}{c} \int dt \frac{\partial \phi}{\partial t} + n \cdot \left( \frac{v_o - v_x}{c} \right),$$  \hspace{1cm} (2)

where the first term is the Sachs-Wolfe effects, the second term denotes the Rees-Sciama effect from a time-dependent potential well of nonstatic structure, and the third term simply represents the Doppler shift. We are interested in the second term, generated by an isolated structure such as a galaxy cluster. For a static potential φ(r) embedded in the expanding universe, we have

$$\phi(r) = -\int \frac{4\pi G \rho(r')d^3r'}{|r - r'|},$$  \hspace{1cm} (3)

in which r and r' are connected to the comoving coordinates through $r = a(t)x$ and $r' = a(t)x'$, respectively. Because of the mass conservation of $4\pi \rho(r')d^3r'$, the partial derivative of φ with respect to t reads

$$\frac{\partial \phi}{\partial t} = -\frac{\dot{a}}{a} \phi.$$  \hspace{1cm} (4)

As a result, the CBR temperature anisotropy from the Rees-Sciama effect of a static potential φ is

$$\Delta T \over T = -\frac{2}{c^2} \int \frac{\dot{a}}{a} \phi ds ,$$  \hspace{1cm} (5)

where the integration is performed along the light path s. If we assume that the cosmological term $\dot{a}/a$ remains roughly unchanged during the CBR photon cross time, i.e., the size of the nonlinear structure represented by the static potential φ is relatively small, the above expression can be written as

$$\Delta T \over T = \frac{\dot{a}}{a} \Delta t ,$$  \hspace{1cm} (6)

$$\Delta t = -\frac{2}{c^2} \int \phi ds ,$$  \hspace{1cm} (7)

where Δt is the relativistic time dilation due to the presence of φ in the framework of the linearized Einstein theory (e.g., Cooke & Kantowski 1975). We can also view the problem from a different angle: the CBR photons can be trapped in the gravitational well φ and separated from the expansion of the universe for a period of Δt. In other words, the CBR photons traveling through a gravitational well can conserve their energy with respect to the background photons. Defining the Hubble constant as $H(t) = \dot{a}/a$, we have from equation (6)

$$\frac{\Delta T_d}{T} = H(t)\Delta t = \sqrt{1 + z_c} H_o \Delta t_0 ,$$  \hspace{1cm} (8)

where the subscript d denotes the time delay component, and the time delay in the observer’s frame is $\Delta t_0 = (1 + z_c)\Delta t$, where $z_c$ is the redshift of the nonlinear structure. Here and hereafter we assume a flat cosmological model with $\Omega_M = 1$ and $H_0 = 50$ km s^{-1} Mpc^{-1}.

We now focus on the numerical computation of the time delay effect of clusters of galaxies. We approximate the mass distribution of clusters by two well-known models: the softened isothermal sphere (SIS) model and the cusped
universal density profile (Navarro, Frenk, & White 1995; hereafter NFW):

\[
\rho_{\text{SIS}} = \frac{\sigma^2}{2\pi G} \frac{1}{r^2 + r_c^2}; \quad (9)
\]

\[
\rho_{\text{NFW}} = \frac{\delta_c \rho_{\text{crit}}}{(r/r_c)(1 + r/r_c)^2}. \quad (10)
\]

In the SIS model, \(\sigma\) is the velocity dispersion of dark matter particles and \(r_c\) is the core radius, while in NFW profile, \(\rho_{\text{crit}} \equiv 3H^2/8\pi G\) is the critical mass density for closure, \(\delta_c\) is the dimensionless characteristic density contrast, and \(r_s\) is the scale length. To ensure the convergence of gravitational potential and the validity of our assumption about the limited effective size of nonlinear structure, we truncate the cluster at its virial radius, defined by

\[
M(r_{\text{vir}}) = \frac{4\pi}{3} r_{\text{vir}}^3 \Delta \rho_{\text{crit}}, \quad (11)
\]

where \(\Delta \rho\) is the overdensity of the dark matter halo with respect to \(\rho_{\text{crit}}\). The gravitational potentials for these two models inside \(r_{\text{vir}}\) are as follows. For the SIS model,

\[
\phi_{\text{SIS}} = 2\sigma^2 \left[ \arctan \frac{x}{\chi} + \frac{1}{2} \ln(1 + x^2) - 1 - \frac{1}{2} \ln(1 + x_{\text{vir}}^2) \right], \quad (12)
\]

where \(x = r/r_c\) and \(x_{\text{vir}} = r_{\text{vir}}/r_c\). For the NFW,

\[
\phi_{\text{NFW}} = -\frac{4\pi G \rho_s}{3} \frac{\ln(1 - x)}{x}, \quad (13)
\]

where \(\rho_s = \delta_c \rho_{\text{crit}}\) and \(x = r/r_s\). Inserting these derived potentials into equation (7) and performing the integration along the light path across the cluster, we can obtain the CBR temperature fluctuations due to the static gravitational potential of clusters approximated by the SIS model and the NFW profile, respectively.

3. COMPARISON

3.1. S-Z Effect

For an isothermal \(\beta\) model as the distribution of the hot plasma inside a cluster, the thermal S-Z effect is (see Rephaeli 1995; Birkinshaw 1999)

\[
\frac{\Delta T_{\text{SZ}}(\theta)}{T_{\text{CBR}}} = \left[ 1 + \left( \frac{\theta}{\theta_{x,c}} \right) \right]^{1 - 3\beta/2}, \quad (14)
\]

\[
g(x) = \frac{x^2 e^{x}}{(e^x - 1)^2} \left( x \cosh \frac{x}{2} - 4 \right), \quad (15)
\]

where \(x = h\nu/kT_{\text{CMB}}\) is the dimensionless frequency, \(T_{\text{CMB}} = 2.726\) K is the present CBR temperature, and

\[
y_0 = 7.12 \times 10^{-5} \frac{\Gamma((3\beta - 1)/2)}{\Gamma(3\beta/2)} \left( \frac{n_{e0}}{10^{-3} \text{ cm}^{-3}} \right) \left( \frac{T_e}{10\text{ keV}} \right) \left( \frac{r_{x,c}}{\text{Mpc}} \right), \quad (16)
\]

where \(n_{e0}\) and \(T_e\) are the central electron number density and temperature, respectively, and \(r_{x,c}\) (or \(\theta_{x,c}\)) is the core radius for the \(\beta\) model. The kinematic S-Z effect due to the peculiar motion \(v\) of the cluster along the line of sight is

\[
\frac{\Delta T_{\text{KSZ}}(\theta)}{T_{\text{CBR}}} = -\frac{v}{c} n_{e0} \sigma_T r_{x,c} \sqrt{\pi} \frac{\Gamma((3\beta - 1)/2)}{\Gamma(3\beta/2)} \left( \frac{\theta}{\theta_{x,c}} \right)^2 \left( \frac{1 + (\theta/\theta_{x,c})}{1 - (\theta/\theta_{x,c})} \right)^{-1 - 3\beta/2}. \quad (17)
\]

There are two remarkable distinctions between the S-Z and time delay effects: (1) unlike the S-Z effect, which is independent of cluster redshift, the time delay effect varies as \((1 + z)^{3/2}\); (2) both \(\Delta T_{\text{SZ}}\) and \(\Delta T_{\text{KSZ}}\) drop sharply with the outward radius from cluster center, while \(\Delta T_d\) is rather insensitive to cluster radius. In order to quantitatively compare the CBR temperature fluctuations arising from the thermal and kinematic S-Z effects and the time delay effect, we take a typical rich cluster at \(z = 0.1\), whose parameters are listed in Table 1, to proceed with our numerical computations. For the NFW profile, we adopt the typical values of \(x = 4\pi G \mu_{\text{nuc}} \rho_s r_v^2 / kT_c\) and \(r_v\) found from fitting the NFW expected X-ray surface brightness profiles of clusters to the observed ones (e.g., Ettori & Fabian 1999; Wu & Xue 2000).

The resulting CBR temperature variations, \(\Delta T(\theta)/T_{\text{CBR}}\), are shown in Figure 1 for two different choices of the truncated cluster radii: \(r = r_{\text{vir}}\) and \(r = 10r_{\text{vir}}\).

It appears that for a typical cluster and an observing frequency of \(v = 32\) GHz, the orders of magnitude of the maximum CBR temperature fluctuations from the thermal and kinematic S-Z effects and the time delay effect are, respectively, \(10^{-4}\), \(10^{-5}\), and \(10^{-6}\). Although a temperature fluctuation of as low as \(10^{-6}\) will be detectable with future space experiments such as MAP and Planck, the fact that \(\Delta T_d/T_{\text{CBR}}\) is a slowly varying function of radius puts the actual measurement of the time delay effect into a difficult position. One possible approach is to measure the temperature difference between two points separated by an angle \(\Delta \theta\). The signature of \(\Delta T_d(\theta - \Delta \theta/2) - \Delta T_d(\theta + \Delta \theta/2)\) could be identified if the S-Z effects can be removed. However, the kinematic S-Z and time delay effects may come to be indistinguishable as a result of the frequency-independent property, unless CBR temperature profiles with a sensitivity of at least \(10^{-7}\) can be obtained. In other words, the presence of the time delay effect may yield an uncertainty of \(\sim 10\%\) in the measurement of the central kinematic S-Z effect of clusters.

3.2. Transverse Motion of Clusters

In the Rayleigh-Jeans limit, the magnitude of the temperature fluctuation, \(\Delta T_d/T_{\text{CBR}}\), due to the transverse motion of a cluster with velocity \(v\) can be estimated through

\[
\begin{array}{c|c|c|c}
\hline
\text{Parameter} & \text{Value} \\
\hline
\sigma & 1100 \text{ km s}^{-1} \\
\beta & 2/3 \\
r_v & 0.25 \text{ Mpc} \\
n_{e0} & 3 \times 10^{-3} \text{ cm}^{-3} \\
T_e & 7 \text{ keV} \\
v & 500 \text{ km s}^{-1} \\
\alpha & 10 \\
r_{\text{vir}} & 0.8 \text{ Mpc} \\
\hline
\end{array}
\]
FIG. 1.—Radial CBR temperature variations generated by the thermal (dotted lines) and kinematic (dashed lines) S-Z effects and the time delay effect (solid line) for a cluster at $z = 0.1$. For the thermal S-Z effect an observing frequency of $v = 32$ GHz is assumed. Cluster properties are summarized in Table 1. Dependence of the effects on the truncated radii is shown for (top) and (bottom).

(Birkinshaw & Gull 1983; Gurvits & Mitrofanov 1986)

$$\frac{\Delta T_c(\theta)}{T_{CBR}} \approx 2\left(\frac{v}{c}\right)^2 \delta(\theta),$$

where $\delta(\theta)$ is the deflection angle produced by the projected cluster mass within $\theta$ along the line of sight. For the SIS and NFW models, we have

$$\delta_{SIS}(\theta) = 4\pi \left(\frac{\sigma^2}{c^2}\right) \sqrt{\theta^2 + \theta_s^2 - \theta},$$

and

$$\delta_{NFW}(\theta) = \frac{16\pi G \rho_s r_s^2}{c^2} \left(\frac{\theta_s}{\theta}\right) \left\{ \begin{array}{ll}
\ln\left(\frac{\theta}{2\theta_s}\right) + \frac{\theta_s}{\sqrt{\theta^2 - \theta_s^2}} \ln\left(\frac{\sqrt{\theta^2 - \theta_s^2} - \theta}{\theta}\right) & \theta < \theta_s, \\
\ln\left(\frac{\theta}{2\theta_s}\right) + \frac{\theta_s}{\sqrt{\theta^2 - \theta_s^2}} \arctan\left(\frac{\sqrt{\theta^2 - \theta_s^2}}{\theta_s}\right) & \theta > \theta_s,
\end{array} \right.$$  

respectively, where $\theta_s$ is the angle distance of $r_s$. Here $\Delta T_c(\theta)/T_{CBR}$ produces a two-sided pattern around the moving cluster. Unlike the time delay and S-Z effects, the CBR will be unaffected by the transverse motion of the cluster if we look through its central region, because $\delta(0) = 0$. The maximum amplitude of $\Delta T_c/T_{CBR}$ relative to $\Delta T_c(0)/T_{CBR}$ for a typical rich cluster is

$$\frac{\Delta T_c}{T_{CBR}} \approx 0.9 \times 10^{-6} \left(\frac{v}{10^3 \text{ km s}^{-1}}\right) \left(\frac{\sigma}{10^3 \text{ km s}^{-1}}\right)^2, \quad \text{SIS};$$

$$\frac{\Delta T_c}{T_{CBR}} \approx 1.1 \times 10^{-6} \left(\frac{v}{10^3 \text{ km s}^{-1}}\right) \left(\frac{\sigma}{10}\right) \left(\frac{T}{7 \text{ keV}}\right), \quad \text{NFW}.$$  

Apart from their very different CBR patterns, $\Delta T_{KSZ}/T_{CBR}$, $\Delta T_{d}/T_{CBR}$, and $\Delta T_c/T_{CBR}$ are all achromatic, and the latter two effects also have the same order of magnitude. Consequently, the uncertainty in the measurement of $\Delta T_{KSZ}$ due to the combined effect of the time delay and the transverse motion of clusters can become even larger than $\sim 10\%$. It has been suggested (Birkinshaw & Gull 1983; Gurvits & Mitrofanov 1986) that the detection of $\Delta T_c/T_{CBR}$ can be used as a method for measuring the peculiar velocities of clusters. Such a motivation can now be complicated by the time delay effect unless the detailed patterns of the CBR anisotropies around clusters can be well mapped.

4. DISCUSSION AND CONCLUSIONS

Indeed, the CBR temperature fluctuation caused by the static gravitational potential of a rich cluster is very small,
\[ \Delta T_d(\theta)/T_{\text{CBR}} \sim 10^{-6} - 10^{-7}, \] which is 2–3 orders of magnitude lower than the thermal (1–2 orders of magnitude lower than the kinematic) S-Z effect, but is nevertheless comparable to the effect produced by a transversely moving cluster as the gravitational lens. The signals of the time delay effect and the transverse motion of clusters may remain indistinguishable from the kinematic S-Z effect in current S-Z measurement, unless one can acquire the detailed CBR temperature profile across clusters with a sufficiently high sensitivity of \( \sim 10^{-7} \). The presence of the time delay effect and the transverse motion of clusters may lead to an uncertainty of \( \sim 10\% \) in the measurement of the kinematic S-Z effect due to the peculiar motion of clusters along the line of sight, which gives a sense of how accurately and robustly one can use the kinematic S-Z measurement of clusters for cosmological purposes.

So far, we have not included the contribution from the time-dependent potential of clusters. This is mainly based on the recent observations that significant evolution of dynamical properties of clusters has not been found since \( z \approx 1 \). Therefore, our conclusion may not hold exactly true if clusters are still in the process of formation, where the free infall plays a dominant role. Our derived CBR temperature fluctuation due to the time delay effect can be comparable to that produced by the time-dependent potential of clusters (e.g., Chodorowski 1991; Tuluie \& Laguna 1995; Tuluie, Laguna, \& Anninos 1996). Nevertheless, in a way similar to the S-Z effect, the \( \Delta T/T_{\text{CBR}} \) caused by the changing gravitational potential of a cluster shows a sharp drop along outward radius. Thus, it would be possible to isolate the time delay effect from the measured CBR fluctuations behind a cluster if one can have the high-sensitivity CBR temperature profile.

Because of the unique property of the “long-distance” effect, i.e., that \( \Delta T_d/T_{\text{CBR}} \) depends approximately on \( \ln(1/\theta) \), one might worry about the issue of whether the time delay effect of clusters can contaminate the global CBR power spectrum measured at small angles (\( \sim 10^{-6} \), because clusters are a rare population in the universe. Without a sophisticated statistical study of the effect on the CBR spectrum, our computation in the present paper suggests that the time delay effect of clusters is unlikely to produce a noticeable contribution of as high as a few times \( 10^{-6} \) to the CBR anisotropies, which is compatible with the Rees-Sciama effect generated by large-scale matter inhomogeneities according to numerical simulations (Tuluie \& Laguna 1995; Tuluie et al. 1996; Seljak 1996). Nevertheless, future precise CBR temperature measurements on smaller angular scales should allow the time delay effect of clusters to be included.

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