The Thermal Sunyaev Zel’dovich effect: a powerful probe for missing baryons

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Abstract. About 90% of baryons in the universe have thus far escaped direct observation. This is known as the missing baryon problem. The Sunyaev Zel’dovich effect (SZ effect) has the potential to directly measure the state of the majority of these missing baryons. The next generation CMB experiments such as AMIBA will provide an unbiased sample of the intergalactic medium through the SZ effect. The existing and upcoming simulations and analytical studies provide a quantitative understanding of the SZ effect. All these make the SZ effect a powerful baryon probe. We present an overview of this probe from both phenomenological and theoretical aspects.

1. Introduction

The universe is turning out to be quite complicated. The favorite cosmology postulates that a mysterious negative pressure field or a cosmological constant accounts for about 2/3 of the total energy budget. The remaining 2/3 is believed to be dominantly cold dark matter. The ordinary baryonic matter only accounts for about 5% of the total matter in the universe. But the directly observed components such as stars, interstellar medium, intracluster gas, etc., only account for about 10% of the total baryon budget (Persic & Salucci 1992; Fukugita, Hogan & Peebles 1998). This is the so called missing baryon problem. These missing baryons are believed to be in the form of the intergalactic medium (IGM) and are elusive to detect. To understand their state, such as density, temperature, peculiar velocity, metalicity, etc., stands as a major challenge to both observation and theory, and is crucial to understanding the thermal history of the universe, galaxy formation, etc.

The IGM has various observable tracers. (1) Neutral hydrogen absorbs the background light of Quasars and produces the Lyman-α forest. (2) The ionized electrons have thermal and peculiar motions and are capable of scattering CMB photons and generate secondary CMB temperature fluctuation, which are known as the thermal and kinetic Sunyaev Zel’dovich effects (TSZ and KSZ effect), respectively. Their precision measurements are becoming routinely available with devoted CMB experiments such as AMIBA. (3) The ionized electrons and pro-
tons interact with each other and emit X-rays through thermal bremsstrahlung and contribute to the soft X-ray (0.5 – 2 keV) background (XRB).

These effects have different dependences on the IGM state and probe different phases. The Lyman-α forest probes the low density neutral IGM phase where the overdensity $\delta \equiv \delta \rho / \rho - 1 \sim 1$. Since our universe is highly ionized, the Lyman-α forest only directly probes a tiny fraction of the missing baryons and radiative modelling is required to extrapolate to the state of the bulk of the gas. The X-ray emission is proportional to $\rho^2$ and primarily probes the densest IGM regions. X-ray flux is diluted by distance and further by the expansion of the universe. So the observed IGM XRB is mostly from the nearby universe ($z \leq 0.5$) and it is difficult to look very deep. X-ray absorption is another possibility (Perna & Loeb 1998), but is strongly temperature and metallicity dependent. In contrast to these two effects, the SZ effect (both TSZ and KSZ) is a universal and powerful probe of baryons. Firstly, it provides an unbiased sampling of the missing baryons. All free electrons participate in Thomson scattering and contribute to the SZ effect. The Thomson optical depth from the epoch of reionization $z \sim 10$ to the present is $\tau \sim 0.1$, which means that a few percent of CMB photons have been scattered by electrons. Secondly, the Compton scattering does not depend on redshift and is not affected by distance or the expansion of the universe. So, the SZ effect can probe the more distant universe. Thirdly, the SZ effect has a weak dependence on the gas density in contrast to the X-ray emission and thus probes a large range of baryon. Fourthly, from a theoretical viewpoint, the SZ effect is easier to model and simulate than the other two effects. In observations, the next generation CMB experiments such as AMIBA are able to measure the SZ effect with high accuracy and cover a large proportion of the sky. All these advantages suggest that the SZ effect is a powerful probe for the missing baryons. Since the thermal SZ effect is about an order of magnitude larger than the kinetic SZ effect, hereafter we focus on the thermal SZ effect.

The biggest shortcoming of the SZ effect is its lack of redshift information. Since scattering is independent of redshift, the SZ effect on one hand allows a direct probe of the IGM to high redshift, on the other hand makes it challenging to disentangle the contributions arising from different redshifts. We have proposed a method to recover the space distribution and time evolution of the IGM (Zhang & Pen 2001) to take full advantage of the SZ effect.

In this paper, we first describe the SZ effect, its observational feasibility and our variational method to extract the 3-D information of the IGM pressure power spectrum in section 2. We outline our theoretical model of the SZ effect in section 3. We conclude in section 4.

2. Observation

The Cosmic Microwave Background (CMB) scatters off all free electrons through inverse Compton scattering, causing a change in the CMB temperature and allows us to “see” the IGM through scattering, in analogy to absorption. This effect is known as the Sunyaev Zel’dovich effect. The temperature distortion
caused by the TSZ effect (Zeldovich & Sunyaev 1969) is:

$$\Theta(\hat{n}) \equiv \frac{\Delta T_{CMB}(\hat{n})}{T_{CMB}} = -y(\hat{n}) \frac{xe^{x}}{e^{x} - 1} \left[ 4 - x/\tanh(x/2) \right] \equiv -2yS(x),$$

(1)

where $\hat{n}$ is the direction on the sky and $x \equiv h\nu/(kT_{CMB})$. Since the typical temperature of the IGM $\sim 10^{7}$ K is much higher than $T_{CMB} = 2.73$K, the photons always gain energy and are kicked up to higher frequencies. Thus, the number density of photons on the (less energetic) left side of the CMB peak decreases and results in an apparent cooling of the CMB temperature in the Rayleigh-Jeans regime. From photon number conservation, the number density of photons on the right side increases and results in a heating. With a multiple frequency SZ survey, this frequency dependence enables us to distinguish the SZ effect from the primary and secondary CMB anisotropies (Cooray, Hu & Tegmark 2000).

For a fixed frequency, what matters is the Compton $y$ parameter, which is defined as

$$y(\hat{n}) = \frac{\sigma_{T}}{m_{e}c^{2}} \int_{0}^{l(z_{cmb})} n_{e}kT_{g}dl = \frac{\sigma_{T}}{m_{e}c^{2}} \int P_{e}(\hat{n})dl.$$  

(2)

Here, $T_{g}$ and $n_{e}$ are the temperature and number density of free electrons, respectively. $P_{e}$ is the gas pressure. $dl$ is the proper distance along the path of CMB protons. The typical value of the temperature distortion is a few µK. The SZ effect has been detected for targeted clusters where $\Delta T \sim m$K. The next step is to carry out a random sky SZ survey to measure an unbiased statistical sample. The next generation CMB experiments such as AMIBA can realize this goal. In such observations, we observe the sky map of the CMB temperature fluctuation and thus the angular power spectrum, which is defined by

$$C_{l} \equiv \langle \sum_{m} a_{lm} \tilde{Y}_{lm} \rangle / (2l + 1)$$

(Here, $\Theta(\hat{q}) \equiv \tilde{Y}_{lm}(\hat{q}) = \sum_{m} a_{lm}Y_{lm}(\hat{q})$). In the small angle approximation,

$$C_{l} = 4(\frac{\sigma_{T}}{m_{e}c^{2}})^{2} \int_{0}^{x(z_{cmb})} P_{SZ}(k,z)|_{k=l/a}a^{2}x(z)dx(z),$$

(3)

where $x(z)$ is the comoving distance and $P_{SZ}(k,z)$ is the power spectrum of the gas pressure. $P_{SZ}$ contains detailed information about the IGM, but is smeared by redshifts. Because the SZ effect is mostly contributed by nonlinear structures at $z \sim 0.5 - 2$ (Zhang & Pen 2001), it should have a strong cross correlation with galaxies in that redshift range. Taking advantage of the cross correlations with a photometric redshift survey such as Sloan Digital Sky Survey, we are able to statistically extract IGM 3-D correlations and evolution. The basic idea is sketched in fig. 1.

We show that the galaxy selection function to maximize the SZ-galaxy cross correlation coefficient is actually the ratio of the 3-D pressure-galaxy cross correlation power spectrum and the galaxy auto correlation power spectrum. With further investigation, we can extract the pressure power spectrum (Zhang & Pen 2001).
3. Theoretical estimation

With all these promising upcoming observational capabilities, we need to understand the SZ effect theoretically. One would like to predict the value of the $y$ parameter, the shape of the SZ power spectrum, the angular scale where it becomes dominant over the primary CMB, contributions to $y$ and the power spectrum from different redshifts, the dependence on the cosmological parameters and the gas parameters and any other information about the intervening IGM that we can infer.

Two analytical models have been considered to answer these questions. The first is the halo model method (see Komatsu & Kitayama 1999 for a review). The contribution to the SZ effect by a single halo is described by the gas distribution in the halo, for example, an isothermal distribution. The collective effect is integrated by the Press-Schechter formalism.

The second approach is to directly deal with the underlying density field as we proposed (Zhang & Pen 2001). The gas temperature depends on the gravitational potential ($T \propto \phi$) and is thus determined by the underlying density field. So roughly $P_e \propto n_e \phi$. Then, we can estimate the evolution of the mean gas pressure, which is shown in fig. 2. Furthermore, the pressure correlation function $\langle P_e(x)P_e(x+r) \rangle \propto (n_e(x)\phi(x)n_e(x+r)\phi(x+r))$. With the hierarchical model of the density field (Fry 1984, Scoccimarro & Frieman 1999), we can decompose this high order density correlation into the products of the 2-point density correlations. The result is shown in fig. 3. Our calculation shows that, for a typical $\Lambda$CDM model, (1) the mean temperature distortion $\Delta T \sim 6 \times 10^{-6}$ K. (2) The SZ power spectrum exceeds the primary CMB anisotropy at $l \sim 2000$ and peaks around $l \sim 3000$ ($\theta \sim 10'$) as shown in fig. 4. The position of the peak is an unambiguous signature of the the underlying gas-dark matter correlation. (3) $C_l$ has a strong dependence on $\sigma_8$ ($C_l \propto \sigma_8^{6-9}$). (4) The dominant contribution to $C_l$ depends on the angular scale, varying from $z \sim 0.4$ at $l \sim 1000$ to $z \sim 1.5$ at $l \sim 10000$. Smaller angular scales probe the more distant universe (fig. 5).

Non-gravitational heating is a key ingredient needed to understand the IGM (Pen 1999). We have estimated its effect and found that it will leave an unambiguous signature in the 3-D power spectrum (Zhang & Pen 2001). If non-gravitational heating is proportional to the gravitational heating, the only signature is an enhancement of the amplitude of the power spectrum. A spatially homogeneous energy injection will produce an uprisng tail in the power spectrum towards smaller scales (fig. 6). The non-gravitational heating parameters including epoch and energy can be extracted from a precise measurement of the SZ map in conjunction with a galaxy photometric redshift survey.

4. Conclusion

We summarize the benefits of using the SZ effect as the probe for the missing baryons:

- The SZ effect is based on the Thomson scattering, which is sensitive to the majority of baryons: the ionized IGM. The interaction between photons
and electrons (about 10% CMB photons are scattered) guarantees the SZ effect to be an unbiased sample of the missing baryons.

- Compton scattering is completely understood physics, so the SZ effect can be cleanly computed from first principles.
- Compton scattering does not depend on redshift and thus the SZ effect can readily probe the IGM at high redshift.
- The upcoming experiments such as AMIBA will provide a wealth of information on the SZ effect. The dependence of the SZ effect on frequency allows the separation from primary and other secondary CMB anisotropies.
- With the aid of galaxy photometric redshift surveys and our variational method, we can obtain the full time and space resolved IGM state.
- We can reasonably estimate the SZ effect in theory both analytically and in simulations from first principles.
- The SZ effect can help us resolve some key questions on IGM such as the role of non-gravitational heating, which is of key importance to galaxy formation.

The SZ effect encodes key cosmological information, is observationally feasible and theoretically tractable. It will allow us to uncover the state of the missing baryons.

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Figure 1. Variational method to extract redshift information. The observables are the SZ angular correlation $C_{SZ}$, galaxy angular correlation function $C_G$, their cross correlation $C_{SZ,G}$ and the 3-D galaxy overdensity correlation. We want to extract the redshift distribution of the IGM pressure $P_e = n_e k_B T$ and its correlations. The freedom in this data set is the galaxy selection function $\phi(z)$. We vary this function and maximize $\frac{C_{SZ,G}(\phi)}{\sqrt{C_{SZ}C_G(\phi)}}$. The optimal $\phi_M(z)$ obtained in this way explicitly tells us the underlying 3D pressure distribution.
Figure 2. The density averaged temperature defined as $\bar{T}_g \equiv \langle \rho T \rangle / \bar{\rho}$. We assume that the gas overdensity is the convolution of the dark matter overdensity with a top hat window of radius $r_g = 1/3 \text{ Mpc/h}$. The gas window function reflects the fact that, due to the gas pressure, the gas is more diffuse than the dark matter.
Figure 3. The variance of the pressure fluctuation $\frac{P - \bar{P}}{P}$. The peak of the variance is mainly determined by $r_g$. 
Figure 4. The SZ angular power spectrum. The SCDM has a much smaller \( \sigma_8 \sim 0.5 \). Due to the strong dependence of \( C_l \) on \( \sigma_8 \), the angular power spectrum of a SCDM cosmology is much smaller than the Open CDM model and the \( \Lambda \)CDM model.
Figure 5. Redshift dependence of $C_l$. The typical peak contribution of IGM to SZ effect is from $z \sim 1$. Smaller peak probes more distant universe.
Figure 6. Effect of non-gravitational heating if not correlated with the gravitational heating. The uprising tail at large $k$ (smaller distance) is the distinct signature of this non-gravitational heating. The power spectrum contributed by the non-gravitational heating is a constant. So, $\Delta_p^2(k) \propto k^3$ and becomes dominant on scales smaller than that of the gravitational heating peak.