SEARCHING FOR GALAXY CLUSTERS WITH THE SUNYAEV-ZEL'DOVICH EFFECT

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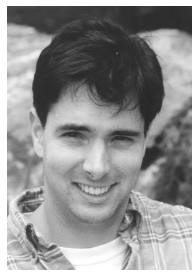

The Sunyaev-Zel'dovich (SZ) effect offers tremendous potential as a probe of the distant universe. We discuss cluster evolution and its effects on SZ surveys, using as a specific example a planned interferometric survey. The yield of an SZ survey will depend on the observing strategy and the evolution of the gas in the intra-cluster medium.

1 Introduction

The Sunyaev-Zel'dovich (SZ) effect[1] arises from the scattering of CMB photons by hot electrons along the line of sight. This scattering imprints a distortion in the CMB spectrum that is insensitive to the redshift at which it occurs. This redshift-independence makes the SZ effect unique and provides a potentially powerful probe of the distant universe.

Clusters of galaxies provide the largest source of the effect, with their hot (few keV) electrons and long path lengths (Mpc), but even here the effect is not expected to much exceed $\Delta T/T_{CMB} \sim 10^{-3}$. Observations of the Sunyaev-Zel'dovich effect and optimized instrumentation are advancing quickly, to the point where detailed images at high signal-to-noise are becoming routine. In the next few years, we can expect more than an order of magnitude improvement in imaging speed, allowing both unprecedented studies of known clusters and also a means to survey fairly large (a few square degrees) fields in order to find new distant clusters.

A selection of distant clusters will be useful for many reasons. The simple existence of high-redshift clusters will provide important information about the evolution of structure, and therefore the relative importance of various energy densities in the universe. The structure of these high-redshift clusters will provide insight into the evolution of the intra-cluster medium (ICM), which could be affected by feedback from galaxy formation.

2 SZ Observables

The SZ effect along a line of sight is given by

$$\frac{\Delta T}{T_{CMB}} = g(\nu) \int n_e \frac{kT_e}{m_e c^2} \sigma_T dl \tag{1}$$

where $g(\nu)$ is a dimensionless function of frequency that approaches -2 in the Rayleigh-Jeans limit, has a null near 217 GHz and is positive at higher frequencies (see Birkinshaw 1998[2] for a review). The electron number density is denoted by n_e and $kT_e/m_e c^2$ indicates the electron thermal energy in units of the electron rest mass energy.

In the case of an isothermal cluster, the decrement (assuming R-J) is proportional to the surface density of electrons. This can be integrated over the extent of the cluster to obtain simply the total number of electrons, up to a factor of d_A^2. This is remarkable, since this does not depend on the distribution of electrons, only that they are isothermal. If we relax the assumption of isothermality, we obtain the integrated thermal energy of the cluster, which is still a very interesting quantity with a simple physical interpretation.

The SZ effect therefore gives an excellent probe of the ICM. The intensity distribution on the sky gives valuable information on the distribution of the gas, while the integrated flux gives a nearly model-independent measure of the total gas mass.

Large-field searches for galaxy clusters using the SZ effect have several options for survey strategies. A large beam can survey a large field fairly quickly and has a simple mapping between sensitivity and mass but could suffer from beam dilution for the distant smaller clusters. An experiment with a small beam, if done carefully, should be able to both measure the total flux and resolve the cluster in order to study the ICM. This requires a large chop and would more than likely require an array of detectors in the focal plane of a large telescope in order to cover a large area in a reasonable amount of time.

3 Cluster Evolution

In the absence of gas dynamics, we would expect clusters to be self-similar. Since gravity has no preferred scale, the final size of a cluster of given mass should be set by the size (at turnaround) of the region from which it collapsed. Given that distant clusters collapsed when the universe was more dense, it would be expected that high-redshift clusters of similar mass would be smaller and denser than nearby clusters. Gas dynamics can modify this picture, as infalling gas may have an entropy excess, which prevents the formation of a dense core in low-mass systems.

High redshift systems can look very different, depending on the entropy of the ICM. We show this in Figure 1, where the central decrement and the core radius as a function of mass and redshift are shown for two gas evolution histories. We have chosen truncated spheres with $\rho \propto (1 + (r/r_c)^2)^{-1} (r < R_{vir})$, with either self-similar evolution (dashed curves) or evolution with a constant entropy core (solid). Each curve is a line of constant mass, with different redshifts marked along each curve. Note that these are not lines of cluster evolution. A cluster will accrete mass with redshift, and therefore will migrate between curves with redshift.

Self-similar evolution was modeled as a constant core-to-virial ratio ($R_{vir}/r_c = 10$). The virial radius was set from the spherical collapse model and the core density followed by setting the baryon fraction at the virial radius to be the global one. Evolution with a constant entropy core[3] was modeled by having the virial radius again set by the spherical collapse model, the core density set by having constant central entropy (assuming a temperature set by the virial relation), and the core radius was again set by assuming that the baryon fraction at the virial radius was equal to the global baryon fraction. These are two extreme models of gas evolution which we expect to bracket the true evolution.

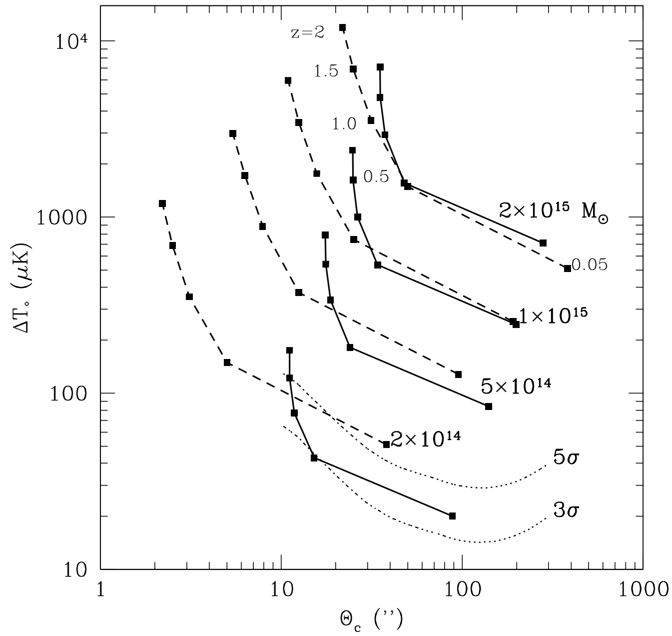

Figure 1: Appearance of clusters of given mass at different redshifts for two gas evolution histories: self-similar (dashed) and evolution with a constant entropy core (solid). The detection threshold of the proposed array described in the text are marked as dotted curves.

Several things are of note in this plot. It is interesting that the central decrements are getting larger with redshift in both models. This is a bit misleading, since the central decrement is not directly observable; it would require a very small beam (a few arcseconds) and a large chop (a few arcminutes). Note that an interferometer would not help, since the interferometer would filter out the large-scale emission which composes a significant fraction of the central decrement. However, there is no doubt that clusters are expected to be smaller with a higher surface brightness at higher redshift, and a well-planned survey could take advantage of this.

It is also interesting that the differences between the two evolution models increase at both lower mass and at higher redshift. A survey probing to high redshifts and low masses would therefore be very important for studying evolution of the ICM.

Finally, note the dotted lines at the bottom of the plot. These indicate the expected sensitivity of a proposed interferometric array operating in SZ "survey mode", where roughly one square degree per month is covered. Details of the array can be found elsewhere[4]; the salient features of the array are ten 2.5m diameter telescopes operating between 26-36 GHz. The limit that is indicated in Figure 1 can be simply translated, using a model, into a mass limit. This mass limit agrees very well with the mass limit obtained by synthesizing observations of simulated clusters from hydrodynamical cluster simulations[5].

It is important to realize that the detection limit in the space of ΔT and θ_c does not depend on cosmology, but simply the detector and the observing strategy. The mapping between mass and this plane is much more model-dependent. We have assumed a global baryon fraction of 20% in order to map from this detection limit to mass limit as a function of redshift both for our analytic models and for our hydrodynamical simulations.

4 Expected Yields

Given a minimum detectable mass at each redshift, we can use the Press-Schechter prescription for calculating number densities of clusters above a given mass as a function of redshift to calculate the number of clusters expected per square degree in different cosmologies above this limiting mass[5]. We expect more clusters in a universe with low matter density. Roughly speaking, structure forms mainly when the universe has matter density close to the critical density. If the matter density is low today, the structure that we currently see must have been more or less assembled by $z \sim 1$, and should be visible out to at least that point. On the other hand, if the matter density today is high, most of the structure that we see will have formed recently, and will not be seen at $z \sim 1$. This is seen in Figure 2, where we show both the differential counts and the integrated counts per square degree for three different cosmologies.

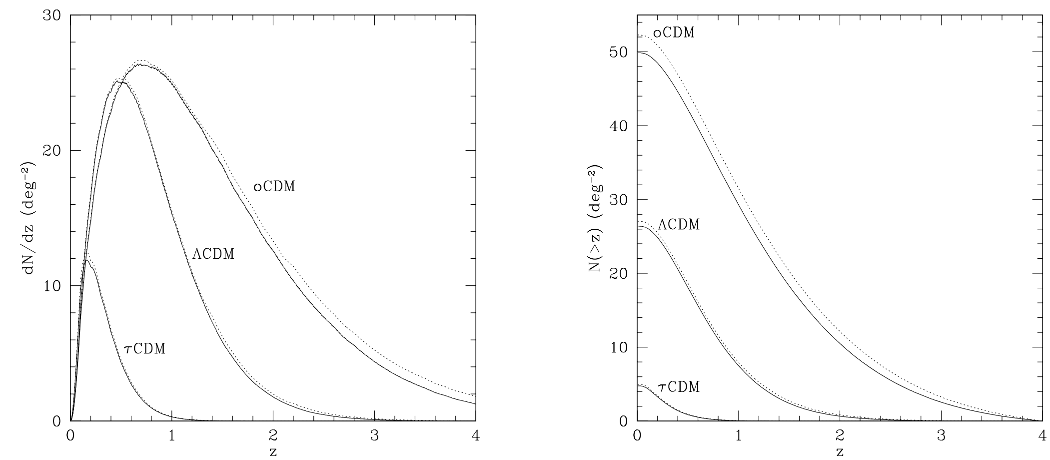

Figure 2: Counts as a function of redshift, both differential (left) and cumulative (right) for three cosmologies, assuming an interferometric survey as discussed in the text. The two curves for each cosmology represent different methods of modeling the uncertainty in the mass limit.

The differences between cosmologies are striking, as are the number of expected clusters. We therefore expect an SZ survey to provide a large catalog of distant clusters. Exactly how large will be an important and useful probe of cosmological parameters, and the catalog itself should yield insight into the evolution of the ICM and galaxy formation.

The exact counts depend on several parameters[5]. For example, Small changes in the normalization of the power spectrum, σ_8, can lead to large variations in the expected yields, but the redshift distributions are not degenerate. The matter density and nature of the dark energy affect the redshift evolution of the amplitude of the power spectrum[6], which cannot be mimicked by a simple shift of the normalization today.

Acknowledgments

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References

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