Overviews of SZ Effect, Dark Matter

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Abstract

We present brief overviews of the potential of the Sunyaev-Zel'dovich effect to probe the cosmological model in various ways and of current and next generation laboratory experiments to detect or constrain the nature of dark matter.

SZ Effect

The abundance and structure of clusters of galaxies, the largest collapsed structures in the Universe; are powerful probes of cosmology. Gas falling into the gravitational potential well of a massive cluster of galaxies is heated to ~ 10^8 degrees Kelvin and ionized. Massive clusters of galaxies can have in excess of $10^{14}M_\odot$ of hot gas bound to their gravitational potentials. At cosmological distances clusters subtend several arcminutes. The CMB on arcminute scales is a nearly uniform back-light to the observable universe since its primary anisotropies are exponentially damped. As many as 1-2% of the CMB photons passing through the cluster can be inverse Compton scattered by the hot intra-cluster (IC) gas. On average, the energy of scattered photons is increased resulting in a spectral distortion of the CMB known as the thermal Sunyaev-Zel'dovich (SZ) effect. Figure 1 shows the resulting difference in observed intensity between the unperturbed CMB and that along a line of sight through a massive cluster of galaxies. At frequencies roughly below the peak in the CMB, the net result is a decrement in the observed intensity. At frequencies above the peak in the CMB, the net result is an increase in the intensity.

The surface brightness of the SZ effect is independent of redshift. As long as an experiment has sufficient angular resolution, it should be able to detect massive clusters at any redshift. If the cluster is moving with respect to the rest frame of the CMB, there is a second component to the SZ effect. The change in intensity due to the Doppler shift imparted to the scattered photons is known as the kinetic SZ effect. There have been several thorough reviews of the SZE effect [1, 2]. Below, we list several of the most important applications of the SZ effect to the study of cosmology.

H_0 and q_0

The SZ effect probes the integrated pressure of the Intra-Cluster (IC) gas along a line of sight through a cluster. This information is complementary to X-ray studies which probe the emission measure of the IC gas which scales as the density squared. The combination of SZ and X-ray data can be used to make a physically based determination of the Hubble constant, H_0 and deceleration parameter, q_0 (see recent [2]). To apply this method precisely, it is necessary to produce detailed images of the SZ effect in clusters of galaxies. Intrinsic variations in the distributions of the cluster gas require that a sample of approximately 25 clusters be accurately measured to determine H_0 to an accuracy of 5%. A sample at redshift of $z \sim 1$ could be used, in conjunction with Chandra (AXAF) and Newton (XMM) observations to make an independent determination of q_0, and thus provide an independent determination of the acceleration of the universe.

Baryon Fraction and Ω_m

The SZ effect, combined with X-ray estimates of the gas temperature, provides a powerful probe of the total baryonic mass in a galaxy cluster. This can be combined with the total mass of the cluster, determined by gravitational lensing or X-ray spectroscopy, to measure the cluster baryon fraction. The universal density of baryons $\Omega_b h^2$, can be estimated by measurements of light element abundances coupled with our understanding of Big Bang Nucleosynthesis~(eg [3]), and by observations of the anisotropies in the CMB [4, 5]. Scaling the universal baryon density by the cluster baryon fraction yields an estimate of the universal matter density $\Omega_M h^2$. Recent work by [6] find a baryon fraction consistent with that found by X-ray observations and results in an independent determination of $\Omega_M \sim 0.25$.

Cluster Peculiar Velocities

Combined with an estimate of the X-ray temperature, observations of the thermal and kinetic SZ effects can be used to determine the peculiar velocity of a distant cluster. In principle, this technique can be used to measure deviations of clusters from the uniform Hubble flow with high precision at any redshift. This is in contrast to methods using standard candles as distance indicators which have errors that increase linearly with redshift. The kinetic component of the SZ effect is due to the relative motion of the cluster with respect to the rest frame of the CMB. The spectrum of the kinetic SZ effect, shown in Figure 1, is identical to the spectrum of intrinsic CMB anisotropies. Therefore, the kinetic SZ effect cannot be spectrally discriminated from the primary CMB anisotropies. Fortunately, the CMB fluctuations are damped on arcminute scales and can be effectively removed by applying a spatial filter. This analysis has been applied to the XBACS [7] sample of local (z<0.3) clusters by [8] in order to predict the peculiar velocity uncertainty for the observation of real clusters with a variety of τ's. Although it will be challenging to determine the peculiar velocities of individual clusters, it should be possible to make accurate determinations of bulk flows involving many clusters [8, 9].

Source Counts

Clusters of galaxies are the most massive collapsed objects in the Universe. Clusters stop forming at a redshift $z \sim 1/\Omega_M$-1. Therefore in a low matter density $\Omega_M \sim 0.3$ universe, cluster formation stopped near $z \sim 2$, and the space density of clusters should remain relatively unchanged out to that redshift. The abundance of massive clusters is a sensitive probe of the growth of structure and has the potential to provide invaluable information on the evolution of large scale structure and the cosmological parameters which describe our universe [10, 11]. The SZ surface brightness produced by a distant cluster of galaxies is independent of the cluster's redshift. For this reason, observations of the SZ effect have the potential to be a uniquely powerful method of locating distant clusters. The growth of structure depends on a variety of cosmological parameters. Recent work by [12] shows that with precise determinations of SZ source counts, it may be possible to provide new and orthogonal constraints on the dark energy equation of state. No experiment yet has achieved the necessary combination of sensitivity and sky coverage to effectively search for clusters, although long integrations with the BIMA interferometer have recently been used to produce statistical detection of excess power which is likely to be due to distant clusters [13].

Instrumentation

The last five years have seen the first significant detections of the SZ effect using both millimeter wavelength bolometer arrays and compact interferometric arrays.

The Arcminute Cosmology Bolometer Array Receiver (ACBAR) is a 16 element 235 mK bolometer array. It operates in four millimeter wavelength bands optimized for the ground based observations of the SZ effect. ACBAR is designed to be used on the 2.0m Viper telescope. All four colors have matched 4' beams, which are well matched to the size of intermediate redshift clusters. The instrument is designed for winter observations at the South Pole, when we expect the detectors to reach their fundamental quantum noise limit. The instantaneous sensitivity of the ACBAR in the 2.1mm band is approximately 200μK $\sqrt{s}$, which is within a factor of two of that achieved in the MAXIMA and BOOMERANG balloon borne experiments. ACBAR has just begun its first season of observation and has already produced images of several galaxy clusters. Although ACBAR is an important step forward in ground based CMB and SZ observations, new technology will be required to fully exploit the power of the SZ effect as a cosmological tool. This revolution will be brought about by the development of large format bolometer arrays coupled to a dedicated large aperture telescope.

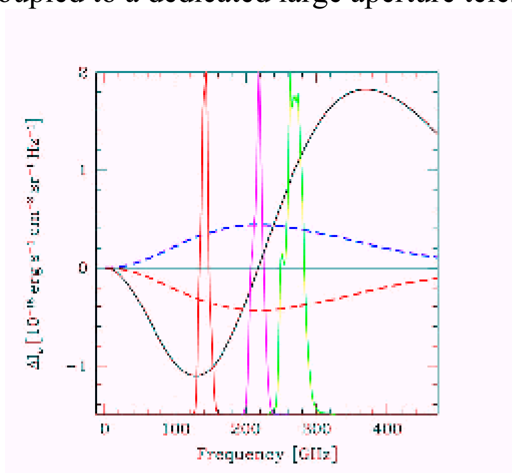

Figure 1: The spectrum of SZ thermal (solid black) and kinetic (dashed) effects with the ACABAR observing bands superimposed.

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Dark Matter

Observational cosmology has made broad advances in recent years. Observational input on structure evolution and formation has come from redshift surveys at low and high redshift, from studies of cluster evolution *via* optical and X-ray photons, and now from SZ decrements. We have constrained the expansion history from supernovae studies. Fluctuations observed in the CMBR at $z \sim 1000$ can be connected to the amplitude of structure observed in the nearby galaxy distribution. A concordant model has emerged which is broadly in accord with the inflationary paradigm, but with a somewhat uncomfortable cocktail of constituents, including both baryonic and non-baryonic matter and some kind of dark energy.

A number of observations indicate that the predominant form of the dark matter is non-baryonic, presumably in the form of elementary particles produced in the early universe. Weakly Interactive Massive Particles form a particularly interesting generic class of candidates as there appears to be a convergence between cosmology and particle physics. The direct observation of the interaction of WIMPs in a terrestrial detector would be of tremendous importance to particle physics and cosmology. The observed WIMPs would be particles that reflect physics beyond the Standard Model of strong and electroweak interactions and the identification of these WIMPs would solve the central problem of dark matter and help us understand the evolution of the early universe and the formation of structure.

Because of a long development effort funded both by NSF and DOE, the sensor technology exists to provide a great step forward in this type of search, giving hope for a positive result. We are now able to simultaneously measure the phonons (thermal or athermal depending on the variant we use) and the ionization produced by the WIMP interactions. This provides a powerful discrimination against the radioactive background. This technology is now being operated at Stanford, in the Cryogenic Dark Matter Search Experiment and has demonstrated the ability to search for dark matter interactions at levels more sensitive than other existing technologies. The principal remaining limitation of CDMS comes from the shallowness of the Stanford site.

Construction of a second generation experiment (CDMS II) is underway at a deep site, the Soudan mine in northern Minnesota. The combination of a deeper site, a more advanced technology (with a lot of overlap with transition edge bolometers), a larger target mass (7kg with 42 detectors) and a longer running time, CDMS II promises to increase the current sensitivity by a factor 100. We should enter definitely into the supersymmetric parameter space, providing information complementary to the current collider programs (CDF and D0 at the Tevatron) and LHC which will start in 2006.

After CDMS II and similar experiments (e.g. CRESST II), the WIMP searches will be at a cross roads. We might find a signal in these second generation experiments. The next priority will then be the detection of the direction of the recoil, to totally link the WIMPs with the galaxies and begin to measure the halo. Alternatively, if we do not find WIMPs, we will need to increase the mass and discrimination capability of our experiments to further explore the supersymmetry territory, complementing the searches at the Tevatron and the LHC.