COSMOLOGY:

Probing the Early Universe with the SZ Effect

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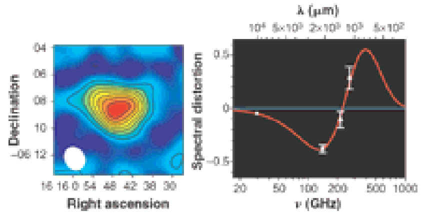
The cosmic microwave background radiation (CMBR) we observe today provides a window to an early stage in our universe's evolution, when the expanding universe had cooled to the point that free electrons and ionized nuclei recombined to form atoms. Before recombination, scattering between photons and free electrons was frequent, and the distance that light could penetrate was small; afterward, with free electrons out of circulation, the universe became largely transparent to light. Small variations in the CMBR intensity trace small perturbations in the primordial matter density, which have been amplified by gravitational forces to form the magnificent, complex structures that make up the present-day universe.

In certain massive objects, however, interactions between CMBR photons and free electrons continue to play an important cosmological role. The largest gravitationally collapsed structures in the universe are clusters of galaxies with masses up to 100,000 times greater than the mass of our galaxy, the Milky Way. At optical wavelengths, clusters are beautiful objects consisting of thousands of galaxies, each containing billions of stars, all bound together by a strong gravitational field. The galaxies and stars, however, only account for a few percent of the total mass. Most of the normal (baryonic) matter resides in the hot (~100 million K) gas that permeates the galaxy cluster. When CMBR photons interact with the free electrons in this ionized gas, a unique feature--the Sunyaev-Zel'dovich (SZ) effect--is imprinted on the spectrum of the microwave background. This feature proves to be of fundamental importance for cosmology.

The interaction of a CMBR photon with a hot cluster electron will, on average, cause the photon to gain a small amount of energy. A cluster of galaxies contains a tremendous amount of gas (~10^{14} times the mass of our sun), but the probability that a CMBR photon will interact with an electron in the cluster gas is nevertheless small. The SZ effect is therefore subtle, changing the brightness of the CMBR spectrum by at most 0.1%. This spectral distortion has a distinct signature: In the low-frequency part of the CMBR spectrum, the SZ scattering process causes the brightness of the CMBR to be diminished toward galaxy clusters, producing "holes" in the background radiation field (see the left panel in the first figure). The scattered photons are shifted to higher energies, producing an excess in the high-frequency part of the CMBR spectrum (see the right panel in the first figure).



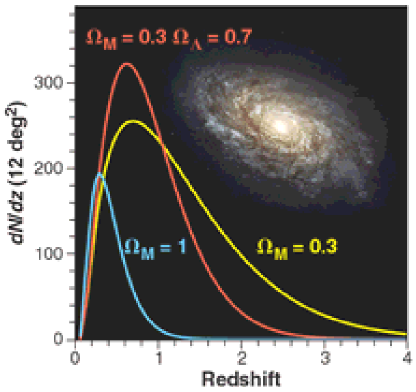
The Sunyaev-Zel’dovich effect. (**Left**) An image of the SZ effect toward the galaxy cluster Abell 2163 (obtained with the Berkeley-Illinois-Maryland Association and the Caltech Owens Valley interferometers) reveals a decrease in the otherwise uniform brightness of the CMBR toward the galaxy cluster (15). The contour interval is two times the root-mean-square noise in the map. (**Right**) SZ effect spectral distortion (in units of MJy/sr) relative to the undistorted CMBR spectrum measured toward Abell 2163 (15, 16). On average, the CMBR photons interacting with the hot cluster gas are shifted to higher energy, resulting in a deficit of photons at low frequencies and an excess at high frequencies relative to the CMBR spectrum (17).

The SZ effect was first proposed 30 years ago (1, 2) but proved exceptionally difficult to detect. Accurate measurements are now possible with experimental techniques developed over the last decade (3, 4). The SZ effect has been used to independently determine the expansion rate of the universe (Hubble’s constant) and the matter density of the universe (W_M).

The ability to determine these important cosmological quantities rests on the fact that the magnitude of the SZ effect is proportional to the total number of free electrons contained in the cluster, weighted by their temperature. An accurate measure of the SZ effect thus leads to an estimate of the cluster gas mass, provided that the gas temperature is known. This temperature is obtained from the x-ray emission spectrum of the hot gas, from which we can infer the kinetic energy and the total mass required to bind the cluster together. It is then possible to determine the fraction of normal matter to total matter contained within galaxy clusters; this fraction is important because the composition of objects as large and massive as galaxy clusters should reflect the composition of the universe as a whole. Finally, the total matter density of the universe is obtained by scaling the measured baryon density of the universe (5) by the baryon fraction derived from SZ effect measurements.

Like other recent techniques, the SZ effect observations indicate that the mass density of the universe, including the mysterious dark matter, is quite low: $W_M \sim 0.25$ (6, 7). This measured mass density accounts for only 25% of the critical density in a flat universe, which is inferred from recent CMBR anisotropy measurements (8-10). This suggests that about 75% of the present energy density in the universe is in some as yet undiscovered form.

The expansion rate of the universe, Hubble’s constant, can be determined by combining the SZ effect and x-ray measurements. The strength of the x-ray emission is proportional to the square of the gas density, in contrast to the SZ effect, which is linearly proportional to the gas density. A combination of the two measurements allows the gas density and cluster distance to be determined; the expansion rate is then obtained by dividing the cluster’s recessional velocity by its distance. SZ effect and x-ray observations of a large sample of galaxy clusters currently under way (3, 4, 11, 12) will provide an independent measurement of the Hubble constant.



Constraining cosmological models. The predicted number density of clusters (*dN*/*dz*) detectable in a deep SZ effect survey, calculated for various cosmological models (13). The mass detection threshold of an SZ effect survey is insensitive to redshift; all clusters of mass greater than 2.5 x 10^{14} times the mass of the sun should be detectable, independent of when they were formed.

SOURCE: NASA

Unlike most emission mechanisms, the brightness of the SZ effect depends only on the properties of the cluster gas and not on cluster distance. It will soon be possible to exploit this powerful and unusual property to explore the distant universe. The SZ effect will be used to determine the abundance and evolution of massive galaxy clusters from the time of their formation to the present, which reflect the underlying cosmological parameters of the universe (see the second figure). A large-area interferometric SZ effect survey will be able to detect massive galaxy clusters at whatever epoch they have formed (13, 14). Present theories, which assume that the initial spectrum of density fluctuations has a normal (Gaussian) distribution, predict that massive clusters should not have formed at redshifts $z \geq 3$, but this has not yet been confirmed experimentally (a higher redshift corresponds to a larger cluster distance and to an earlier period in the evolution of the universe). If large non-Gaussian fluctuations existed in the early universe, then clusters will have formed at earlier epochs than currently predicted. Because the SZ effect is independent of distance, results of SZ effect surveys will provide an incisive test of theories of the structure and evolution of the universe, as well as an independent determination of fundamental cosmological parameters.

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