same site, the Rajmahal volcanic field near the Bihar/West Bengal state boundary in eastern India. But unlike previous investigators, Tarduno *et al.* concentrated on measuring the weak (~10^{-11} A/m^2) but geologically stable magnetic moment from millimeter-sized single crystals of plagioclase, rather than whole rocks. The reason was simple: Although whole rocks ~2.5 cm in size may have more easily measurable magnetic moments, laboratory reheating inevitably causes some degree of chemical alteration, compromising the reliability of the measurement. Tarduno *et al.* show that whole rock samples contain clay minerals formed since crystallization by weathering at Earth's surface. These rapidly break down during laboratory reheating and produce new, very effective carriers of magnetic remanence (the magnetization that remains after the removal of an external field). This excess magnetite conspires to produce a remanent magnetization of the same magnitude as observed today in nature (the natural remanent magnetization, NRM) but in a weaker field than the original geomagnetic paleointensity. In contrast, the tiny (100- to 350-nanometer diameter) magnetite inclusions sealed inside the plagioclase crystals are safe from chemical change and thus yield the true paleointensity during the Cretaceous superchron. This leads to the deduced high value for the VDM.

A site of more than scientific interest. This Buddha sculpture is at the famous Buddhist school at Nalanda, near the Rajmahal volcanic field.

CREDIT: FREDERICK ASHER/VISUAL ARTS CENTER, DEPARTMENT OF ART HISTORY, UNIVERSITY OF MINNESOTA

Of the 149 single crystals of plagioclase that were studied, 56 satisfied rigorous reproducibility tests. The latter come from eight lava flows that erupted at different times within 0.1 to 1 Ma. The average value from all the flows and all the 56 crystals with reproducible data can thus be taken to represent the true dipolar field during Cretaceous superchron. The averaging process removes potential sources of error in VDM magnitude due to the highly variable (in space and time) nondipole components of the total geomagnetic field. These have shorter than 10,000-year periodicities and hence cancel out when data are averaged over 0.1 to 1 Ma.

The fact that it represents a reliable time average distinguishes Tarduno *et al.*'s VDM value from those deduced with an earlier, equally innovative method that targeted submarine basaltic glasses found in ocean sediments (*6*). The magnetite carriers of NRM are again protected from chemical change in the laboratory by their natural glass armor. However, unlike the layered stratigraphy of the Rajmahal volcanic lavas, individual submarine glass samples cannot be shown to be from sources that erupted over a sufficiently long time interval to cancel out nondipole contributions. This may explain why studies based on submarine basaltic glasses (*4*, *5*) have yielded equivocal answers as to whether the VDM was unusually high or low during the Cretaceous superchron.

One may argue that compared with the 35-Ma length of the superchron, we have so few reliable VDM values that the jury is still out. But there is some conceptual and model support for the high value of Tarduno *et al.* The late Allan Cox suggested (*7*) that during times of high dipole field strength, nondipoles cannot randomly drive the total field to reversal and furthermore (*8*) that even though core reversals may be stochastic, their frequency may be set and reset in intervals of ~100 Ma by processes in the core-mantle boundary. And in a recent three-dimensional numerical modeling study by Glatzmaier *et al.* (*9*), the field did not reverse when the imposed core-mantle boundary heat flux pattern was in phase with the convected flux from the liquid core. This led to very high dipole field values.

The tales of Panchatantra, a Buddhist book of fables, were written within a few hundred kilometers of the volcanic field of Rajmahal. It tells the well-known story of five blind men in complete disagreement about the shape and size of an elephant that they could all touch (but at different spots on the elephant). We need many more "seeing eyes" to explain why superchrons occur, but we are one step closer to knowing what characterized them.

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PERSPECTIVES: COSMOLOGY

Probing the Early Universe with the SZ Effect

Marshall Joy and John E. Carlstrom

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.

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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.

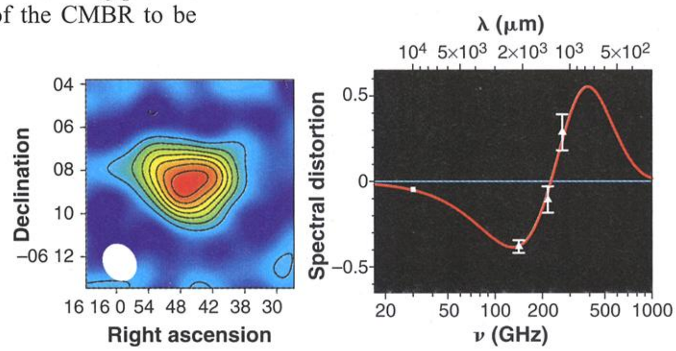
The interaction of a CMBR photon with a hot cluster electron will, on average, cause the photon to gain a small amount of energy. A cluster of galaxies contains a tremendous amount of gas (~10^{14} times the mass of our sun), but the probability that a CMBR photon will interact with an electron in the 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 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 (Ω_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.

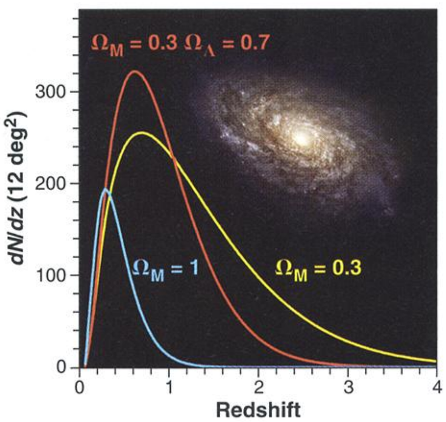
Like other recent techniques, the SZ effect observations indicate that the mass density of the universe, including the mysterious dark matter, is quite low: $\Omega_M \sim 0.25$ (*6*, *7*). This measured mass density accounts for only 25% of the critical density in a flat universe, which is inferred 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.



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*).

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.



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 2.5×10^{14} times the mass of the sun should be detectable, independent of when they were formed.

SOURCE: (BOTTOM) NASA

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