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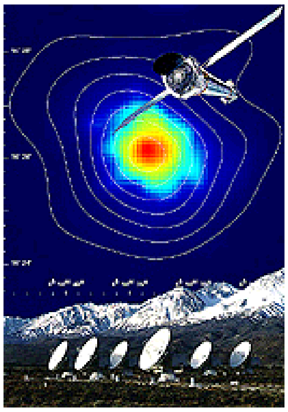
Chandra will target the age of the Universe

Astronomers plan X-ray measurements of galaxy clusters for a new measurement of the Hubble Constant

Feb. 22, 1999: In recent years astronomers have come to realize that the Universe is somewhere between 12 and 18 billion years old. They arrive at this estimate by measuring how fast the Universe is expanding due to the Big Bang and whether the expansion is accelerating or decelerating. By tracing the cosmos back in time to an era when the entire Universe was contained in a single point, they can estimate the time elapsed since the Big Bang.



Right: This image combines a view of the Caltech radio millimeter interferometer and an artist's concept of the Chandra X-ray Observatory with a radio/X-ray map of the "Sunyaev-Zeldovich Effect."

Unfortunately for cosmologists, who would like to know exactly when the Big Bang happened, it's difficult to measure precisely how fast the Universe is expanding and how the rate of expansion has changed since the Big Bang. Traditional methods lead to rather large uncertainties in the final answer.

Now two astronomers, Dr. Marshall Joy (NASA/MSFC) and Dr. John Carlstrom (University of Chicago), may have a new way to tackle the problem. For the past 7 years Joy, Carlstrom, and their colleagues have used radio interferometers to probe tiny fluctuations in the Cosmic Microwave Background Radiation (or "CMBR"). By combining their radio-wavelength images with data from NASA's Chandra X-ray Observatory they hope to open a new window on the history of the Universe.

"We could be on the brink of answering some important cosmological questions," says Joy, "but we need more data that only Chandra can provide."

Joy and Carlstrom’s quest for the age of the Universe begins with a little-known phenomenon called the Sunyaev-Zeldovich Effect that causes small fluctuations in the cosmic microwave background. One of the astonishing things about the CMBR is its smoothness. When astronomers compare the intensity of the CMBR in different parts of the sky, the differences they find are all smaller than 1 part in 10^5. In 1980, the Russian physicists Sunyaev and Zeldovich suggested that tiny fluctuations in the CMBR might be found if astronomers looked in the direction of giant clusters of galaxies. Their reasoning went like this:

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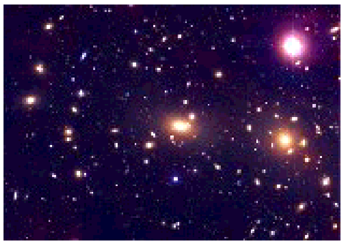
The Universe is filled with conglomerations of galaxies called clusters that are millions of light years across, consisting of hundreds or thousands of galaxies held together by gravity. Mostly clusters have atmospheres of very hot gas that we can see because of the X-rays they emit. Sunyaev and Zeldovich realized that something interesting happens when a CMBR photon passes through such a cluster. There is a good chance that it will collide with one of the electrons in the hot atmosphere. In the process, some photons would gain energy while others would lose energy. At microwave radio frequencies, they predicted, the intensity of the CMBR would appear to be depleted in the direction of the cluster because the photons would be "scattered" to other frequencies outside the microwave frequency band. This process is called the Sunyaev-Zeldovich Effect.



Left: The Coma Cluster of Galaxies is one of the densest clusters known - it contains thousands of galaxies. Almost every object in the above photograph is a galaxy. The hot atmosphere of the Coma Cluster is visible in images made at X-ray wavelengths.

The effect they predicted was very small, but also very important. Observations of Sunyaev-Zeldovich fluctuations in the CMBR could potentially determine the age of the Universe and also reveal answers to important questions about the cosmos, like "How big is it?", "How fast is it expanding?", and "Will it collapse on itself in the Big Crunch?"

To measure the age of the Universe by means of the Sunyaev-Zeldovich effect, it is necessary to have high-quality X-ray observations of a cluster’s atmosphere and corresponding radio images of the CMBR in the direction of the cluster. One without the other is just an interesting observation, but together they address some of the most important questions in science.

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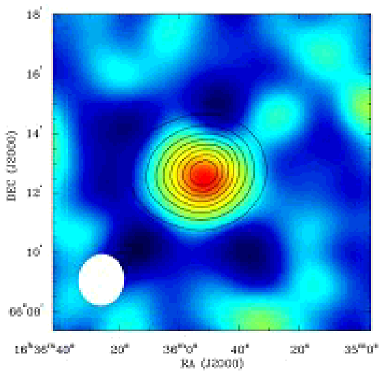
In 1992 Carlstrom, a radio astronomer, and Joy, an X-ray astronomer, decided the time was right to join forces and tackle the problem. According to Dr. Joy, "One of the key science drivers for the Chandra X-ray Observatory is the Sunyaev-Zeldovich effect. Chandra has the collecting area and the sensitivity to high energy X-rays to make high quality images of the hot cluster atmospheres. If we could get radio maps of the same clusters and measure the size of the Sunyaev-Zeldovich effect, we could begin to do some interesting cosmology."

Left: The Berkeley-Illinois-Maryland Interferometer at Hat Creek, Calif. (Links to 720x481-pixel, 186K JPG.) The Owens Valley Millimeter Interferometer, located near Bishop, CA, is pictured in the graphic near the top of this story. Another image of the Owens Valley array may be viewed here.

Carlstrom and Joy have since been granted months of observing time at two radio observatories: the Caltech Millimeter Array at the Owens Valley Radio Observatory (OVRO), and the Berkeley-Illinois-Maryland Array (BIMA) at Hat Creek, CA. Both radio telescopes are "synthesis interferometers," which means that they are able to make images at radio wavelengths much like familiar optical photographs. The BIMA and OVRO arrays were designed to work at radio wavelengths around 3 millimeters, but Carlstrom and Joy expected the Sunyaev-Zeldovich effect to be greatest at a longer wavelength, around 1cm. "We had to build our own receivers for 1 cm" explained Dr. Joy. "Because the S-Z effect is so small everything has to work well, the receivers need to be very stable and low noise, and we are constantly making improvements to increase our sensitivity. The millimeter arrays are really ideal for this work because at 1 cm their fields of view are large enough to include the entire cluster, and the surface accuracy of the antennas is very high."

So far Carlstrom, Joy and their collaborators have detected Sunyaev-Zeldovich fluctuations around 27 clusters of galaxies. Typically, the deficit in the CMBR is only 0.05% of the cosmic microwave background intensity. Detecting these small perturbations requires lots of observing time and painstaking data reduction. A sample of their data is pictured right, where an X-ray image and radio map of the galaxy cluster A2218 are superimposed.



The Sunyaev-Zeldovich effect around cluster Abell 2218. Click to view a larger image.

Right: The image shows a map of the sky around the galaxy cluster Abell 2218. The contours are 28.5 GHz radio data obtained by Carlstrom et al using the BIMA interferometer. They represent levels of constant *negative* intensity where there is a deficit of CMBR photons caused by the Sunyaev-Zeldovich effect. The colored areas are X-ray emission from hot gas imaged by the ROSAT PSPC instrument. The radio hole is deepest where the emission from the hot gas is most intense.

Life, the Universe, and Everything

Radio images of Sunyaev-Zeldovich holes are one piece of a great cosmological puzzle. To complete the picture Joy and Carlstrom need X-ray data from the Chandra X-ray Observatory. "X-ray emission depends on the cluster gas density, and so does the SZED effect, but the dependence is not the same," explains Dr. Joy. "Doubling the density of the cluster gas will simply double the size of the Sunyaev-Zeldovich effect, but it will roughly *quadruple* the X-ray emission." The differing sensitivity of x-rays and radio waves to gas density means that scientists can measure the size and mass of a cluster by combining x-ray and radio images.

By measuring the size of a galaxy cluster, astronomers can directly estimate the age of the Universe. Suppose that Sunyaev-Zeldovich measurements show the cluster to be 5 million light years in diameter, and the cluster subtends an angle in the sky of 0.03 degrees. The cluster must then be 10 billion light years away to appear so small. Once the distance to the cluster is known, the next step is to measure the *recession velocity* of galaxies inside the cluster. Galaxies throughout the cosmos appear to be moving away from us because the whole universe is expanding -- that's the basic idea behind Big Bang cosmology. The doppler shift of spectral lines in starlight reveals how fast a galaxy is receding. Once the recession velocity and the distance of a galaxy are known it is straightforward to calculate the Hubble Constant (see the sidebar). The reciprocal of the Hubble Constant (i.e., "1" divided by "H") is the approximate age of the universe.

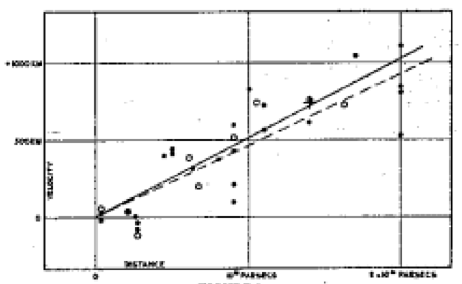


FIGURE 1

Above: Hubble's original data showing that galaxies recede faster the further away they are. The slope of the line in the plot is called the Hubble Constant. Click for a larger image.

The Hubble Constant

In 1929 the astronomer Edwin Hubble announced his discovery that galaxies everywhere appeared to be moving away from us. The further the galaxy was from Earth, the faster it was receding. Hubble's discovery was the beginning of Big Bang cosmology, which postulates that the entire universe is expanding due to an explosion around 12 billion years ago. No matter where you are in the cosmos, the rest of the universe appears to be receding, faster and faster as you peer further and further away.

The Hubble constant is a number that relates the distance of an object, like a galaxy, to it's recession velocity. It can be stated as a simple mathematical expression, $H = v/d$, where v is the galaxy's radial outward velocity (in other words, motion along our line-of-sight), d is the galaxy's distance from Earth, and H is the Hubble Constant. The Big Bang theory says that 1/H is the approximate time elapsed since the Big Bang explosion, or in other words 'the age of the Universe.'

Unfortunately obtaining the correct value for H is complicated. Astronomers need two measurements. First, spectroscopic observations reveal the doppler shift of a galaxy's spectral lines which, in turn, gives its radial velocity. The second measurement, the most difficult value

Joy and Carlstrom plan to combine X-ray data from Chandra with their existing radio images to estimate the absolute distances to a number of galaxy clusters. By combining their distance measurements with optical redshift data they can calculate the Hubble constant for each cluster.

"There are various systematic errors in Sunyaev-Zeldovich estimates of Hubble's constant. But if we're careful, we can arrive at a new value for the age of the Universe that's truly independent of values obtained by other means," said Marshall Joy.

to determine, is the galaxy's precise distance from Earth. Astronomers try to use various 'standard candles' such as variables stars and supernovae to estimate distances, but different methods give different answers. Current estimates for the value of the Hubble Constant range from 50 to 100 km/s/Mpc (the units are "kilometers per second per megaparsec"). Proponents of the Sunyaev-Zeldovich effect note that it can be used to measure the distance to galaxies in a way that is independent of all previous methods, and thus give a new measurement of the Hubble Constant.

Weighty Questions

"We can also use Sunyaev-Zeldovich measurements to draw some conclusions about the total mass in the Universe," said John Carlstrom.

One of the great questions in cosmology is "how much does the Universe weigh?" If the Universe contains too much mass, then it will eventually stop expanding, reverse directions, and collapse under the force of its own gravity. That's called the Big Crunch. On the other hand, if the mass density of the cosmos is below a certain critical value, the current expansion will go on forever. No one is sure what will happen because scientists haven't found a reliable way to total up all the mass in the cosmos.

The most massive objects in the Universe are the huge clusters of galaxies that Joy and Carlstrom are studying. There are three components that make up the mass in these clusters: the galaxies themselves, the gaseous cluster atmospheres, and "dark matter." Dark matter is mass that we can't see. It doesn't give off light, like stars, but we know it's there because it affects the motions of stars and galaxies. It is thought that the gas in clusters outweighs the galaxies by a large margin, and that the dark matter outweighs the gas by more still.

"It's only by accounting for all three -- the galaxies, the gas, and the dark matter -- that we can get a handle on the cosmological mass density," explained Dr. Joy. "And the Sunyaev-Zeldovich effect offers a new way to total up the gas component. What we're measuring is actually the gas pressure inside the clusters, from which we can derive the gas mass without too much difficulty. By invoking nucleosynthesis calculations and primordial abundance measurements, we can infer the baryon fraction and place constraints on the critical density of Universe."

Carlstrom and Joy have already been granted time on the new X-ray observatory to image clusters where they've detected the Sunyaev-Zeldovich effect. "We're optimistic", said John Carlstrom anticipating the launch of Chandra later this year, "because we'll be getting real answers to some of the most important questions in cosmology."