Chandra Probes Deeper into the Mystery of the X-Ray Background FREE

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the sign of the permeability changes when the wave's frequency crosses the SRR resonance. Another method for tailoring μ_{eff} that is being explored by Pendry and his colleagues is a spiral or "Swiss roll" structure.

The UCSD team built a two-dimensional periodic array of SRRs (photo, page 17) and measured its transmission spectrum (see figure at right) with the magnetic field oriented along the resonator axis. The spectrum revealed a notch, or stop band, in the vicinity of the SRR resonance. Although simulations showed that the notch was due to negative μ_{eff} in that frequency range, the experimental transmission spectrum by itself cannot establish whether such a stop band is indeed due to negative μ_{eff} or arises from negative ε_{eff}.

To verify that the stop band is due to crossing a resonance in μ_{eff}, the experimenters combined the SRR array with an array of wires—a medium known to have negative ε_{eff} at these frequencies[2] and, therefore, a stop band covering the entire range of the figure at right. If the observed SRR stop band were due to negative ε_{eff}, the negative contribution of the wire array to ε_{eff} would only increase the stop band. Instead, the intercalated arrays, with **H** along the resonator axis and **E** parallel to the wires, showed a transmission window. This window must therefore correspond to the spectral region where both ε_{eff} and μ_{eff} are negative.

"Left-handed" material

In a medium with ε_{eff} and μ_{eff} both negative, the index of refraction is real and radiation can propagate. But that's not the end of the story. Over 30 years ago—when no material with simultaneously negative ε and μ was known—Victor Veselago (Lebedev Physics Institute, Moscow) realized that such a medium should give rise to several peculiar properties.[4]

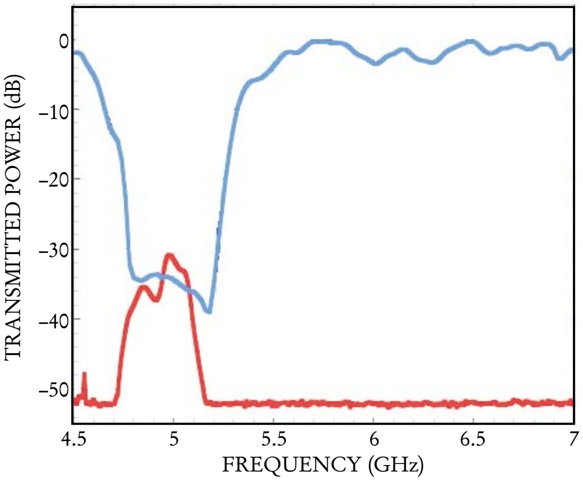
The cross product of **E** and **H** for a plane wave in regular media gives the direction of propagation and of energy flow; in a medium with negative ε and μ, $\mathbf{E} \times \mathbf{H}$ for a plane wave still gives the direction of energy flow, but the wave itself (that is, the phase velocity) propagates in the opposite direction. Veselago therefore termed such a medium "left handed." As one immediate consequence of this behavior, because the group velocity is in the same direction as the energy flow, a pulse traveling to the right in a left-handed material can be decomposed into plane waves traveling to the left.

Snell's law gets a twist, too, with left-handed media: When a wave in a right-handed material hits an interface with a left-handed medium, it will have a *negative* angle of refraction—the refracted wave will be on the same side of the normal as the incident wave. In other words, the index of refraction, as used in Snell's law, is negative, too, with left-handed media. Thus, lenses of left-handed material will behave oppositely from their right-handed counterparts: Convex lenses will be diverging and concave lenses converging.

The Doppler and Čerenkov effects will also be reversed in a left-handed medium: An approaching source will appear to radiate at a lower frequency, and charged particles moving faster than the speed of light in the medium will radiate in a backward cone, not a forward cone.

Although these counterintuitive properties follow directly from Maxwell's equations—which still hold in these unusual materials—they have yet to be demonstrated experimentally. That's a high priority of the UCSD researchers. Part of that work will be making the medium more isotropic: Currently it is only left-handed for one direction and one polarization of propagation. Also, the demonstration of negative μ has only been done at microwave frequencies. "It will be a challenge to get to the optical," says Schultz, "and the important step right now is for us to get a better understanding of all the implications of negative ε and negative μ and the dependencies on the material and geometrical properties."

Richard Fitzgerald



Transmission spectra of the split-ring resonator array by itself (blue) and combined with an array of thin wires (red). The resonators by themselves produce a stop band in the vicinity of 5 GHz, which corresponds to the region where the effective permeability μ_{eff} is negative. The wire array alone produces an effective permittivity ε_{eff} that is negative below the array's 12 GHz plasma frequency. When the arrays are combined, microwaves are transmitted in a pass band near 5 GHz where *both* μ and ε are negative. (Adapted from ref. 1.)

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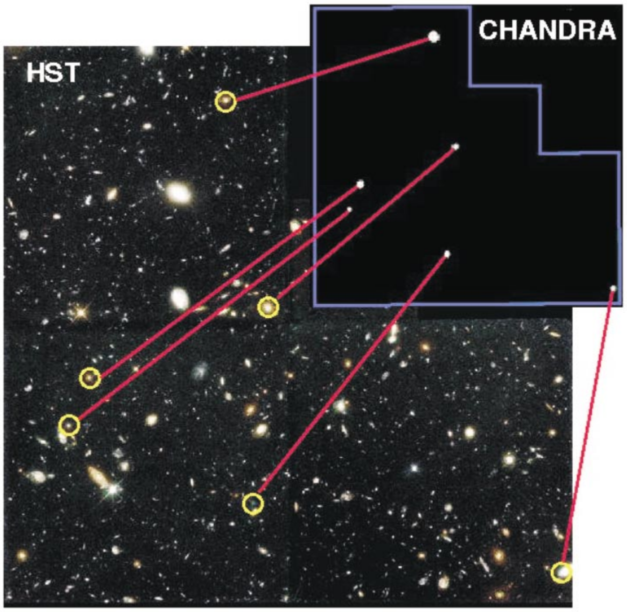
Chandra Probes Deeper into the Mystery of the X-Ray Background

Thanks to its superb sensitivity, angular resolution, and positional accuracy, NASA's Chandra x-ray observatory has detected nearly all the individual sources that collectively make up the cosmic x-ray background.

One minute before midnight on 18 June 1962, an Aerobee rocket was launched from White Sands Missile Range in New Mexico. Packed into its nose cone were three Geiger counters, which Riccardo Giacconi, Herbert Gursky, Frank Paolini, and Bruno Rossi hoped would detect solar x rays fluorescing off the moon. But when the four researchers analyzed the data, they instead found something more remarkable: x rays from a point source in the constellation of Scorpio and a background signal from the sky.



SOURCES DETECTED BY CHANDRA in the northern Hubble Deep Field are identified with circles in the main image. The smaller image shows the (smoothed) Chandra image itself. (Adapted from ref. 2.)

Thus, a 10-minute rocket flight gave birth to cosmic x-ray astronomy, and the first cosmic background radiation was discovered.

That first observation yielded only the mean flux of the x-ray background (XRB). Now, after nearly 40 years of effort, the XRB in the 0.5–10 keV energy range has been almost completely resolved. That is, the combined flux of the distant individual sources that Chandra detects in the "blank" sky constitutes 70–80% of the mean sky flux.

Historical background

Despite being seen first, the XRB remained mysterious for much longer than its more illustrious sibling, the cosmic microwave background, whose discovery, announced two years later, was accompanied by a ready-made explanation and garnered Nobel Prizes for Arno Penzias and Robert Wilson.

The first big clue about the XRB's origin came in 1970, when Uhuru, the first x-ray satellite observatory, found that the XRB looked the same in all directions. Because the Milky Way is so anisotropic in shape, the Uhuru result implied that the XRB originates outside the Galaxy. Launched four years later, Ariel V discovered that active galactic nuclei (AGN) are bright point sources of x rays. Putting the two findings together, Giancarlo Setti and Lodewijk Woltjer proposed in 1973 that the background is made up of the combined emissions from a multitude of distant AGN.

Measured with 1970s technology, the spectrum of the x-ray background does resemble that of AGN. But in 1980, the improved spectral resolution and sensitivity of the HEAO-1 mission produced a surprise: Frank Marshall and his colleagues found that the background spectrum could be explained by thermal bremsstrahlung from diffuse gas at a temperature of 500 million kelvin. Though other models could conceivably fit the HEAO-1 data, Marshall's result spawned the notion that hot gas pervading the universe—not the combined emissions from innumerable point sources—was responsible for the XRB. That red herring was ultimately dispensed with in 1994, when COBE's exquisitely sensitive observations of the microwave background failed to find the blueshift expected when cold photons encounter hot gas.

To identify what sort of point sources make up the XRB requires an imaging detector. The first fully imaging x-ray telescope was launched in 1978 on board HEAO-1's successor, the Einstein Observatory. Peering deeply at source-free regions of the sky, Einstein could resolve only 25% of the XRB. However, by analyzing how the blank-sky flux varied from one Einstein field to another, Tom Hamilton and David Helfand demonstrated that the XRB was so smooth that at least 3000 sources contributed to the emission in each square-degree patch of sky. Standard quasars, they proved, are not numerous enough to account for the XRB.

The next big XRB breakthrough came from the ROSAT satellite, which in 1995 and 1996 made very long observations of an area of blank sky known as the Lockman hole. Guenter Hasinger and his colleagues who analyzed the Lockman data were able to resolve 70–80% of the background and to make optical identifications of the individual sources, which turned out to be mostly AGN with relatively little intrinsic absorption. Had ROSAT solved the XRB? Yes, but only partly. ROSAT's two detectors, the PSPC and HRI, covered the soft part of the x-ray band, 0.1–2.5 keV. Because the spectrum of the ROSAT sources falls off more steeply with energy than does the XRB's, the ROSAT sources cannot account for the hard XRB.

While they waited for Chandra to provide the right combination of pass band and angular resolution to resolve the hard XRB, astrophysicists continued on a different tack. By concocting model backgrounds from populations of synthetic sources, they tried to re-create the observed properties of the XRB, such as the mean spectral shape and sky brightness. Given the soft spectrum of the ROSAT sources, matching the overall 0.5–10 keV spectrum requires a population of sources whose spectra are harder than the mean XRB. One way to harden the spectrum of an AGN is through photoelectric absorption, which preferentially removes soft photons. The model builders, therefore, proposed that the hard XRB was made up of obscured sources, such as the Seyfert II galaxies, whose x-ray spectra had been characterized by EXOSAT and subsequent missions.

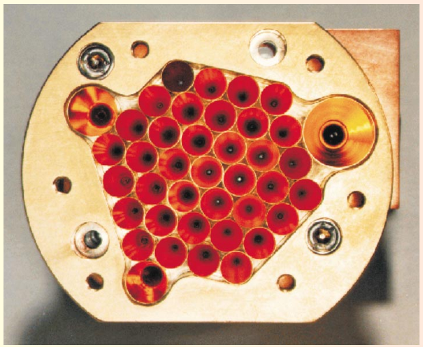
Obscured by clouds

Not only did such a scheme nicely bridge the soft and hard x-ray bands, but it also jibed with the so-called unified model of AGNs, which holds that much of the rich diversity of AGN types—blazars, quasars, Seyfert Is and IIs, BL Lac objects, and the like—arises principally from viewing from different angles the same basic object: a galaxy that contains a central accreting black hole surrounded by a bagel-shaped region of absorbent gas and dust. Look through the side of the bagel, and the source will appear as a heavily obscured Seyfert II galaxy. Look directly down the bagel's hole and you'll see an unobscured Seyfert I galaxy.

So, before Chandra's launch last year, astrophysicists anticipated using Chandra's superb optics and detectors to hunt down the obscured AGN that they thought would make up the XRB in the 2–10 keV range. Several groups have been hard at work analyzing long Chandra observations of blank sky, but first into print was a team consisting of Richard Mushotzky and Keith Arnaud from NASA's Goddard Space Flight Center and Len Cowie and Amy Barger from the University of Hawaii.[1] As their target, they picked a field known as SSA13, which had already been surveyed by the 10-m Keck telescope on Mauna Kea, Hawaii. In the 100 × 100 arcminute Chandra field, they found a total of 37 x-ray sources, some predominantly soft, others hard. Combined,

SCUBA, Star Formation, and the X-Ray Background

When x rays hit dust particles, their energy is absorbed and re-radiated in the infrared. If the sources that make up the hard x-ray background are shrouded by gas and dust, then one way to find them is to search for observational evidence of warm dust. At redshifts greater than one, that means looking in the submillimeter band.



ROYAL OBSERVATORY EDINBURGH PHOTOLABS

The most efficient way to map the sky in the submillimeter waveband is to use the Submillimetre Common-User Bolometer Array (SCUBA; see figure), which has been installed at the James Clerk Maxwell Telescope on Mauna Kea since 1997. Two years ago, a team led by the University of Hawaii's Amy Barger used SCUBA to discover a new population of highly obscured, highly luminous sources that appear to be distant analogs of the ultraluminous, infrared-emitting galaxies (ULIRGs). Because the ULIRGs are hotbeds of star formation, the same could be true of the SCUBA galaxies. But there's an alternative interpretation. The SCUBA galaxies could be AGN whose central black holes are deeply embedded inside a cocoon of gas and dust that allows only hard x rays to escape—just the kind of source that could account for the hard XRB.

Whether the SCUBA sources are obscured AGN or galaxies in the throes of vigorous star formation can be determined by looking in the hard x-ray band. Star-forming regions emit x rays—largely from supernovae from previous generations of stars—but far less copiously than a typical AGN, which is powered by accretion into a black hole.

Despite their theoretical attraction as a major source of the XRB, SCUBA sources have turned out to be rather feeble x ray sources. Of the ten most securely identified SCUBA sources in the northern Hubble Deep Field, not one has been detected by the Penn State team in its Chandra data.[2] Says Penn State's Ann Hornschemeier: "Either these submillimeter sources are powered by star formation, or, if they're AGN, the x-ray source is deeply buried or weak." Moreover, in a forthcoming paper in the *Monthly Notices of the Royal Astronomical Society*, Andy Fabian (University of Cambridge) and his coworkers show that the emission from one source that is detected in both SCUBA and Chandra bears the spectral signature of star formation, rather than accretion into a black hole. Says Barger, "It's possible that the XRB is made up of relatively nearby relatively weak systems. The intrinsic power of these systems is too low to heat up enough dust to be detected in SCUBA."

the fluxes of the sources make up at least 75% of the mean background flux.

As expected, when the Goddard–Hawaii team matched Chandra and Keck sources, they found a handful of soft x-ray-emitting AGN of the sort found by ROSAT. They also expected to see lots of narrow emission line galaxies, which are the optical counterparts of highly obscured Seyfert IIs. Instead, the data contained two surprises.

The first surprise was that nine of the 37 sources turned out to be bright (by the sensitive standards of Keck) galaxies at moderate redshifts that show none of the classic spectral signs of activity in their optical spectra. Such underactive AGN had been seen before, but weren't thought of as common. "But there they were," recounts Mushotzky, "the largest class of identified objects that contribute to the x-ray background!"

The second surprise was bigger. Twenty-seven of the Chandra sources—73% of the total—correspond to a previously unknown group of optically ultrafaint objects. The sources are so dim that even the mighty Keck has trouble accumulating usable spectra for them. Identifying these weak sources will be very difficult, especially because it's not clear that they even form a homogeneous group. They could be the high-redshift counterparts of the brighter galaxies, but that's difficult to confirm without redshifts, which are hard to obtain for such faint sources. To find out more about these enigmatic sources, Barger and her colleagues are observing the SSA13 field in the radio and submillimeter bands (with SCUBA; see adjacent box).

Analyzing a different Chandra field—one centered on the famous northern Hubble Deep Field—Penn State's Gordon Garmire, Niel Brandt, and their coworkers have also resolved about 70% of the XRB—maybe more[2] (see figure on page 19). Their follow-up spectroscopy with the Hobby–Eberly telescope has revealed a mixed bag of sources. Says Brandt: "We're not seeing large numbers of the dead-obvious Seyfert II galaxies. Instead, we've found a complex mixture of moderately obscured things of many different types."

One of the XRB's original discoverers, Giacconi, is also busy analyzing Chandra XRB data—from a patch of sky dubbed Chandra Deep Field South. He and his coworkers have already discovered 120 x-ray sources, of which they have studied about a quarter spectroscopically. Most of the sample has been observed in long exposures with the European Southern Observatory's Very Large Telescope, and all but a tenth seem too dim to be detected.

Although the mystery of the XRB has not been solved, Giacconi is far from despondent: "When I started off, the first source I looked at had a flux of 10^{-7} erg cm^{-2} s^{-1}. Now I'm looking at sources at 10^{-16} erg cm^{-2} s^{-1}. Nine orders of magnitude fainter within my scientific lifetime—that's not so bad!"

Charles Day

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Have Heavy Ion Collisions at CERN Reached the Quark–Gluon Plasma?

As the torch passes to RHIC, the heavy-ion program at CERN takes stock of six years of Pb-beam results.

With Brookhaven's Relativistic Heavy Ion Collider (RHIC) about to begin its experimental program and CERN's heavy-ion program winding down at the venerable Super Proton Synchrotron (SPS), a celebratory day of talks at CERN was convoked in February to summarize six years of investigating nuclear matter *in extremis* at the SPS with a relativistic beam of lead ions.[1] Much of the discussion that day revolved around the