

with the Kamland results. A typical fit of this kind, carried out by John Bahcall (Institute for Advanced Study) and coworkers,² is shown in the lower figure on page 15. “The Kamland results decisively shrink the allowed range of the solar-neutrino parameters,” says Bahcall. “And they limit a possible sterile component to less than 9%.”

The Kamland result is also good evidence that antineutrinos and neutrinos share the same oscillation parameters, as required by fundamental theory. But the theory does allow the neutrino mixing matrix to include a complex phase that might engender a subtle neutrino–antineutrino asymmetry (leptonic *CP* violation) strong enough to explain the upsetting of the matter–antimatter balance in the early cosmos. (See the article by Helen Quinn in *PHYSICS TODAY*, February 2003, page 30.) The triumph of the LMA solution raises the prospect that future long-baseline neutrino experiments may find evidence for leptonic *CP* violation.

The MSW effect

For neutrinos coming from the solar core, the LMA solution implies that vacuum oscillation on the journey to Earth plays second fiddle to an irreversible

flavor change that takes place in high-density regions of the Sun: the Mikheyev-Smirnov-Wolfenstein (MSW) effect. If vacuum oscillation with a λ very much shorter than our distance from the Sun were the dominant process, the energy dependence of the solar-neutrino shortfall would be almost completely washed out. But that’s not the case; the solar-neutrino detectors do see a clear energy dependence.

Because of its association with the electron, a ν_e passing through matter feels an extra interaction energy, proportional to the ambient electron density, beyond the matter-interaction energy common to all the neutrino flavors. In 1986, Stanislav Mikheyev and Alexei Smirnov at the Institute for Nuclear Research in Moscow, using a formalism developed by Lincoln Wolfenstein (Carnegie Mellon University), pointed out that this extra energy term should produce a flavor metamorphosis when a ν_e produced in the core passes through a critical-electron-density region of the Sun. The critical density, and thus the distance from the core at which it’s encountered, depends on the neutrino’s energy. When the neutrino finally emerges from the Sun it is, to good approximation, in a coherent superposition of flavor states

that constitutes a mass eigenstate. A pure mass eigenstate would experience no vacuum oscillation on the rest of the journey to Earth. There is now good evidence that this mass eigenstate, the heavier of the two whose splitting is given by Δm^2 , is roughly an equal superposition of all three neutrino flavors. The MSW mechanism was originally invoked to explain how a *small* mixing angle might cause a large solar-neutrino shortfall.

“I’m sometimes asked whether our first Kamland result is a discovery or just a confirmation of what we already believed,” says Giorgio Gratta (Stanford University), the US contingent’s other spokesman. “I like to compare it to the first creation of spectral lines in the laboratory in the 19th century. Fraunhofer had already found lines in the solar spectrum. But until they were also made on Earth, one couldn’t be sure that they were more than just something that happened only in stars.” **Bertram Schwarzschild**

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X-ray Observations Deepen Mystery of What Happens in the Cores of Galaxy Clusters

Simple physics says huge amounts of gas in cluster cores should cool and collapse. Simple physics is wrong—but why?

A cluster of galaxies looks different at optical and x-ray wavelengths. In the optical band, you see the galaxies themselves—typically about a hundred—in orbit about the cluster’s center of mass. In x rays, you can still see the biggest galaxies, but the smaller ones are lost against a bright background of diffuse plasma that fills intracluster space.

The plasma is a byproduct of cluster formation. In the early universe, vast volumes of dark matter and baryons collapsed under their own gravity to form infant clusters. Following the collapse, most of the baryonic matter ended up as shock-heated plasma. The rest, about a fifth, formed galaxies. Unreactive even with itself, the dark matter presumably lay idle, but it has always dominated the clusters’ gravitational potential. And the gravitational potential, through virialization, is what has heated the plasma in clusters to temperatures of 10^7 K and higher.

The plasma radiates in the x-ray band through a combination of thermal bremsstrahlung and collisionally excited line emission. Both processes depend strongly on density, which, thanks to gravity, is highest in the cluster cores. In 1977–78, three pairs of astronomers independently realized that the plasma in some cluster cores loses so much energy through radiation that it should cool rapidly.¹ Unable to match the pressure of the outer layers, the cooling plasma would slump inward. The phenomenon became known as a cooling flow.

Flow motion

Not all clusters have strongly peaked x-ray emission and, by inference, cooling flows. But analysis of x-ray images in the 1970s and later suggested that, in some clusters, hundreds of solar masses of plasma cool every year. What happened to the cooling plasma? Stars form in cold clouds of gas, so astronomers looked in the cen-

tral regions of clusters for pools of cold material and enhanced star formation. They found some, but not enough by an order of magnitude, to match the cooling plasma’s inferred mass.

Meanwhile, astronomers tried to catch intracluster plasma in the act of cooling by measuring its x-ray spectrum. As in the rest of the universe, hydrogen and helium make up all but a few percent of intracluster plasma, but other elements are present, too. Among the admixtures, iron is an especially good thermometer. Its series of L lines ranges in wavelength from the lithium-like Fe XXIV at 10.6 Å to the neon-like Fe XVII at 16.8 Å. If intracluster plasma were cooling, its spectrum would bristle with emission lines, each indicating a particular temperature range.

Unfortunately, the L lines are closely spaced. The spectrometers aboard such missions as ROSAT (1990–99) and ASCA (1993–2001) couldn’t exploit the lines’ diagnostic power, nor, through other temperature diagnostics, could they find the cooling plasma.

NASA’s Chandra mission, which

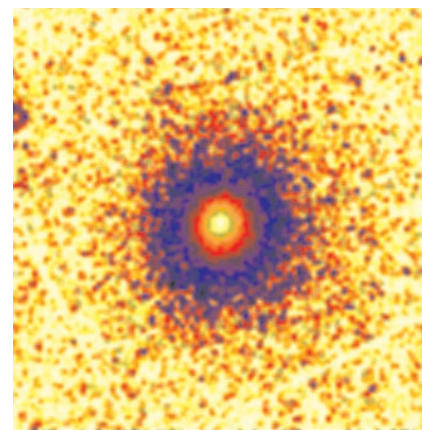
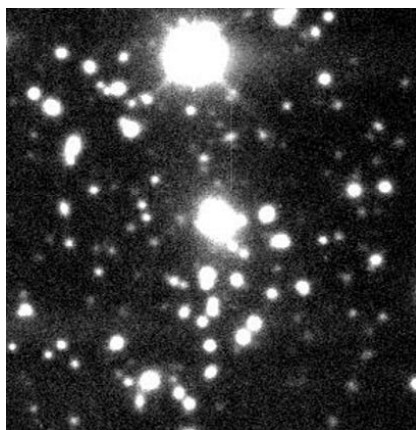
was launched in July 1999, carries a grating spectrometer that can resolve iron L lines. Gratings separate photons of different energies by dispersing them: The longer the wavelength, the bigger the dispersion angle. But for extended sources, like the cores of nearby clusters, photons of the same energy are also dispersed simply because they originate from different places on the source.

Untangling the two sources of dispersion is a challenge for Chandra's grating. It's far less of a problem for the grating spectrometer on board the European Space Agency's XMM-Newton mission. Launched five months after Chandra, XMM-Newton complements Chandra's strengths. Chandra has the sharper vision, but XMM-Newton, at the expense of lower acuity, collects more photons. In that tradeoff lies the reason why XMM-Newton can easily resolve cooling-flow L lines. To compensate for its blurrier vision, XMM-Newton's grating spectrometer disperses photons by much wider angles than Chandra's. For the 1-arcminute cores of nearby clusters, dispersion by energy greatly exceeds dispersion by extent.

When XMM-Newton observed a cooling-flow cluster, Abell 1835, for the first time, it discovered the unexpected: A large amount of plasma—around 1000 solar masses per year—is indeed cooling, but only as far as a third of its starting temperature. That's still x-ray hot.

Astronomers are notorious for explaining away anomalous results by inventing new subclasses of objects. But that escape route has been blocked by a new study about to appear in the *Astrophysical Journal*.² In that paper, Columbia University's John Peterson, Steven Kahn, and Frits Paerels and their collaborators from the Netherlands' National Institute for Space Research (SRON) and the University of California, Berkeley present the results of analyzing the x-ray spectra of 14 clusters whose inferred cooling flows range in magnitude up to 1000 solar masses per year.

The bottom figure on this page shows one example, that of a cluster called 2A 0335+096. The blue line represents a model spectrum and indicates what XMM-Newton's grating spectrometer would see if the plasma in the cluster's central regions cooled radiatively all the way down to a notional 0 K. The red line represents the same model, but with the cooling plasma's final temperature adjusted to fit the data. In this best-fitting model, the iron L lines from the lowest temperatures are weak or absent.



Galaxy clusters, as revealed by the optical image of Abell 1068 on the left, contain galaxies orbiting in the cluster potential. The XMM-Newton x-ray image of Abell 1835 on the right shows the sharply peaked brightness profile of the hot intracluster medium. (Left image courtesy of Brian McNamara of Ohio State University; right image courtesy of John Peterson.)

Evidently, large amounts of gas aren't cooling completely.

Death of the cool

The results from the other clusters tell the same story: Something stops most of the plasma from cooling beyond about one-third of the initial temperature. What could be the culprit? The explanations, all of which have strengths and weaknesses, fall into three basic categories: conduction, mixing, and heating.

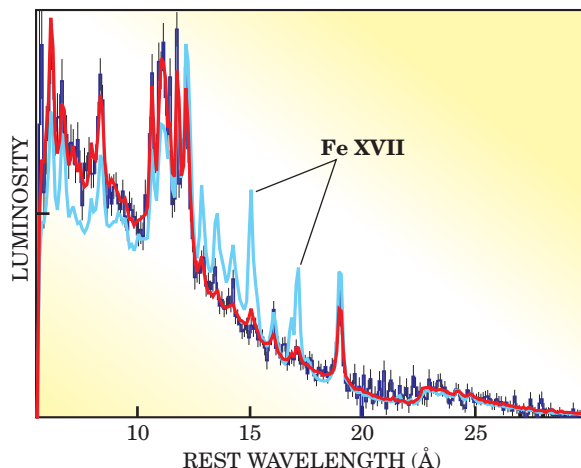
The conduction explanation seeks to prevent cooling in cluster cores by bringing in heat from the hotter surroundings. In 1956, Lyman Spitzer worked out that thermal conduction in a magnetized plasma could proceed efficiently provided the thermal gradient lined up with the magnetic field. Perpendicular to the field, ions and electrons orbit in tight spirals. The configuration of the magnetic fields that pervade intracluster plasma is hard to measure, but it's unlikely to be neat and radial. A conduction-frus-

trating tangle is more likely.

But in 2001, Ramesh Narayan of Harvard University and Mikhail Medvedev of the University of Toronto proposed a way to boost conduction.³ If the plasma is turbulent, then a property of chaotic systems—Lyapunov scaling—could, reasoned Narayan and Medvedev, raise the direction-averaged conduction to as much as one-fifth of the field-aligned value.

But the conduction explanation faces problems. Chandra's high-resolution images of several clusters reveal sharp features of differing temperatures within the plasma. Conduction, if universally effective, would wipe out temperature gradients. Moreover, conduction plummets as the temperature decreases. Heat could be efficiently conducted to the outer regions of a cooling flow, but not to its cooler inner parts.

Like the conduction explanation, the mixing explanation doesn't rely on a new heat source. Rather, mixing supplants radiative cooling with a cooling



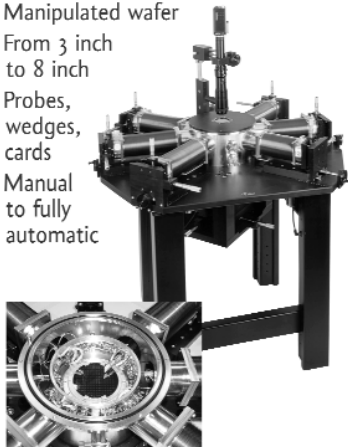
The XMM-Newton spectrum (black) of the central region of the cluster 2A 0335+096. The blue line shows what one would expect to see if the gas cooled much further than its initial temperature of 3.7×10^7 K. The red line represents a model in which the plasma cools only by a factor of one-third. (Courtesy of John Peterson.)

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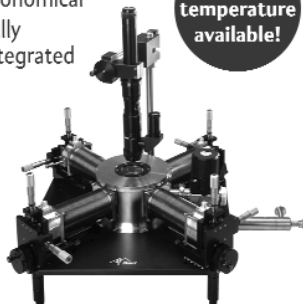
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mechanism that, being nonradiative, doesn't show up in a spectrum. In a mixing model proposed by Andrew Fabian of Cambridge University and his collaborators, small metal-enriched clouds float in the otherwise uniform plasma. Thanks to their copious line emission, such clouds cool quickly and, like ice cubes in a gin and tonic, cool the warmer fluid surrounding them.⁴ Observations don't rule this explanation out, but they don't rule it in, either. Whether metal-enriched clouds exist is not clear.

The heating explanation relies on the observation that at the heart of nearly all cooling flow clusters lies a big elliptical galaxy. And fully 70% of those galaxies harbor an active galactic nucleus (AGN). AGNs shoot huge jets of relativistic plasma into their surroundings. Could the jets be responsible for arresting cooling flows?

Chandra observations appear at first glance to support this idea. Vast bubbles of evacuated plasma, presumably created by AGN jets, have been found in the inner regions of some clusters.⁵ The energy required to inflate the bubbles is close to what's needed to halt a cooling flow, but, as with the other explanations, there are problems. Spectral analysis of the Chandra images reveals that the bubbles are wrapped in gas that's colder, not hotter, than the surroundings. Moreover, jets inject energy anisotropically. Somehow, in plasma prone to thermal instabilities, the energy must end up uniformly distributed.

New theories

Paul Dirac believed he understood an equation when he could predict the properties of its solutions—even without solving it. Is it possible to foresee a successful denouement to the cooling-flow mystery?

The arrested cooling flows observed so far have a substantial range of ini-

tial temperatures and luminosities, yet they all stop cooling at what seems to be a constant half to one third of the initial temperature. That feature smells of a universal feedback mechanism.

One such mechanism involves AGN heating. Imagine an AGN at the center of a cluster. Material from a full-blown cooling flow accretes onto the AGN's central black hole, which uses the energy to propel jets into the surrounding plasma. The jets halt the cooling flow and cut off the AGN's fuel source. Starved of fuel, the jets wither, the cooling flow resumes, and the cycle continues.

Of course, this picture suffers the same defects as generic AGN heating, but it might be made to work by incorporating extra features. Mateusz Ruszkowski and Mitchell Begelman of the University of Colorado in Boulder have recently added conduction to an AGN feedback model.⁶ Their 1-D simulations appear to stave off thermal instabilities and can mimic observed density profiles.

Ironically, the XMM-Newton results may have made one aspect of cooling flows less of a puzzle. The spectral fits don't exclude plasma cooling all the way down in amounts that match the observed star formation.

Charles Day

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Laser Technique Follows Turbulent Flow in Three Dimensions

A simple equation, the Navier-Stokes, completely describes a fluid's flow. A single parameter, the Reynolds number, flags a flow as smooth or turbulent. But a true understanding of turbulence—one that would furnish accurate predictions of a hurricane's path or a car's drag—remains out of reach.

Studying small-scale eddies could bring that goal closer. Tornadoes and breaking waves look different from afar, but their kinetic energy ends up

Making movies of stirred-up beads illuminates the baffling problem of turbulence.

in the same sort of localized viscous heating. If, as fluid dynamicists suspect, small-scale eddies behave in a universal way before they dissipate, it might be possible to build up reliable predictions of large-scale behavior.

But even if one explored the smallest scales, one property of turbulence