

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.

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.

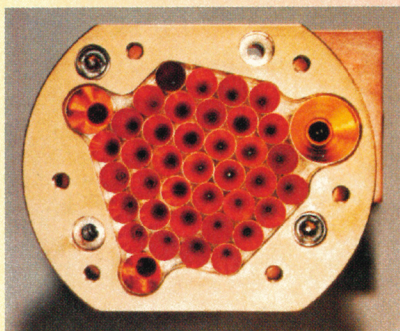
Whether the SCUBA sources are obscured AGN or galaxies in the throes of vigorous star formation can be determined by looking in the hard x-ray band. Star-forming regions emit x rays—largely from supernovae from previous generations of stars—but far less copiously than a typical AGN, which is powered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



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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 more² (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!"

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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

question of whether or not the CERN experiments had achieved fleeting visits to the quark-gluon plasma—the promised land envisioned by quantum chromodynamics. QCD is the standard field theory of nuclear matter in terms of its quark constituents and the gluons that bind them.

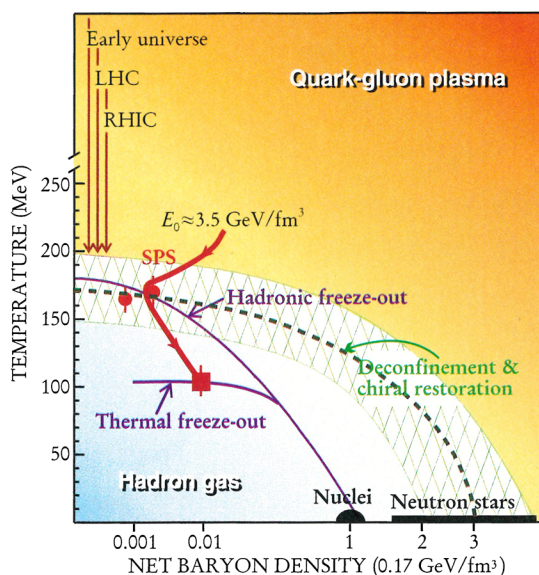
Press reports notwithstanding, the international community of relativistic heavy-ion theorists and experimenters has not yet reached consensus on this central issue. QCD predicts a phase transition to the quark-gluon plasma at a critical boundary on the phase diagram of nuclear matter. (See the figure at right.) At sufficiently high temperature and/or *net* baryon density in a violent collision between large nuclei, the quarks that had been rigorously confined in individual hadron “bags” (3 quarks to a proton or neutron bag) are predicted to break free to roam unconfined over the extended nuclear volume. (Net baryon density means baryon minus antibaryon density, or 3 times the density of quarks minus antiquarks.)

But the location of the critical boundary in the phase diagram and the detailed character of the deconfining transition are not well determined. They have to be wrested from a theory notorious for its calculational difficulty. The quark-gluon plasma is thought to have been the state of the cosmos before it cooled down enough for individual nucleons to make their appearance a few microseconds after the Big Bang.

It is clear that the CERN Pb-beam experiments, carried out by seven large international collaborations, have excited nuclear matter to unprecedentedly high energy densities, and that the data have exhibited an impressive variety of striking effects predicted for quark-gluon matter. But more than a few of the *cognoscenti* on both sides of the Atlantic argue that an unambiguous demonstration of the quark-gluon plasma will have to wait for the RHIC data.

Relativistic Pb nuclei

It's not that RHIC will have heavier ions or higher beam energies than the SPS. The heavy-ion injector installed in 1994 lets the SPS accelerate fully stripped ions as heavy as Pb to energies of 158 GeV per nucleon. That comes to 33 TeV for Pb, whose atomic mass number $A = 207$. RHIC will accelerate ionic species as heavy as gold ($A = 197$) to 100 GeV/A. (See



PHASE DIAGRAM of nuclear matter, showing the critical boundary (dashed, with uncertainty crosshatched) between a gas of ordinary hadrons and a plasma of gluons and deconfined quarks. Net baryon density is in units of cold nuclear baryon density, and arrows indicate its value in the early cosmos and at future colliders. The red curve indicates the estimated initial energy density and subsequent cooling in head-on Pb-Pb collisions at CERN.

PHYSICS TODAY, October 1999, page 20.) But whereas the target nuclei at the SPS reside in stationary metal foils, RHIC is a heavy-ion *collider*. Countercirculating beams of gold nuclei will collide with a center-of-mass energy of almost 40 TeV.

That's an order of magnitude greater than the useful (center-of-mass) collision energy one gets with stationary targets at the SPS. Collision at RHIC should generate significantly higher temperatures and energy densities, comfortably beyond the theoretically still fuzzy phase-transition region. Furthermore, because the thermal radiation from a hot source grows like the fourth power of its temperature, the RHIC experiments should demonstrate much clearer direct evidence of such radiation from a quark-gluon plasma.

Why wasn't the SPS, with its proud history as a proton-antiproton collider, used as a heavy-ion collider? It's because countercirculating proton and antiproton beams, having opposite charges, could share the SPS's single ring of bending magnets; but all the heavy ions, alas, are positively charged. RHIC, with two separate magnet rings, will also have the considerable advantage of being a dedi-

cated heavy-ion machine, with state-of-the-art detectors designed explicitly for that purpose. The SPS heavy-ion program was limited by having to share time and facilities with CERN's elementary-particle programs.

Almost all the experimental results summarized at the February CERN symposium were already well known. The most recent results had largely been reported at the Quark Matter 99 conference in Italy last May.² But, CERN director general Luciano Maiani told his February symposium audience, combining all the results of the seven experiments “has given a clear picture of a new state of matter.” This new state “featu-

res many of the characteristics of the theoretically predicted quark-gluon plasma,” said CERN theorist Ulrich Heinz in his overview talk. But he cautioned that all the evidence accumulated thus far is “indirect.” That is to say, it comes from particles that have suffered “significant reinteractions between the early collision stages and their final observation.”

Last year at Quark Matter 99, introductory speaker Jean-Paul Blaizot (Saclay) was even more circumspect. “We are not yet in a position to offer outsiders compelling evidence that quark-gluon plasma has been produced,” he said. “Calculating its properties turns out to be a difficult task. Thus we have, so far, no unique signature.”²

Charmonium suppressed

Among the most striking experimental hints at the appearance of a quark-gluon plasma in the CERN Pb-beam experiments has been the suppression of J/ψ production in Pb-Pb collisions, relative to what one would expect from straightforward extrapolation of data from lighter-ion and proton-proton collisions. The J/ψ “charmonium” meson, more than 3 times as massive as the proton, is a bound state of the charmed quark and its antiquark. Its much heralded discovery in 1974 was the first sighting of a heavy quark.

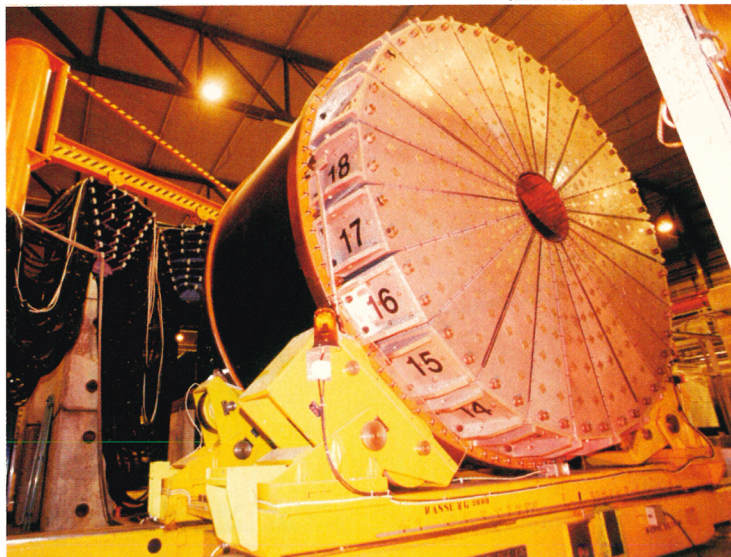
Because it's so massive, the J/ψ would be produced mostly in the earliest and thus hottest moments of the fireball engendered by the collision. Therefore it should serve as a good probe of the fireball's history. Since 1986, theorists have been pointing out that a quark-gluon plasma should manifest itself by its anomalously low

J/ψ yield. The quark-gluon plasma, they argued, would screen the confining quark-antiquark potential, much as an ordinary plasma can subvert the formation of neutral atoms by Coulomb screening.

At the February symposium, Louis Kluberg (Ecole Polytechnique) summarized the strong evidence, from SPS experiment NA50 and its predecessor, for such J/ψ suppression. The degree of suppression increases strikingly with the masses of the colliding ions and with the "centrality" of the collision. The centrality (or conversely, the impact parameter) of a collision is estimated from the number of charged particles it produces and from the amount of "transverse energy" they deposit in detector elements at large angles to the beam direction. A really head-on Pb-Pb collision at the SPS produces several thousand charged pions.

One expects J/ψ suppression and other manifestations of the quark-gluon plasma to be most prominent in the central phase-space region of collision products, where longitudinal (beam-direction) velocities relative to the center of mass are smallest. At SPS and RHIC energies, two heavy ions colliding head-on are surprisingly transparent to each other. They are, of course, fragmented by their encounter, but the two fragment bundles depart the scene in roughly the same directions (in the center-of-mass frame) with which the nuclei came in. But they leave behind much of the collision energy in the excited central vacuum region, now largely devoid of the incident baryons. This hot vacuum boils off myriad quark-antiquark pairs that ultimately manifest themselves as particles with small longitudinal velocities in the center of mass.

One can estimate the initial energy density and temperature of this central region by examining the longitudinal and transverse energy distributions of the emerging particles. As indicated by the red curve in the phase diagram, calorimetric measurements by the NA49 collaboration suggest that the central region in head-on Pb-Pb collisions starts out with an energy density of about 3.5 GeV/fm^3 . (See the photo above.) That's 20 times the normal energy density (0.17



ELECTROMAGNETIC AND HADRON calorimeter at the downstream end of the NA49 collaboration's target and general-purpose hadron detector at CERN's SPS accelerator ring. The high-energy beam of Pb nuclei passes on horizontally through the hole in the center of the 3-meter-diameter calorimeter. This array of scintillators sandwiched between Fe and Pb layers is segmented radially and azimuthally to measure the transverse-energy distribution of heavy-ion collision products.

GeV/fm^3) of cold nuclear matter. To the extent that the fireball approximates thermal equilibrium, this record energy density corresponds to a temperature of about 230 MeV. Then, as the fireball expands and cools, it is presumed to recross the critical boundary back to the domain of ordinary hadrons and finally to a "thermal freeze-out" temperature of about 100 MeV, where the departing hadrons suffer their last collisions.

A temperature of 230 MeV is somewhat above the range of transition-temperature estimates arrived at by numerical lattice gauge calculations for vanishing baryon density. But these prodigious feats of number crunching require the simplifying assumption that the three different light quarks (up, down, and strange) are all massless. In the real world, however, the mass of the strange quark is uncomfortably close to the estimated transition temperature. One cannot easily rule out the possibility that the Pb-Pb results, thus far, are simply manifestations of ordinary hadronic matter at extraordinary energy densities. "To eliminate the possibility that the observed J/ψ suppression might just be a kinematic

effect," says Brookhaven theorist Larry McLerran, "you really should look at how the suppression varies with beam energy. RHIC will be able to do that, but it would be difficult for the NA50 detector."

More strangeness

Accompanying the J/ψ suppression in the SPS experiments was an equally striking increase in the fraction of strange particles—mostly K mesons—among the collision products. These results, summarized at the symposium by Reinhard Stock of the NA49 experiment and Emanuele Quercigh of the WA97/NA57 collaboration, are also taken to be evidence of a quark-gluon plasma. Above the critical temperature at small net baryon density, one would expect the hot vacuum to create up, down, and strange quark-antiquark pairs in roughly equal numbers. The result would be a much higher ratio of kaons to pions than one sees produced in high-energy collisions of protons or light nuclei. An even more sensitive manifestation of the unwonted abundance of strange quarks was the particularly strong population enhancement of baryons with two or three strange quarks—the hyperons Ξ and Ω .

The kaon and hyperon enhancements appear to be manifestations of something more general: a statistical distribution of hadron types frozen out (at about 180 MeV) from a thermal equilibrium population of unconfined quarks and antiquarks created in a very hot vacuum, with little regard for the quark flavors in the parent ions. But the case is not airtight. Similar population distributions, except for the strangeness enhancement, have also been able to describe electron-positron collision data. And, as McLerran points out, experiments at Fermilab have shown significant strangeness enhancement in proton-antiproton collisions that produce unusually large numbers of particles.

The CERN experiments have been perfecting techniques to measure the size and expansion speed of the fireball. Applying a pionic variant of Hanbury Brown-Twiss stellar interferometry introduced by Gerson Goldhaber and coworkers at Berkeley in 1962, the SPS groups have measured the

The Quantum Hall Effect—in Pentacene?

Organic materials have long held promise as possible inexpensive semiconductors in field-effect transistors (FETs) for electronic circuits. No one, however, had dreamed that one might use them to create a two-dimensional gas of electrons or holes and with it to study fundamental electronic behavior. Thus, Bertram Batlogg of Bell Laboratories, Lucent Technologies, stunned an audience at the March Meeting of the American Physical Society in Minneapolis by showing textbook curves of the fractional and integer quantum Hall effects and of an apparent metal-insulator transition—all seen in FETs made with tetracene and pentacene (chains of four and five benzene rings, respectively).

To make these measurements, Batlogg, J. Hendrik Schön, Steffen Berg, and Christian Kloc (all of Bell Labs) created their FETs by growing very pure single crystals of tetracene and pentacene, covering them with insulating layers and adding gates atop the insulator. A source and drain were connected to either end of each crystal. When a positive (negative) voltage was applied to the gate in one of these FETs, electrons (holes) were attracted to the interface between the crystal and the insulator. The resulting charge layer had all the hallmarks of the two-dimensional electron (or hole) gases known to form in silicon or gallium arsenide devices traditionally used to study such phenomena as the quantum Hall effect.

To manifest the quantum Hall effect or the metal-insulator transition, the charges in a sample must have a sufficiently high mobility, a measure of the ease with which charges can move through the material. That means the organic crystals must be as free as possible of impurities that scatter or trap the charges. At temperatures of 1–2 K, the Bell Labs FETs had mobilities as high as $100\,000\text{ cm}^2/(\text{V}\cdot\text{s})$ for holes, as good or better than most inorganic devices.

At room temperatures, Batlogg said, the Bell Labs crystals had mobilities better than those reported so far for tetracene and pentacene, either in bulk or thin-film form. Because the crystal mobilities are high for both electrons and holes, the Bell researchers reported in February¹ on the potential of these devices as ambipolar field-effect transistors, which can be switched from hole-based to electron-based by reversing the polarity of the gate voltage. A practical device would have to be made from pentacene thin films, and Batlogg told us that their pentacene thin films perform at room temperature almost as well their bulk crystals.

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size of the fireball's volume at thermal freeze-out by examining how the bosonic correlation of final-state pions decreases with increasing distance in momentum space. That's important for estimating the fireball's energy density. The volume, in the SPS experiments, turns out to be comparable to that of a Pb nucleus. And from the transverse-momentum distributions of final-state particles of different masses, the experimenters conclude that the fireball is expanding at more than half the speed of light.

Chiral restoration

The lattice gauge calculations suggest that another phase transition—the restoration of chiral symmetry—should occur simultaneously with the deconfinement transition. In the approximation that all the quarks are massless, the QCD Lagrangian is perfectly symmetrical between left- and right-handed fermion couplings. (*Chiros* is Greek for hand.) In the vacuum ground state, this symmetry is spontaneously broken. Some QCD calculations predict that one manifestation of chiral symmetry restoration in a

quark-gluon plasma should be a temperature dependence of the mass of the ρ vector-meson resonance that would severely broaden the observed resonance. And indeed, the sharp ρ resonance one would ordinarily see in the invariant-mass spectrum of emerging e^+e^- pairs is smeared out almost to invisibility in the Pb-Pb runs at the SPS. But once again there's an alternative explanation: One could argue that it's just ordinary collision broadening in a very dense hadronic medium.

"There is no question that all these exciting observations constitute a quantum jump in our understanding of matter at extremely high temperatures and densities," Heinz summarized. "But the evidence is not yet enough to prove, beyond reasonable doubt, the creation of a quark-gluon plasma."

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