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X RAYS FROM THE REST OF THE UNIVERSE

X-ray sources in space are serving more and more as valuable laboratories for astrophysics, nuclear physics, relativity, plasma physics and cosmology.

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Just as x rays from a cathode-ray tube in Wilhelm Röntgen's laboratory revealed the bones in his wife's hand, x rays from space have revealed new objects and physical processes hidden from the view of optical telescopes. X rays from beyond Earth's atmosphere were first detected in 1949 in a 5-minute V-2 rocket observation of the Sun.[1] Thirteen years later, the first nocturnal rocket flight quite unexpectedly discovered the existence of a diffuse isotropic glow of 10-kilo-electron-volt x rays across the celestial sphere, as well as the first discrete source of x-ray emission from beyond the Solar System.[2] By 1965 the number of known sources of celestial x rays totaled 10; at this writing the number exceeds 10^5.

Neutron stars were detected in the x-ray band five years before the discovery of radio pulsars. The diffuse x-ray background was discovered two years before the first detection of the cosmic microwave background, and major discoveries about the hottest and most violent places in the universe have followed regularly ever since. The ubiquity of x-ray-emitting stellar coronae, the 10^6–10^7-kelvin component of the interstellar medium and the 10^8-K gas that pervades galaxy clusters were all high-energy surprises. Even the basic energy sources for the x-ray and optical emitters we detect are different: The visible universe is dominated by objects that derive their energy from nuclear reactions, whereas most objects detected in the x-ray regime are powered by gravity, magnetic fields or kinetic energy.

In this brief review it is not possible to cover all of the discoveries of the past three decades and to describe their importance in other areas of physics. Nor am I able to provide a detailed history of the discipline or an inventory of the innovative instrumentation that physicists and astronomers have developed to advance our observational capabilities.[3] Instead, I have selected for discussion four fundamental contributions to our understanding of the universe that exemplify the new branch of astronomy occasioned by Wilhelm Röntgen's discovery.

Black holes exist

Although the original notion of a *corps obscurs* is generally attributed to Pierre Simon, marquis de Laplace, who described it as a body with a gravitational force "so large that light could not flow out of it," an English rector named John Michell published the first (Newtonian) description of this phenomenon in 1784. In the second of two papers on general relativity that he wrote in 1915, Karl Schwarzschild demonstrated that the surface of any object within a radius of $R_s = 2GM/c^2$ has an infinite redshift; J. Robert Oppenheimer and Hartland Snyder later suggested that such an object could form as the result of the collapse of the core of a massive star. John Wheeler coined the term "black hole" in 1968.

One of the most significant accomplishments of x-ray astronomy is the experimental confirmation that black holes exist beyond the confines of theorists' imaginations. The extremely rapid variability discovered in 1964 in the double-star system Cyg X-1 requires that the emitting region be less than about 1 light millisecond (300 kilometers) across; otherwise, incoherent variations from different parts of the source would wash out the fluctuations. The enormous energy radiated by the system (roughly 10^5 times that of the Sun), coupled with its small size, require that a massive, compact object be involved and that gravity be the ultimate power source; nuclear and electromagnetic sources could not maintain this luminosity in a stable configuration for decades—let alone the 10^4–10^5-year lifetime expected for the system.

We know of three stable configurations for objects of stellar mass: normal stars, balanced in hydrostatic equilibrium between gravity and thermal pressure; white dwarfs, in which gravity is balanced by electron degeneracy pressure; and neutron stars, held up by neutron degeneracy pressure. Finally, in black holes, gravity wins.

In the 1930s Subrahmanyan Chandrasekar showed that the maximum stable mass for a white dwarf is 1.4 times the mass of the Sun, $M_\odot$. While the comparable maximum value for a neutron-star mass is less well defined owing to uncertainties in the equation of state for matter at supranuclear densities, an absolute upper limit of about 3.5 $M_\odot$ can be determined assuming only that general relativity is correct, the star is stable and the speed of sound in the star is less than c. The 14 neutron stars with well-determined masses are consistent with this limit, clustering between 1.3 and 1.8 $M_\odot$. Thus, by process of elimination, any compact object exceeding 3.5-$M_\odot$ must be a black hole.

The mass determination for a double star depends only on the observable quantities P, the double-star system's orbital period, and v_1, the radial velocity of one of the stars determined from Doppler shifts of atomic lines in its optical spectrum. The mass function, then, is given by

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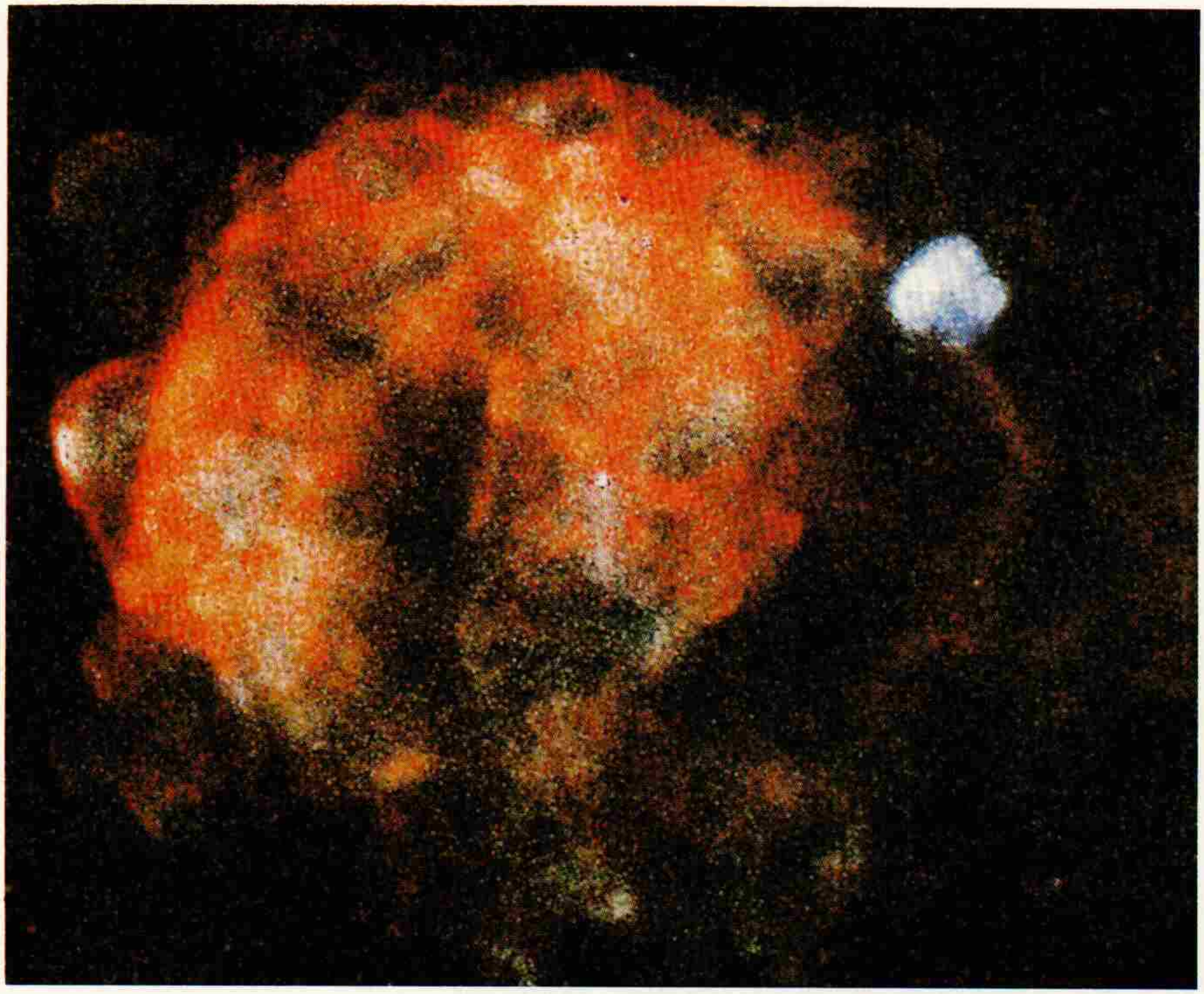


ROSAT image in the 0.1–2-keV band spanning 10° of the southern sky. Colors (red to blue) represent x-ray temperatures (low to high) for the emitting diffuse plasma. The nearby 10 000-year-old Vela supernova remnant dominates the image, with the younger Puppis A remnant visible in the upper right. (Courtesy of Bernd Aschenbach, Max Planck Institute for Extraterrestrial Physics, Garching.) FIGURE 1

$$f(M_1, M_2, i) \equiv \frac{Pv_1^3}{2\pi G} = \frac{(M_2 \sin i)^3}{(M_1 + M_2)^2}$$

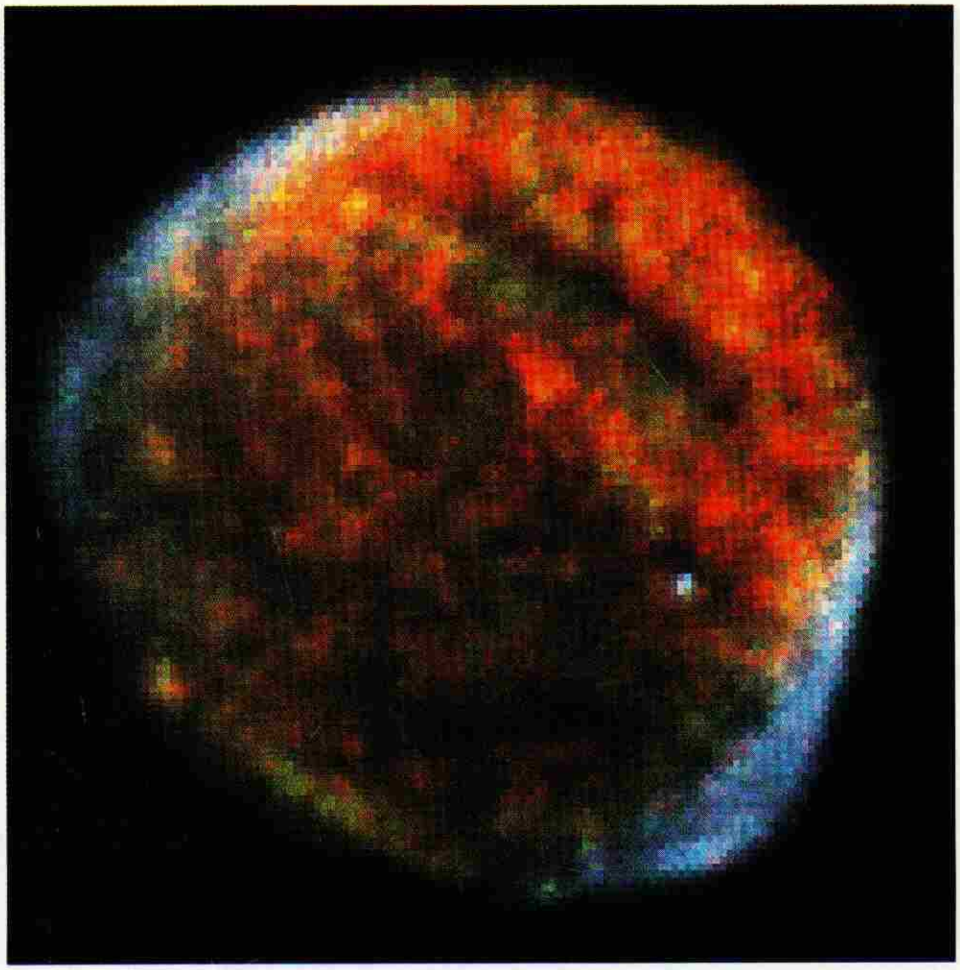
where M_1 and M_2 are the masses of the two stars and i is the inclination of the plane of the orbit with respect to the line of sight.

For Cyg X-1, P is 5.6 days and v_1 is ± 75 km/s. The mass of its companion, however, is not well determined; normal stars of this type have masses of 20 $M_\odot$, although values as small as about 8 $M_\odot$ are possible given the uncertainties in the observed distance and luminosity. The lack of x-ray eclipses allows one to combine the stellar radius and orbital semimajor axis to constrain the angle i and thus set a lower limit on the x-ray-emitting companion of at least 3.4 $M_\odot$, far above the measured values for neutron-star masses and right at the upper limit for such stars imposed by causality.

For a decade Cyg X-1 remained the most convincing black hole candidate. This single example, while fully consistent with the black-hole interpretation, was insufficient to convince skeptics, because special circumstances can always be invoked to explain away one such object. Over the last 10 years, however, several more examples have been found, and the case for the existence of stellar-mass black holes is now overwhelming. Three of the brightest x-ray double stars in our neighboring galaxy, the Large Magellanic Cloud, have inferred masses[4] considerably in excess of 3 $M_\odot$.

More important, a new class of black-hole double stars has been found among the so-called soft-x-ray transients. These objects flare suddenly, often becoming for a few weeks the brightest objects in the x-ray sky, and then fade by up to eight orders of magnitude on a time scale of several months. In quiescence it becomes clear that the normal-star components in these systems are low-mass stars, allowing unambiguous lower limits to be established for their unseen companions. The record holder is the 1992 transient V404 Cygni, whose minimum mass is 6.3 $M_\odot$, far above the neutron-star upper limit.[5] In another system, which flared in 1994, periodic eclipses of the normal companion star have recently been detected, allowing its black-hole mass of 4.6 $M_\odot$ to be determined[6] to an accuracy of 15 percent.

REMNANT OF THE SUPERNOVA of 1006 AD, imaged by ROSAT. Spectral analysis indicates that the blue edges are dominated by synchrotron radiation while the interior is dominated by a thermal plasma. The color scale represents mean x-ray photon energy from low (red) to high (blue). (From reference 11.) **FIGURE 2**



Gravitational accretion of matter onto such compact objects is an extremely efficient energy source, generating about 10% of mc^2 for any matter accreted. Thus, accretion is a natural process to exploit in attempting to explain the prodigious sources of energy emanating from the cores of so-called active galaxies, which produce luminosities exceeding 10^{14} times that of a normal star in a volume less than that enclosed by Jupiter's orbit about the Sun. The detection of large fluctuations in x-ray intensity on the time scale of an hour in these sources sets stringent limits on the parameters of the central engines. Black-hole masses in the range of 10^6–10^9 $M_\odot$ are implied. Recent optical and radio observations have provided dynamical evidence for such massive compact objects in several relatively nearby galaxies by viewing the orbital motion of gas within a few light years of the galaxy centers (see PHYSICS TODAY, August 1994, page 17, and March 1995, page 9).

Dramatic confirmation that, in at least one case, this central object must be relativistic was reported this year by Yasuo Tanaka and his coworkers based on an x-ray spectrum obtained with the Japanese–US satellite ASCA.[7] Using the satellite's CCD imaging spectrometers to observe the active galaxy MCG-6-30-15, Tanaka's Japanese–British collaboration has detected the 6.4-keV iron K_α emission line from the inner edge of the disk of swirling matter only 3–10 Schwarzschild radii from the black hole itself. The line is Doppler broadened by a remarkable 100 000 km/s and redshifted by a combination of transverse Doppler and gravitational redshift effects. These data provide the strongest evidence to date for the existence of supermassive black holes. In addition they allow the researchers to derive the structure of the innermost regions of the hole's accretion disk—a major step forward in understanding active galactic nuclei. Future observations of the time delay between fluctuations in the continuum and line intensities may make possible the direct determination of both the black hole's mass and its rotation rate.

Thus, astrophysicists now discuss the mass and angular momentum distributions of black holes, study their environments and construct evolutionary models, just as for any other astronomical entity. The profound question of the existence of black holes, much in evidence at the birth of x-ray astronomy, has been answered resoundingly in the affirmative.

Equation of state for cold nuclear matter

The detection of thermal photons from a stellar surface serves as our principal window on the properties of a normal star: Its radius, surface gravity, chemical composition, magnetic field strength and other physical attributes are derivable from the measured flux and spectrum. In neutron stars we expect rather extreme conditions to prevail in the atmosphere, which has a scale height of only about one centimeter. Surface magnetic fields can exceed 10^{12} gauss; the surface gravitational redshift is more than 10%; and the composition may be pure iron. These attributes, while interesting in their own right, complicate our primary quest of using whatever photons from the surface we can detect to determine directly the radius of a neutron star, and, in the process, provide an important constraint on the equation of state for nuclear matter. In the 1930s Oppenheimer and George Michael Volkoff calculated an expected radius of about 10 km for a neutron star of mass about 1 $M_\odot$. Modern calculations using various equation-of-state assumptions predict radii

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of 7–17 km for a 1.4 $M_\odot$ star.[8]

Measurement of a 10-km radius at a distance of at least 10^{15} km is a daunting experimental problem, especially when even the basic composition of the body in question is uncertain. If the neutron star's material remains fermionic to the center, the neutrons are expected to exist as a superfluid. However, the formation of a Bose–Einstein condensate of pions or kaons in the inner core cannot be excluded, because, for soft equations of state, densities greater than three times that of normal nuclei could be reached. Even a phase transition to pure quark matter, expected to occur at 5–10 times nuclear matter density, may be possible in stars of slightly higher mass.

The degree of our experimental ignorance is perhaps best illustrated by the fact that we have no idea even of the sign of the mass–radius relationship for neutron stars: For fermionic matter the radius is inversely proportional to mass, while for kaon-dominated stellar cores the proportionality is direct. In essence the very name "neutron star" may be a misnomer; "strange star" or "quark star" might be a more accurate description. The observational determination of even a single neutron star's radius, then, would help enormously to constrain the properties of bulk nuclear matter in the high-density, low-temperature portion of its phase diagram, complementing the lower density, high-temperature domain to be probed by the Relativistic Heavy Ion Collider under construction at Brookhaven National Laboratory.

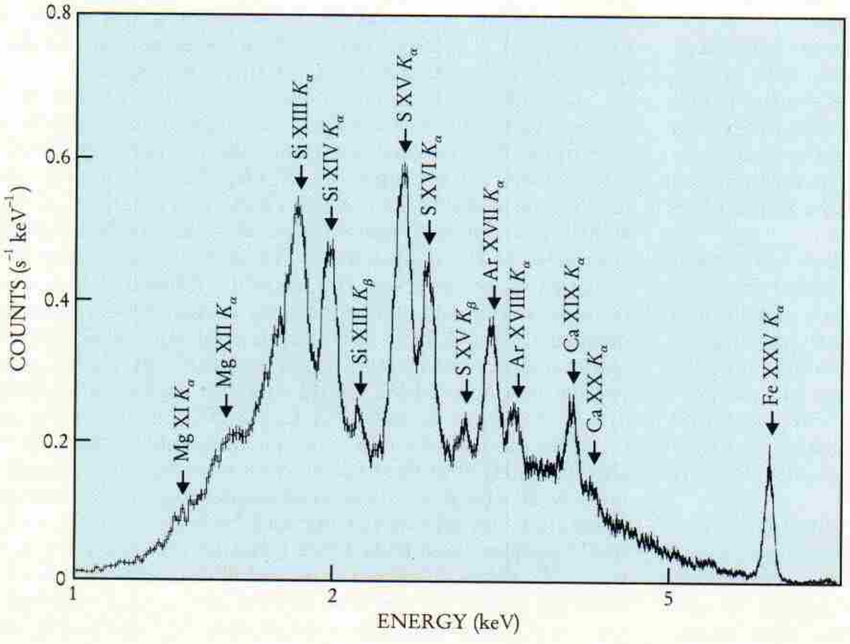
X-ray astronomy has provided several possible approaches to measuring fundamental neutron-star parameters in addition to the masses derived for those in double-star systems. Following the thermonuclear explosion that we witness as an x-ray burst, the star's surface cools and, in principle, we could obtain a direct radius measurement by simple application of the Stefan–Boltzmann law for luminosity, $L = 4\pi R^2 \sigma T^4$, assuming that the radiation is blackbody, the temperature T can be determined from the x-ray spectrum, and the distance is established using the optical counterpart. In practice it has been difficult to disentangle uncertainties in radiative transfer effects in the exploding atmosphere whose structure after the flash is not well understood. The spectra of other accreting systems, however, have yielded one important confirmation of our standard picture: Cyclotron lines at energies of tens of keV have been detected in several objects, showing directly that surface magnetic fields in the range of 10^{11}–10^{13} gauss are present.

Isolated neutron stars, discovered primarily as radio pulsars, offer alternative approaches. For example, the cooling rate of a hot, young neutron star is primarily dependent at early times on the neutrino emissivity of the stellar core, which, in turn, is a strong function of the core's composition. Bose–Einstein condensates, for example, enhance neutrino emissivity, leading to more rapid early cooling. Quantitative constraints have been hampered, however, by the small number of young pulsars known, the complication that several of them also display nonthermal, beamed x-ray emission from their magnetospheres, and uncertainties in distance and interstellar absorption. The radii derived from the Stefan–Boltzmann law in some older stars are far smaller than the nominal value of 10 km, probably indicating that we are seeing hot spots on the surface heated by magnetospheric discharges rather than a uniform-temperature blackbody. The extreme chemical and magnetic properties of the surface also distort the observed spectrum from a pure blackbody form, further complicating the measurement.

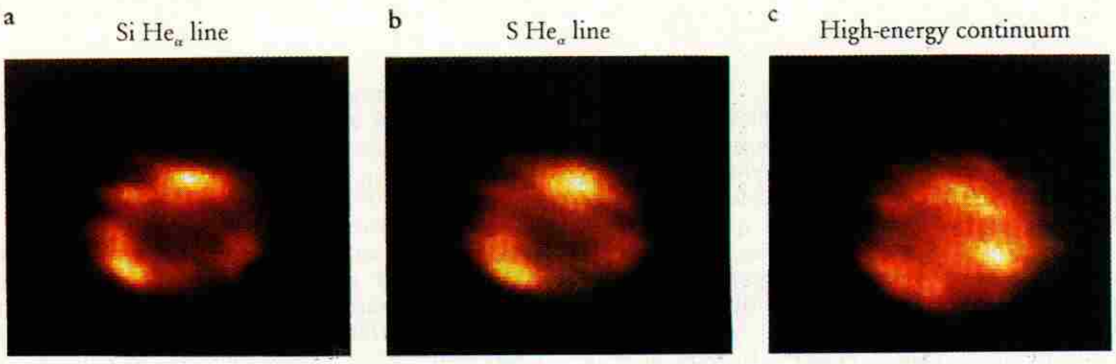
Recently my colleagues and I demonstrated a new technique for measuring a star's radius by detecting the effects of gravitational light bending near the stellar surface on pulsed emission from a hot magnetic polar cap on a nearby pulsar.[9] The result, $R = 9 \pm 3$ km, is comforting but insufficiently precise to provide a serious constraint on the equation of state. Higher-sensitivity measurements with future instruments could well yield an answer to an accuracy of ±10%. It is likely that in the next decade substantial progress will be made in applying several of these x-ray techniques to determining the properties of these macroscopic laboratories for nuclear physics.

Quantitative tests of stellar nucleosynthesis

With the exception of the three lightest elements—hydrogen, helium and lithium—all of the natural atomic nuclei in the universe were synthesized in stars. This realiza-



SPECTRUM of the young Milky Way supernova remnant W49, as measured by the CCD camera on the Advanced Satellite for Cosmology and Astronomy. (Adapted from reference 18.) **FIGURE 3**



YOUNGEST SUPERNOVA REMNANT known in the Milky Way. These three images of Cas A were taken with the ASCA satellite's CCD detector. The high spectral resolution of the instrument allows images to be constructed in individual atomic lines, giving clues to the star's nucleosynthetic history and the dynamics of the explosion. **a:** The remnant in the light of the helium-like silicon 2–1 transition. **b:** The helium-like sulfur 2–1 transition. **c:** A high-energy continuum band. (From reference 14.) **FIGURE 4**

tion, less than 40 years old, has enabled us to construct detailed models of the chemical evolution of the universe by calculating isotopic yields from both the normal chain of fusion reactions that powers the stars and the explosive nucleosynthesis that accompanies their demise. Most of the observational constraints on chemical-evolution models, however, are rather indirect. They include abundance patterns in different stellar populations in our own and other galaxies, cosmic-ray abundances, and optical spectra of distant supernovae.

These abundance measurements either sample the integral over billions of years of stellar evolution or measure trace amounts of freshly synthesized matter from individual exploded stars. Ideally, we would like to assay in quantitative detail the chemical composition of all the ejected material from many recent supernovae to inform models both for presupernova evolution and for the event itself.

Imaging x-ray spectroscopy is making this process possible. A supernova remnant displays a complex density and temperature structure in a plasma that is enriched in heavy elements and is in a state of nonequilibrium ionization. The challenge is to obtain sufficient spatially resolved spectral data on such an object that one can determine accurate abundances for the elements carbon through iron, and can set constraints on the hydrodynamics of the supernova explosion and subsequent remnant evolution.

Nearly 50 supernova remnants have been detected at x-ray wavelengths in the Milky Way, along with a like number in the Magellanic Clouds and other nearby galaxies.[10] (See figure 1.) For most, however, we have images in only one or a few broad spectral bands. Nevertheless we are able to test the general picture of hydrodynamic evolution for individual remnants and, in the case of the Large Magellanic Cloud, for the population as a whole.

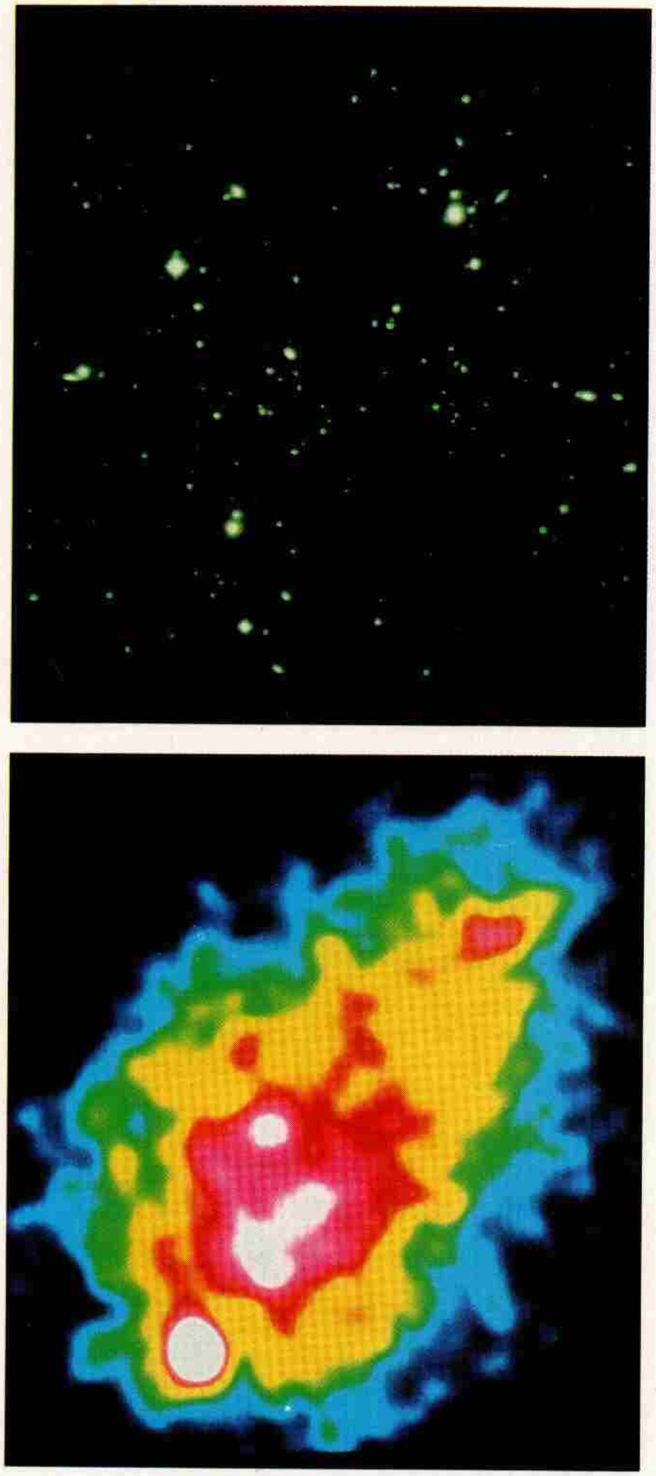
Such images also have led to the discovery of compact objects in a number of remnants; a young pulsar is either seen directly or its presence is inferred from a nonthermal synchrotron x-ray source powered by its relativistic beams. In a few cases, evidence for a synchrotron component fed by shock-accelerated electrons is beginning to emerge.[11] (See figure 2.) Future work in this area will lead to an enhanced understanding of particle acceleration in astrophysical shocks, an important process that occurs in many other types of celestial objects.

The bulk of the emission from most supernova remnants, however, is found to be thermal bremsstrahlung from the hot electrons plus line emission from highly ionized states of the most abundant elements in the remnants: oxygen, neon, magnesium, silicon, sulfur, argon, calcium and iron. For a few of the brightest remnants, Bragg crystal spectroscopy with 1-eV resolution has made possible the measurement of the relative intensity of emission lines, the detection of Doppler expansion velocities and other detailed plasma diagnostics.[12] It is with the advent of CCD imaging spectrometers and high-quantum-efficiency x-ray calorimeters, however, that we will begin to see rapid progress in this area.

A first glimpse of this progress is emerging from the observations of supernova remnants carried out with the CCD detectors on the ASCA satellite. (See figure 3.) With a spatial resolution of a few arc minutes and spectral resolution of less than 100 eV over the 0.5–10-keV band (in which the K_α and K_β lines of all the prominent atomic species lie), the full power of plasma diagnostic techniques can be brought to bear on the issues of nucleosynthesis and explosion hydrodynamics. My coworkers and I have already shown, for example, that the relative strengths of the Ne, Mg, Si, S and Fe lines in spectra of the Large Magellanic Cloud remnants can be used to distinguish whether the remnant progenitor was a massive star that underwent a gravitational core collapse or a low-mass star that exploded as a consequence of a thermonuclear detonation.[13] These two supernova types have very different nucleosynthetic yields, and a determination of the ratio between them is crucial to understanding the chemical evolution of a galaxy. Direct evidence of nonequilibrium ionization is present in many of the ASCA spectra.

In addition, it is now possible to make images of a supernova remnant in the line of a single atomic transition (see figure 4), allowing us to map the temperature distribution from, for example, the K_α/K_β ratio of an element, and to see whether or not the elements remain spatially stratified in young remnants as they are in the parent star prior to the explosion.[14] The degree of stratification provides a window on the seconds following the core collapse itself, and will enable us to test recent notions derived from the first two-dimensional and three-dimensional supernova models, which suggest that violent convective motions (which would mix the various elements) are an essential feature of a successful stellar explosion.

The quality of these new astrophysical spectra have shown clearly that the atomic codes used by x-ray astronomers to fit the x-ray data need improving. For instance, anomalous abundances of Mg and Ne inferred from early ASCA spectra were traced to a large error in the predicted Fe L_α/L_β ratio. It is not unreasonable to expect that, as with the initial discovery of helium in the solar spectrum over a century ago, the next decade of high-resolution



OPTICAL AND X-RAY IMAGES of the cluster of galaxies Abell 1367. The images span a region 6 million light-years across; the cluster is 400 million light-years away. The thermal plasma filling the intracluster space has a temperature of about 50 million K and includes more mass than is present in all the stars in all the cluster galaxies. (Upper image courtesy of Fredrick Seward and Christine Jones; lower image courtesy of Jones, Robert Stern and William Forman, Harvard-Smithsonian Center for Astrophysics.) **FIGURE 5**

x-ray spectroscopy will again see contributions to atomic physics coming from celestial observations.

Cosmology and the hot intracluster medium

The notion that dark matter—undetected material whose presence is inferred as a consequence of its gravitational influence—dominates the universe has been called the ultimate expression of the Copernican Principle: Not only do we not occupy a special place in space and time, but we, our Earth and our Sun are not even composed of the dominant form of matter in the universe. Recent limits on nucleosynthesis in the early moments of the Big Bang and evidence (not uncolored by strong theoretical prejudice) that the universe has a density Ω precisely equal to the critical density Ω_0 that divides the regimes of eternal expansion and recollapse, suggest that baryons in all forms make up only about 5% of all matter. X-ray observations of galaxy clusters, however, have lent some surprising twists to this canonical view.

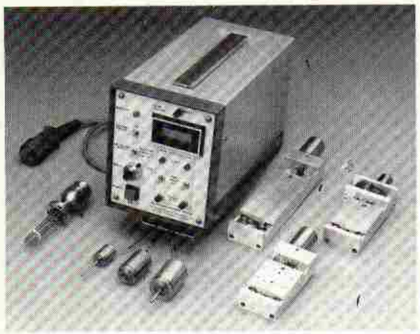
The first unexpected result came in the early 1970s, when the Uhuru x-ray observatory discovered that the dark voids between the galaxies in optical pictures of galaxy clusters were suffused with a hot intergalactic medium at a temperature of 10^8 K, roughly the virial temperature inferred from the individual galaxy velocities. (See figure 5.) In fact, it has since been shown that the total mass of this hot gas is 2–5 times that to be found in all the galaxies of a cluster combined, although it still falls short of the gravitational mass needed to keep the clusters from flying apart.

The study of the gas itself has yielded useful insights into both galaxy and cluster formation and evolution. The detection of heavy elements in the gas demonstrates that the material is not purely primordial, and provides a constraint on the early phases of galaxy evolution. The detection by ROSAT of clumps of x-ray-emitting gas in many clusters provides clues as to how galaxy clusters aggregate and consequently sets constraints on the formation of large-scale structure in the universe.

Perhaps the most surprising result in recent years is the discovery that in many clusters, 10 to 1000 $M_\odot$ per year of hot gas is cooling and condensing out in the central cluster galaxy.[15] These so-called cooling flows may prove important in understanding the formation of massive galaxies and the systems of globular star clusters that surround them.

The hot intracluster medium is also an important cosmological probe. For example, the cosmic microwave background photons Compton scatter off the hot electrons in the gas. As a consequence we observe a decrement in the microwave background temperature in the direction of a rich galaxy cluster. This process, the Sunyaev–Zeldovich effect, makes possible a direct determination of the expansion rate of the universe (the Hubble constant H_0) independent of the cosmic distance ladder and its many uncertain rungs. To date, both the quality of the microwave background data and uncertainties in the detailed temperature and density distribution in the cluster gas have limited the accuracy of the determination of H_0 to about 50%, similar to that of more traditional approaches. It is noteworthy, however, that the half-dozen measurements of this type reported in the literature all yield a best-fit value on the low side of the currently accepted range for H_0 of 45–90 km/s per million parsecs. (A lower value of H_0 corresponds to an older universe.)

A second cosmological inference from the study of intracluster gas poses a direct challenge to the standard Big Bang model. As Simon White and Carlos Frenk originally pointed out, the nearby massive cluster in Coma has nearly 30% of its total inferred mass in the form of baryons (visible galaxies and the dominant hot intracluster gas).[16] Because Big Bang nucleosynthesis calculations are constrained by the observed abundances of light ele-



ments to a total baryonic component of only 5% of Ω_0, the Coma observation indicates either that dark matter and baryons cluster differently (contrary to what is expected in standard cold-dark-matter scenarios) or that something else fundamental is wrong with the picture. Recent results have shown that this baryonic excess is a common feature of rich clusters.[17]

The most obvious solution to this problem is that the density of the universe is significantly less than the critical value; in Coma, for example, a value for Ω/Ω_0 of about 0.3 would be consistent with both primordial nucleosynthesis and the measured baryonic mass fraction in the cluster. Such a low value for Ω is in conflict with several other types of observations, however, and encounters strong theoretical objections. Other potential solutions to the problem include a mixed brew of dark matter (some of which clumps with baryons and some of which doesn't), a nonzero cosmological constant, a revision of primordial nucleosynthesis calculations (perhaps as a consequence of inhomogeneities in the Big Bang) and a revision of the estimates of x-ray gas masses. Observations in the next few years will give us a better estimate of these gas masses, thus strengthening an important constraint on all cosmological models.

The future

In concentrating on just four of the contributions x-ray astronomy has made, I have ignored large areas of dramatic discovery and conceptual advance. The fundamental insights into the magnetohydrodynamic dynamos that power the Sun and other stars, the primary laboratory that x-ray sources provide for the study of accretion, and the importance of the cosmic x-ray background in constraining the structure and evolution of the universe, are but a few of the areas in which past x-ray astronomy experiments have been critical to progress in modern astrophysics. The suite of large observatories scheduled for launch in the next five years will further enhance our ability to use cosmic x-ray sources both as basic physics laboratories and as probes of the processes that dominate the high-energy universe.

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