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Cosmic X-ray Sources: A Progress Report

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The recent discoveries of x-ray astronomy are stimulating new interest in the physics of highly condensed matter and in cosmology. Models of the evolution and structure of neutron stars can now be compared with detailed observations of their behavior as pulsars and as accretion-type x-ray sources in binary star systems. The possibility that the x-ray source Cygnus X-1 is a black hole is strongly indicated; observations of the emission properties of such a black hole can test general relativity in novel ways. In the field of cosmology the existence of intergalactic matter has been a crucial observational unknown. X-ray astronomy introduces unique possibilities for revealing the invisible mass of the universe and establishing its physical parameters.

A decade of observations with instruments carried on rockets and balloons, capped by the launching of the first small x-ray astronomy satellite (SAS-1), UHURU, has provided evidence of some 125 discrete sources (*1*). The UHURU instrumentation covers the spectral range 2 to 20 thousand electron volts. At lower and higher energies the observational evidence has been derived primarily from rockets and balloons. About 80 sources lie within 20 degrees of the galactic plane and most likely exist within the galactic disk; the remainder are possibly extragalactic. Underlying the strong discrete sources is a diffuse background that has been spectrally mapped from 100 to 100 million electron volts. This background is characterized by high isotropy at all energies, but its spectral character is complex and probably reflects a variety of different sources, both intrinsically diffuse and so abundantly discrete as to appear diffuse when observed with the modest spatial resolution of present instrumentation. Truly diffuse x-ray emission could originate in hot intergalactic gas as thermal x-ray bremsstrahlung, or as nonthermal x-rays if a universal distribution of cosmic rays is scattered by inverse Compton collisions with photons of the microwave background at 3 K. In this article I review the present knowledge of discrete sources, treating a few examples in some detail, and estimate the importance of discrete and diffuse contributions to the background.

X-ray Stars and Nebulas

Only a small fraction of the galactic x-ray sources have been identified with optical or radio counterparts. At least two major classes exist—those associated with supernova remnants and those associated with binary pairs. Among the x-ray emitting supernova remnants are the Crab Nebula, SN Tycho Brahe, Cassiopeia A, Vela X, and the Cygnus Loop. Although some 70 radio pulsars have been discovered, only the Crab pulsar (NP 0532) and possibly the Vela pulsar (PSR 0833-45) emit x-ray pulses. Several eclipsing binaries have been detected in x-rays and must be members of a large class of x-ray sources that derive their power by mass transfer from a visible primary to an invisible compact companion. It is somewhat surprising that the number of galactic x-ray sources thus far discovered does not exceed 100 since it is estimated that the galaxy contains about 70,000 close binary pairs.

The discovery of pulsars and binary x-ray stars has led to renewed theoretical effort in modeling the supernova process and, more generally, the evolution of collapsed cores and the shedding of stellar envelopes. According to present concepts, stellar evolution depends on initial mass in roughly the following way. Stars with masses originally less than 3.5 solar masses ($M_{\odot}$) evolve to white dwarfs and, in the process, shed enough mass to leave less than 1.4 $M_{\odot}$ (the Chandrasekhar limit) in the compacted star. If the initial mass is 3.5 to 10 $M_{\odot}$ the cores collapse to neutron stars with residual mass less than 3 $M_{\odot}$, which is the maximum that can be supported by neutron degeneracy pressure. The excess mass is dispersed by the accompanying supernova explosion. When the original mass lies in the range 10 to 60 $M_{\odot}$, collapse is not accompanied by explosion of the outer layers. Material continues to rain down on the collapsing core, overwhelms neutron degeneracy pressure, and thus forces collapse to a black hole.

Two processes are of paramount importance in gravitational collapse to a neutron star. First, conservation of angular momentum requires that the gravitational energy derived from contraction be converted largely into kinetic energy of rotation. If the sun were compressed to a radius of 10 kilometers, its 1-month period of rotation would decrease to a millisecond. Second, the original stellar magnetic field strength at the surface would be am-

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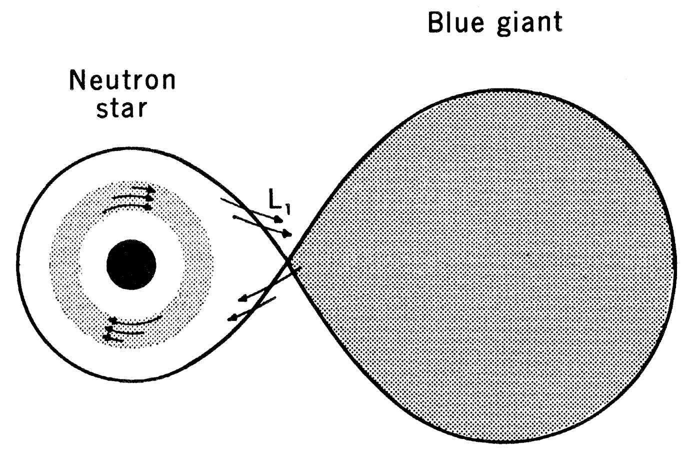

Fig. 1. Schematic representation of a typical close binary pair: an early-type supergiant and a neutron star. The figure eight defines the Roche critical equipotential surface. Gas overflows from the giant star through the region of the inner Lagrangian point (L_1) and collects in a disk that revolves about the neutron star.

plified by compression. A field of about 1 gauss at the solar surface would transform to 10^{10} gauss at a radius of 10 km. The energy derived from gravitational collapse far exceeds the nuclear binding energy, so that the compact spinning neutron star begins its life with more kinetic energy of rotation ($> 10^{50}$ ergs) than its parent star could derive from nuclear fusion.

Slowdown of a spinning neutron star and the accompanying dissipation of energy may be associated with magnetic dipole radiation, provided the magnetic axis is inclined to the spin axis. Electrons and protons become locked in phase with the expanding spherical electromagnetic waves and are swept along to relativistic energies. An alternative acceleration mechanism is homopolar magnetic induction. Plasma surrounding the neutron star conducts current between the poles and the equator of the spinning magnetized sphere. If the spin axis and the magnetic dipole axis are coaligned, an electric field as great as 10^{16} volts per centimeter may be generated close to the star and can accelerate charged particles to relativistic energies.

The details of the supernova implosion-explosion process are still theoretically unclear. One currently held theory requires that implosion of the core be followed by an outgoing shock wave, which reaches relativistic velocities in the thin outer layers of the star. This shock powers the explosive dispersion of debris and may accelerate particles to energies of 10^8 to 10^{21} ev, accompanied by intense neutron fluxes. Pulsars could play a major role in generating the highest-energy cosmic rays ($> 10^{12}$ ev), but would be inadequate to supply the much larger energy flux observed in the range 10^9 to 10^{12} ev. The pulsar mechanism may also work for white dwarfs. If they evolve by collapse of normal stars to about 1 percent of their original radii, their magnetic fields must reach strengths of about 10^4 gauss and their rotation periods must reduce to 10 to 100 seconds. An electric field of about 10^6 volt/cm can be generated near the surface, sufficient to accelerate particles to energies greater than 10^8 ev, possibly as high as 10^{14} ev. The large number of white dwarfs—of the order of 10^{10}—which are believed to populate the galactic disk with a scale height of about 1 kiloparsec (kpc) would satisfy the requirements of isotropy observed in the cosmic rays. Compton scattering in the high-density photon field near the surface of a white dwarf would produce gamma rays with energies in the million electron volt range, perhaps in sufficient intensity to account for the diffuse cosmic background flux above 1 Mev (*2*).

Accretion of gas onto a compact star is a very efficient means of developing hot plasma and x-ray emission (*3*). For example, a proton falling onto a neutron star can acquire 10 Mev of kinetic energy. At the rate of 10^{-9} $M_\odot$/year raining onto a neutron star or black hole of about 1 $M_\odot$, conversion of thermal energy to x-rays would generate about 10^{36} ergs per second. A white dwarf could produce a comparable luminosity by collecting 10^{-7} $M_\odot$/year. It is well established that some variable binary stars such as Beta Lyrae eject about 10^{-5} $M_\odot$/year and that roughly half of the ejected gas may impact on the companion star. The rate of accretion onto a neutron star or black hole in interstellar space would be many orders of magnitude less than in a close binary system. In the spiral arm regions an isolated black hole of 1 $M_\odot$ might accrete about 10^{-15} $M_\odot$/year and the resulting luminosity would reach about 10^{31} erg/sec. If a supermassive black hole ($\sim 10^8$ $M_\odot$) existed near the galactic center, accretion could reach 10^{-3} $M_\odot$/year and the power generated would exceed 10^{43} erg/sec.

Several galactic x-ray sources have been identified with binary pairs in which accretion takes place by mass transfer from a visible primary to an invisible compact secondary, such as a neutron star or black hole. Figure 1 illustrates a hypothetical binary situation. The visible primary may be a blue supergiant which fills its Roche critical equipotential surface. Gas leaks through the inner Lagrangian point and is gravitationally drawn toward the compact companion star. Because the gas has high angular momentum relative to the compact star, accretion is not spherically symmetrical. The gas enters into Keplerian orbits and accumulates in a disk somewhat resembling Saturn's rings, but with much greater density. The disk circulates about the star and gas slowly spirals inward. Viscosity removes angular momentum and heats the gas so that it radiates bremsstrahlung x-rays. The formation of an x-ray emitting region—and its spectrum, power, stability, and geometrical emission pattern—are determined by various parameters of the compact object.

Accretion onto a neutron star (*4*) will depend on the magnetic field strength and the spin rate. If the magnetic field is only moderately strong and the spin is relatively slow, accretion can progress steadily onto the gas disk and down to the surface of the star at the magnetic poles. The spectrum would be composed of contributions from both the gas disk and the stellar surface. If the field is very strong and the spin rate is high, accretion becomes more difficult and the observed emission must then come from a pulsar-like process as in the case of NP 0532. If accretion is toward a black hole, a modest flow to the surrounding gaseous disk could produce thermal emission with a range of temperatures corresponding to different depths of accretion. The resulting composite spectrum would resemble a power law even though the basic process is thermal. Accretion at a very high rate could disrupt the simple symmetry and channel the mass flow into localized hot spots. The resulting x-ray emission would then be sporadic and flare-like. Symmetrical accretion is ultimately limited by radiation pressure. The photon scattering cross section is some 10^6 times greater for electrons than for protons, whereas gravity works equally on the masses of electrons and protons. Charge separation takes place and an electric field is created, which drags the protons after the electrons. Gravitational accretion is balanced by this radiation pressure when the luminosity reaches about $10^{39}\ M/M_\odot$ erg/sec, where M is the mass of the accreting star. This critical luminosity is known as the Eddington limit.

Crab Nebula and NP 0532. The Crab Nebula and its pulsar have been studied intensively over the wide spectral range from radio waves to about 1-Gev gamma rays (*5–7*). The supernova was seen in A.D. 1054 and the present extent of the nebula ($\sim$ 6 light-years) fits the observed rate of expansion of the explosion debris into interstellar space and the elapsed time. Its nebular spectrum is highly polarized and is most likely produced by the synchrotron radiation of relativistic particles spiraling in a field of about 10^{-4} gauss. Before the discovery of the pulsar it was difficult to understand the energy source of the visible and x-ray synchrotron emission, because particles with energies high enough to produce the radiation (10^{12} to 10^{14} ev) must decay with lifetimes of less than a few hundred years for the optical radiation and less than a few years for the x-rays. It now appears that the pulsar can supply relativistic particles to the nebula for tens of thousands of years. The stellar collapse that triggers a supernova may endow the spinning neutron star with 10^{49} to 10^{52} ergs of rotational kinetic energy. Pulsar NP 0532 is dissipating this energy at the rate of 10^{38} erg/sec (10^5 times the energy radiated by the sun), thus lengthening its period about 15 microseconds per year. Conversion of this energy to particles and radiation with 10 percent efficiency can account for the total pulsed and nebular x-ray emission, which is about 10^{37} erg/sec.

Pulsar NP 0532 pulses 30 times per second. Figure 2 shows the pulse profile in various spectral regions from optical to gamma ray. If the magnetic dipole axis is inclined to the spin axis of the neutron star, the north and south poles will alternately be visible from the earth and radiation will beam past the earth twice per cycle. Although the profile does show two pulses, the secondary pulse follows the principal pulse by 13.4 msec, which is 3 msec sooner than half the full period of 33 msec. The asymmetry may be explainable in terms of time delay if the magnetic dipole is inclined at 45 degrees to the spin axis and the direction to the earth is at a latitude of about 20 degrees, so that the emission region linked to one magnetic pole always comes about 3 light-milliseconds ($\sim$ 1000 km) closer to the earth than the region of opposite polarity when its beam sweeps by (*8*).

Throughout the spectrum to the billion electron volt range, the principal pulse remains sharp (full width at half-maximum about 1 msec) but the secondary pulse broadens in the range 10 to 400 kev and gains in intensity relative to the principal pulse. The 13.4-msec region between the two pulses fills with a substantial flux of radiation at the higher energies. At the very highest energies ($\sim$ 1 Gev) the observations are still marginal but the basic pulse pattern seems to persist. Pulsar models have not been sufficiently developed yet to explain these detailed features and their spectral dependence.

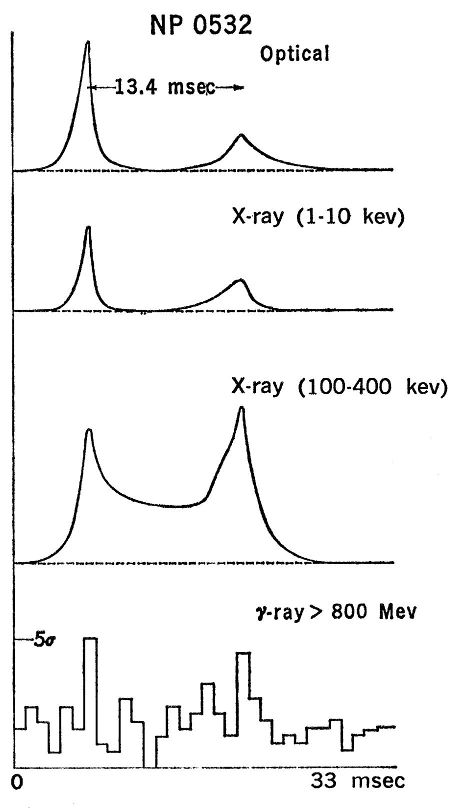

Fig. 2. Pulse profiles of NP 0532 at different energies. The soft x-ray (1 to 10 kev) and optical patterns are very similar. With increasing energy, the secondary pulse gains in intensity and width relative to the principal pulse, and the interpulse region fills in markedly. At the highest energy (> 800 Mev) the double pulse pattern appears to persist (*6*) although the statistics are somewhat marginal. (5σ = 5 standard deviations)

The Crab pulsar is the fastest and, presumably, the youngest of the roughly 70 pulsars thus far detected by the radio astronomers. With increasing age the pulsed power must decline rapidly. Although the pulsations may continue for several tens of thousands of years, the spectral distribution should shift toward longer wavelengths. Why have not x-ray pulsations been identified with supernova remnants still younger than the Crab? Continuous x-rays have been detected from Tycho SN 1572 and from Cassiopeia (Cas) A (estimated occurrence about 1700) but not from Kepler SN 1604, which is perhaps too distant (7 to 10 kpc) to have been found with the sensitivity of UHURU. The x-ray emission from Cassiopeia A may result from thermal bremsstrahlung of the hot plasma created behind the shock front of the expanding nebula, because the interstellar density there is as high as 30 cm^{-3}. Weak pulsations could be masked by the high thermal flux. In the vicinity of Tycho SN 1572 the interstellar gas is very thin, less than 0.1 cm^{-3}, and the nebula is quite extended so that thermal emission is inefficient. The observed x-ray emission is therefore most likely associated with the neutron star itself. Failure to detect pulsing may simply be a matter of orientation of the beam away from the earth. Shklovsky (*9*) proposes that the observed x-rays may still be attributed to a pulsar, but may be blurred by emission from a broad interpulse region rather than a sharply peaked pulse. He notes that the region between the principal pulse and the secondary pulse in NP 0532 fills in with radiation as the energy increases until it accounts for as much flux as the sharp pulses in the range 100 to 400 kev. Thus, a broad interval of "quasi-isotropic" x-ray emission may exist in some pulsars, perhaps associated with energetic particles trapped in the neutron star's magnetosphere. For Tycho 1572, the emission associated with a hypothetical pulsar 2.5 times as powerful as NP 0532—consistent with its younger age—could explain the observed continuous emission. A search for a small component of rapid modulation with more sensitive instruments would be desirable.

Neutron stars older than the Crab pulsar must be very abundant. Their pulsations having died out, all that remains to identify them is the extended nebula, thermal radiation generated by accretion, or possibly the blackbody emission of the stellar surface. The Veil Nebula in Cygnus (about 50,000 years old) is an example of a supernova remnant in which all the remaining emission is confined to the shock front of the nebula, where it expands against the interstellar gas. Its x-ray spectrum (*10*) is consistent with free-free emission from a thin plasma at about 5×10^6 K. In theory, the surface of a neutron star cools rapidly, to about 10^6 K within about a year after its formation. At that relatively low temperature it is difficult to observe the flux of very soft x-rays against the diffuse background with detectors that have the large fields of view typical of the mechanical baffles presently employed. The spectrum of Circinus X-1 is consistent with a blackbody source at 10^7 K, but that temperature is much higher than theoretical models of neutron stars allow (*11*). Table 1 lists the various supernova remnants that have been identified with x-ray emission.

Hercules X-1. The class of x-ray stars associated with mass transfer to a spinning neutron star in a binary pair is best illustrated by Hercules X-1. The optical counterpart is the binary HZ Herculis (*12*), an irregular optical variable with a light difference from maximum to minimum of 1.5 magnitudes. It exhibits x-ray pulsations with a period of 1.24 seconds, attributable to a spinning neutron star which is eclipsed by its giant companion for about 6 hours every 1.7 days. Over the course of half a year of observation, the pulsation period decreased by 4.5 μsec. This spin speedup may result from transfer of angular momentum of the infalling mass to the spinning star. The fast pulsation undergoes a Doppler shift in synchrony with the eclipse period. From the parameters of the system it is estimated that the mass of the x-ray source is 0.3 to 1.0 $M_{\odot}$.

The x-ray emission appears to be further modulated with a 35-day period during which the x-ray flux is on for 10 or 11 days and off during the remaining 25. While the orbital period remains very constant, the 35-day period is somewhat irregular. When first observed, the turn-on time was precise to about 1 hour in 35.7 days. Fourteen months later, the period was 34.9 days with a scatter of plus or minus 1 or 2 days. Precession of the spinning neutron star may cause the beam to oscillate into and out of the direction of view from the earth with the 35-day period. The asymmetry that induces the precession might result from accretion of matter onto the star in the regions of the magnetic poles (*13*).

Table 1. Supernova remnant x-ray sources.

Supernova remnant	Age (years)	X-ray power (erg/sec)	Energy (kev)
Crab Nebula	900	10^{37}	1–200
NP 0532	900	10^{36}	1–10^6
Cassiopeia A	300	5×10^{36}	1–10
Tycho 1572	400	5×10^{36}	1–10
Puppis A	10^4–10^5	10^{36}	0.2–3
Vela X, Y, Z	10^4–10^5	10^{36}	0.2–3
Cygnus Loop	10^4–10^5	2×10^{36}	0.2–1
IC 443		2×10^{34}	2–10
MSH 15-52A		5×10^{35}	2–10

The 1.24-second pulse profile determined from UHURU data shows a principal pulse and an intermediate pulse somewhat resembling those of NP 0532. However, the widths are much greater, indicating a broad beaming, and the x-ray emission is almost fully modulated by the pulsation. A recent rocket observation (*14*) resolved a double-peaked structure in the principal pulse (Fig. 3) and revealed variations in amplitude and shape in only a matter of seconds. Broad beaming might be expected from a thermal source, generated at the surface of the star if geometrical shadowing and optical opacity were the limiting factors. However, it has also been proposed that the emission mechanism is cyclotron radiation (*15*) in higher harmonics of the cyclotron resonance frequency, and that the emission is beamed in a wedge pattern at right angles to the magnetic field direction with an opening angle of about 30 degrees. The observed spectrum up to 40 kev is fit well by a model of thermal bremsstrahlung at approximately 6×10^7 K.

With the beginning of each 10- to 11-day on period, the x-ray onset is abrupt; the intensity increases for 3 to 4 days and then decreases to the end of the on period. The x-ray flux appears sharper at emergence from eclipse, and disappears more gradually at entry into eclipse. Such behavior may be related to the geometry of the gas flow in the accretion region and the opacity of intervening gas.

The 35-day period can be traced in optical data, which show a sinusoidal variation of 1.5 magnitudes synchronized with the 1.7-day eclipse, with minimum light at the middle of the x-ray eclipse. The stellar brightening, when the x-ray source is on the visible side of the star, is produced by absorption and conversion of the x-ray energy in the stellar photosphere. Examination of Harvard Observatory plates dating back to 1900 shows that the variations disappear for years at a time and then return.

Centaurus X-3. Centaurus X-3 (*16*) resembles Hercules X-1 in many respects. Its pulsation period is 4.8 seconds and the eclipse period is 2.1 days. No longer periodicity is present, but the x-ray signals disappear from time to time for periods of days. No optical counterpart has been found, perhaps because of high obscuration in the galactic plane. Other eclipsing binary sources detected by the UHURU satellite and their eclipse periods are: 2U(0900-40), 8.95 days; 2U(1700-37), 3.4 days; and 2U(0115-73), 4 days, in the Small Magellanic Cloud. The power of the last source is about 10^{38} erg/sec, close to the Eddington limit.

Cygnus X-1 (a black hole?). Special interest attaches to Cygnus X-1 because of the possibility that it may be a black hole. The x-ray emission shows extreme variability (*17*) down to the shortest time scale detectable, approximately 0.1 second, but there is no evidence of steady, rapid pulsation, or of a binary eclipse. It does, however, very nearly coincide with a radio and optical variable. The optical source is a 9th-magnitude B0I spectroscopic binary, HDE 226868, with a 5.6-day period. The mass of the blue supergiant, inferred from its apparent spectral class, should be about 20 $M_{\odot}$. From the orbital parameters, the mass of the companion star is then estimated to be approximately 13 $M_{\odot}$. In theory, neutron degeneracy pressure cannot support more than about 3.2 $M_{\odot}$; accordingly, Cygnus X-1 should be a black hole. However, some reservation should be attached to the estimate of the mass of the primary.

Theorists have been developing detailed models of disk-type accretion onto a black hole. Rapid fluctuations in x-ray emission are predicted on a variety of time scales down to tens of microseconds. The shortest fluctuations may result from focusing and defocusing of the x-rays by the curvature of space close to the black hole. Doppler shifts for an orbiting hot spot near the inner edge of the gas disk would be very pronounced. According to general relativity the minimum period should be approximately 70 μsec. The study of such short-lived bursts of x-rays will require highly sensitive large-area detectors with effective apertures of the order of square meters, such as were planned for the High Energy Astronomy Observatory (HEAO) program of the National Aeronautics and Space Administration.

Cygnus X-3. Cygnus X-3 is a unique x-ray variable (*18*) with a period of 4.8 hours—much longer than can be attributed to rotation of a pulsar and very short for an eclipsing binary. It is difficult to believe that a compact star could be orbiting a giant companion at such high speed. Over an extended period of observations with UHURU, its spectrum has shown strong variability in long-wavelength absorption that may be associated with a thick and variable hydrogen cloud either surrounding it or nearby. On 2 September 1972, its radio flux increased a thousandfold and then slowly returned to normal in about a week. Four repeats of such a radio outburst were registered by 6 October, but no x-ray variations were recorded (*19*).

It cannot be assumed for certain that the x-ray and radio sources are the same object. The radio behavior somewhat resembles that expected from the expanding cloud model of active radio quasars (quasi-stellar objects) and Seyfert galaxies. Each outburst of Cygnus X-3 appears to expel clouds of relativistic electrons in tangled magnetic fields (about 10^{40} ergs of particle energy per cloud), but there is no evidence relating these outbursts to the x-ray source and its 4.8-hour period.

Scorpius X-1. Scorpius X-1 is the brightest x-ray star and was the first to be discovered. It has been identified with a 12th-magnitude blue star and with a radio star. In spite of a wealth of observational detail in all parts of the spectrum accumulated over a decade of observations and many efforts to develop theoretical models, its fundamental nature is still mysterious (*20*).

Transient sources. Three transient sources with intensity variations similar to those of optical novas have been observed in the past few years. The source 2U 1543-47 was seen in Lupus in late 1971 when its brightness increased a thousandfold to match the flux of the Crab Nebula, the second brightest x-ray source in the sky (*21*). It slowly died away over the course of a year. The other two transients were Centaurus X-2 and Centaurus X-4 observed for about 80 days each. Each reached a brightness greater than that of Scorpius X-1 at maximum.

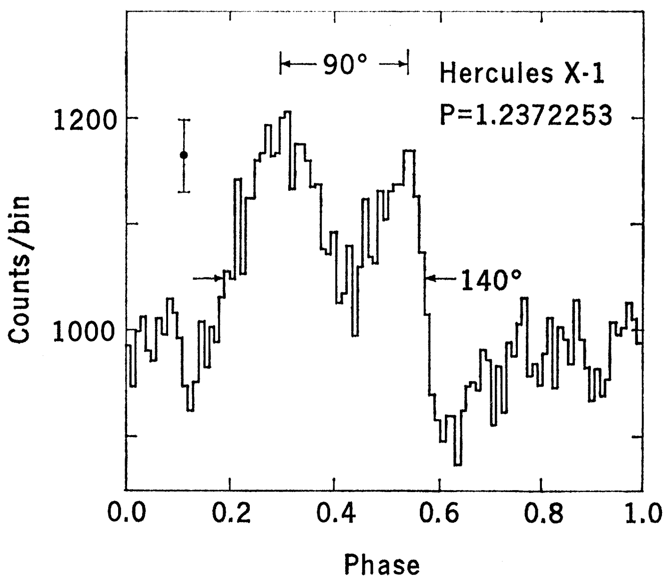

Fig. 3. Pulse profile of Hercules X-1 obtained from rocket flight (*14*). The principal pulse shows a double structure which varied markedly in pattern and amplitude during the few minutes of flight. The period (*P*) is in seconds; a phase of 90° corresponds to one-quarter of a period.

Summary of galactic sources. The sources described above are the best characterized of the approximately 80 sources near the galactic plane. Additional conclusions about the nature of x-ray stars can be sought from statistical considerations of the number distribution with respect to brightness and from spectral evidence of interstellar attenuation. Several of the strongest sources show large, nonvarying absorption at low energies, which implies that they are at about the distance of the galactic center. Accordingly, their x-ray luminosities must be of the order of 10^{38} erg/sec, close to the Eddington limit for accretion onto 1 $M_\odot$. The 17 brightest sources in the UHURU survey lie within 40 degrees longitude of the galactic center and group about 3 degrees median latitude. Analysis of the distribution of the remaining sources indicates that they occupy the spiral arms at an average distance of 2 kpc, corresponding to x-ray powers of about 10^{36} erg/sec. The conclusion drawn from these distributions is that nearly all of the sources detected thus far radiate at approximately 10^{36} erg/sec or more (1 to 10 kev).

X-ray Galaxies and the Diffuse Background (1 to 10 kev)

The roughly 45 discrete x-ray sources which lie at high galactic latitudes (> 20 degrees) may include many distant galaxies and clusters of galaxies. Underlying these sources is the diffuse background, which is highly isotropic. The relative contributions of discrete sources and diffuse radiation processes to the composite background are not clear. Observations of x-rays from Andromeda and the Magellanic clouds, as well as our own galaxy, indicate that most normal galaxies radiate at a few times 10^{39} erg/sec. Integrating the contribution of all such galaxies over a Hubble radius (*22*), about 10 billion light-years, would lead to a background flux (1 to 10 kev) about 50 times less than observed.

A new pulsar may outshine the total of all other x-ray sources in the galaxy. If it is endowed with 10^{52} ergs of kinetic energy of rotation, conversion to x-rays at 1 percent efficiency would provide 10^{50} ergs over the lifetime of the pulsations. If we assume that one supernova per 100 years leads to a pulsar, the time-averaged contribution to galactic x-ray luminosity would be 10^{41} erg/sec. Thus, the combined x-ray emission from all galaxies could equal the observed diffuse background. Estimates of the initial energy of rotation differ widely, however, from as low as 5×10^{49} to as high as 10^{53} ergs. So far, only upper limits of 10^{50} to 10^{51} ergs are available from a few x-ray observations of distant galaxies at times of visible supernova events (*23*).

X-rays have been detected from powerful radio galaxies, Seyfert galaxies, one quasar, and several rich clusters of galaxies. Although the statistics of the small sampling of known sources hardly justifies any great confidence in estimating the integrated cosmic contribution to the background, the evidence does support the possibility that discrete extragalactic sources can supply much of the background radiation (1 to 10 kev). The brightest x-ray galaxies are also powerful nonthermal sources of radio and infrared emission. Among the best-studied objects are the radio galaxies M 87 (NGC 4486, Virgo A), NGC 1275 (Perseus A), and NGC 5128 (Centaurus A); the Seyfert galaxy NGC 4151; and the quasar 3C273. The first three are among the most spectacularly active galaxies and have many morphological similarities.

M 87. The first extragalactic x-ray source to be discovered by rocket astronomy was M 87 (*24*). Optically, it is a large elliptical galaxy characterized by an extended jet, which emerges from the nucleus to a distance of about 1500 pc (Fig. 4). A counter jet is also faintly discernible, formed of two approximately parallel bands of irregular intensity stretching about 10 kpc from the core of the galaxy (*25*). A similar structure can be seen in NGC 5128, but the filaments reach a length of about 30 kpc. The orientation is perpendicular to the dark band (dust lane) across the equatorial plane of the galaxy. The source NGC 1275, when photographed in the Hα line of hydrogen, is highly filamentary, out to a distance of about 60 kpc. The filaments form a radial pattern emerging from the nucleus to about 3 kpc, and then turn abruptly, presumably along the direction of the outer magnetic field (Fig. 5).

The bluish light of the jet of M 87 is highly polarized, which is indicative of synchrotron radiation. Several knots, or condensations, dot the length of the jet, and various authors have suggested the possibility of synchrotron x-ray emission from these knots (*26*). The relativistic electrons could be generated by (i) proton-proton collisions, (ii) clouds of million of pulsars, or (iii) the spin-off from large rotating magnetoids (*27*) (magnetized plasma bodies of about $10^4 M_\odot$). Alternatively, the x-ray source may be concentrated toward the nucleus. Radio astronomers have found an intense compact core only 4 light-months in diameter, which could be the origin of x-ray emission generated by inverse Compton interactions between relativistic electrons and the high density of radio photons in the nuclear region.

Additional features of the radio image are an extended halo and a fan jet. The optical jet and counter jet probably describe the major magnetic field direction about which the galaxy is rotating, with the fan jet spreading in the equatorial plane over approximately one-third of a galactic revolution. The fan jet suggests that gas clouds are expelled from a compact rotating body. Shklovsky (*25*) estimates that repeated releases from the central body supply a few million solar masses to the various jet forms. To sustain a reservoir of material and energy, gas may be constantly accreting onto a large rotating mass in the nuclear region; the origin of this gas could be planetary nebulas separated from old-population red giants. By analogy with our galaxy, the rate of evolution of planetary nebulas in M 87 should be about 30 per year, releasing about 0.1 $M_\odot$ of gas each in clouds that fall toward the core of the galaxy. In an elliptical galaxy such as M 87, these infalling clouds will have little angular momentum relative to the nucleus and gas cloud collisions will inhibit star formation, thus permitting the gas to fall steadily onto the central rotating magnetoid. To account for the observed x-ray emission of 10^{43} erg/sec there must be a compact nuclear mass of about $10^9 M_\odot$ onto which 3 $M_\odot$ per year of gas released in planetary nebulas is steadily falling.

The UHURU observations of M 87 suggest that the x-ray source is somewhat extended (*28*) or that a localized emission from the galaxy is superposed on a more diffuse emission region. It is not possible to characterize the x-ray spectrum as uniquely thermal or nonthermal. There is some evidence for

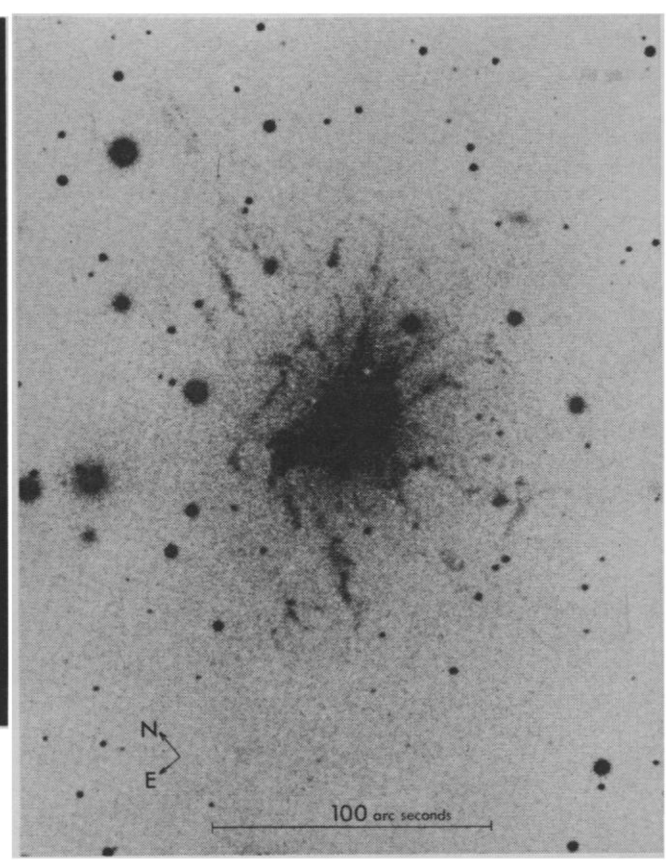

Fig. 4 (left). M 87, showing jet emerging from the core of the elliptical galaxy. [U.S. Naval Observatory, Flagstaff, Arizona] Fig. 5 (right). NGC 1275 photographed in Hα to show extended filamentary structure. [Kitt Peak Observatory] snort-term variability (of the order of months) in both the x-ray flux and the spectrum, but the observations need to be extended. Radio observations over a span of 18 months have shown no significant flux variations or changes in size of the core (*29*).

The galaxy NGC 5128, which is located at the center of the extended radio galaxy Centaurus A, radiates about 6×10^{41} erg/sec in the range 1 to 10 kev (*30, 31*). The radio galaxy is of the common double source type produced by the ejection of matter from the central region of the galaxy in two roughly comparable streams oppositely directed. Two distinct explosions are defined by two pairs of radio plasmons, symmetrically placed (Fig. 6) about 2×10^4 and 10^6 light-years apart on a line running through the nucleus of the galaxy. The distance of Centaurus A is only 4.5 Mpc and it covers about 10 degrees of arc, so that even the 0.5-degree resolution of the x-ray detector of UHURU is adequate to set rather narrow limits on the extent of the source of x-ray emission, which is confined to the central region of the optical galaxy and is limited to a diameter smaller than the separation of the two innermost radio lobes. Most likely, the x-ray source coincides with a very compact radio (*32*) and infrared source (*33*) in the nucleus. The upper limit on x-ray emission from the extended radio lobes does not exceed the flux of inverse Compton x-rays that should be expected from collisions of relativistic electrons of the synchrotron radio source with the universal background photons at 2.7°K. The total x-ray power from NGC 5128 is only about 10^{42} erg/sec; if this is typical of most radio double galaxies it suggests that they are not adequate to make up the background radiation. However, x-rays have been detected from the direction of a rich cluster of galaxies that include the most powerful radio double galaxy, Cygnus A (*1*). If the x-rays originate in Cygnus A, its power is approximately 8×10^{44} erg/sec.

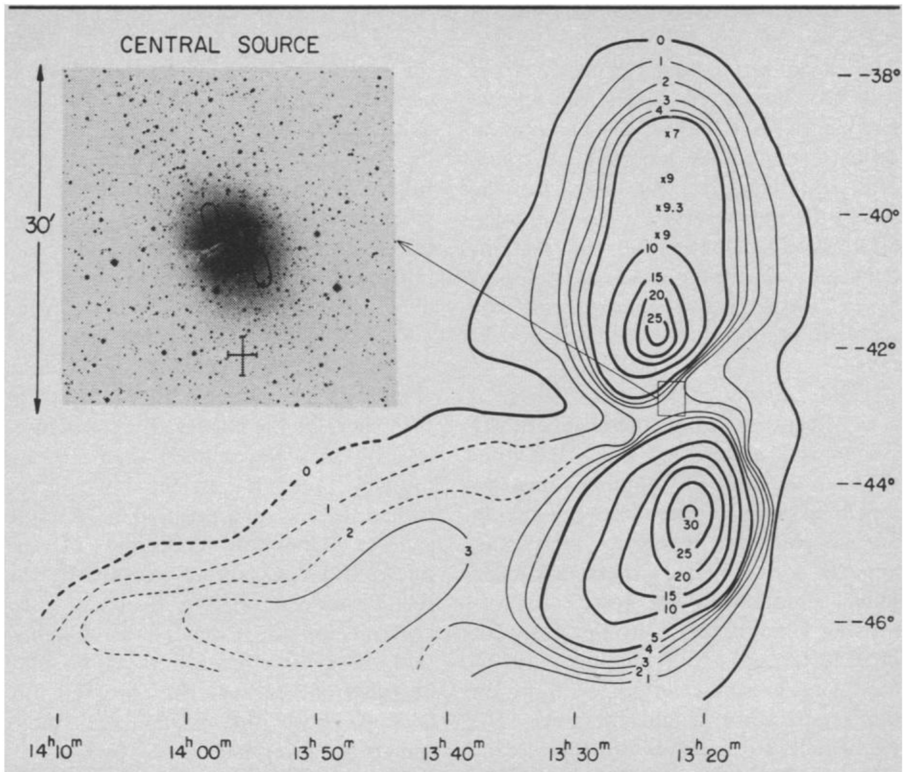

Fig. 6. NGC 5128 (Centaurus A); the optical galaxy is shown in the inset. The radio contours (labeled in relative intensities) show the typical double source structure of a radio galaxy. Evidence of a more recent explosion is given by the double radio source still located within the optical galaxy, with a component separation of 25,000 light-years. The abscissa gives the right ascension; the vertical measure on the inset is 30 arc minutes.

Seyfert galaxies. One or two percent of all galaxies appear to be Seyferts. They are characterized by compact, brilliant nuclei which contain 10^9 to 10^{10} stars within a diameter of about 1000 light-years. Strong, widened optical emission lines and a polarized continuum indicate high-velocity gas clouds, hot gas, and nonthermal processes. The source NGC 1275 exhibits many of the properties of a Seyfert and is also one of the most violently active radio galaxies. Its radio structure is of the core halo type, with a core less than 1 light-year in diameter. Repeated explosions in the nucleus on a time scale of about 10 years release clouds of relativistic particles into the halo, where they accumulate over subsequent millions of years. The nuclear region is orders of magnitude brighter in the infrared than in visible light, and its x-ray power (about 4×10^{45} erg/sec) approaches its infrared power (about 3×10^{46} erg/sec) (*34*).

The more typical Seyferts—NGC 4151, NGC 1068, and NGC 4051—have been scanned by UHURU. Only NGC 4151 is a detectable x-ray source. If, on the average, one-third of all Seyferts were as powerful x-ray sources as NGC 4151, the integral contribution would come close to satisfying the background flux and isotropy requirements.

Quasars. The source 3C273 is the nearest and brightest of the quasars thus far discovered (*30*). Quasars behave like hyperactive Seyferts; the continuum radiation almost swamps the line emission. Typically, a quasar is about a hundred times as luminous in visible light as a normal galaxy, even though its diameter is nearly an order of magnitude smaller. But the infrared luminosities are even more spectacular. For 3C273 the infrared luminosity is about 6×10^{48} erg/sec, approximately three orders of magnitude greater than its visible luminosity. Its x-ray power is about 10^{46} erg/sec. The x-ray observations are still too crude to indicate spectral character or short-term variability comparable to that observed in the infrared. If the space density of quasars is about 10^{-8} Mpc^{-3} and 3C273 is assumed to be typical, the contributions to the diffuse background would be only about 2 percent of the observed flux.

Clusters of galaxies. Galaxies may cluster in groups of as many as 10,000, and hundreds of such clusters may agglomerate into superclusters. The density of galaxies toward the center of a rich cluster may reach 10^3 to 10^6 times the average galactic density of the sky. The three rich clusters closest to us are Virgo, Coma, and Perseus. Their x-ray luminosities are 10^{43}, 2×10^{44}, and 4×10^{44} erg/sec, respectively. Several of the weaker x-ray sources found at high galactic latitudes appear to be centered on dense clusters, so it is reasonable to assume comparable x-ray powers for all rich clusters. The mean x-ray fluxes expected from just the integrated fluxes of normal galaxies in rich clusters is at least an order of magnitude less than observed. Hot, intergalactic gas may be the source of the observed x-ray emission; alternatively, nonthermal interactions between relativistic particles released by a single active galaxy and the ambient photon field may produce x-rays.

Coma cluster. The Coma cluster is a rich, centrally condensed, spherically symmetrical system for which the virial theorem suggests a binding mass as much as seven times that present in normal galaxies (*35*). Since the cluster appears to be bound, there has been much attention to the search for the missing binding mass in the form of intracluster gas. If a binding mass of gas were present, the upper limit on the temperature would be about 10^8 K, which corresponds to the escape velocity. The absence of 21-cm radio emission or absorption (*36*) implies that the gas is hotter than 3×10^4 K. An upper limit on the flux of soft x-rays below 1 kev sets the temperature somewhat higher, above 5×10^5 K (*37*). The observed x-ray flux in the range 2 to 10 kev can be interpreted as bremsstrahlung from a gas of density 6×10^{-4} cm^{-3} in a volume with a radius about 0.5 Mpc at a temperature of 7×10^7 K, but the total mass is only a few percent of the binding mass (*38*). If a binding mass of ionized gas exists in the temperature range 3×10^4 to 5×10^5 K, it should be detectable as hydrogen Lyman-alpha recombination emission. At the red shift of Coma, Lyman-alpha appears at about 1250 Å, which places it well outside the intense geocoronal Lyman-alpha background at 1216 Å. Rocket observations (*39*) of the Lyman-alpha emission from Coma almost suffice to rule out any appreciable fraction of a binding mass of gas in the temperature regime below 5×10^5 K. The combined evidence of all spectral observations, therefore, rules against the existence of a binding mass of gas and raises questions about previous estimates of the mass-to-light ratio of the galaxies, unless one resorts to more esoteric explanations such as an abundance of black holes.

The size of the x-ray emitting region gives additional clues to the nature of the source. It extends over a diameter of about 45 arc minutes (about 1 Mpc). Internal cluster gas may be accreted from intergalactic gas outside the cluster, or it may be ejected from centrally located active galaxies. Whether the gas is accreted or ejected, its distribution could be expected to follow the spatial distribution of the galaxies, which appear to be concentrated within 10 arc minutes at half-maximum intensity, a region considerably smaller than the x-ray source (*40*). A better size match is found with Coma C, an extended radio source about 40 arc minutes in diameter at the center of the cluster. It is structureless on a scale smaller than 30 arc minutes and is presumably diffuse rather than a superposition of discrete sources. Compton scattering of the microwave background photons by the relativistic electrons in Coma C may account for the extended x-ray emission. X-ray synchrotron radiation may be ruled out because the observed flux is well above the extrapolated radio spectrum power law.

Perseus cluster. Perseus, in contrast to Coma, is highly irregular. The velocity dispersion of its galaxies is very large, and either most of the mass required by the virial theorem is invisible, or the system has positive energy. X-ray emission from the Perseus cluster is centered on NGC 1275, but the source is extended to a diameter of about 0.5 degree, about the same size as the radio halo 3C84B. The resolution of x-ray measurements is not sufficient to distinguish between emission from NGC 1275 and from the extended region. The spectrum is not clearly thermal or nonthermal. It may be a composite of various temperature regimes from 10^7 to 10^8 K, but could just as well be fitted to inverse Compton or synchrotron power laws. The relativistic electrons needed to generate nonthermal x-rays may be abundantly produced by the violent activity in the compact nucleus of NGC 1275. An inverse Compton model requires similar spectral indexes for both the radio and x-ray portions of the spectrum. The spectral index of a power law fit to the x-ray data for Perseus A is 1.1, but the radio synchrotron emission fits a power law with a spectral index of only about 0.7. However, there is enough uncertainty in both indexes that they cannot be assumed to disagree.

In summary, several possible processes might contribute to the x-ray emission from rich clusters:

1) Thermal bremsstrahlung from gas at 10^7 to 10^8 K, with a density of about 10^{-4} to 10^{-3} cm^{-3};

2) Inverse Compton scattering of the microwave background radiation in the halos of active galaxies by relativistic electrons escaping from the nuclear regions;

3) The combined emission of a few very powerful x-ray galaxies, each radiating about 10^{43} erg/sec.

In addition to Coma, Virgo, and Perseus, other cluster candidates for identification with x-ray sources at high galactic latitudes are Abell 401, 3C129, Abell 1367, Abell 2256, and the cluster centered on Cygnus A. Their x-ray powers range from 5×10^{43} to 8×10^{44} erg/sec. The space density of rich clusters is about 10^{-6} Mpc^{-3}. At an average x-ray power of about 10^{44} erg/sec, they would come close to supplying the diffuse background.

Diffuse Radiation

The full spectrum of the diffuse background radiation is shown in Fig. 7. Inflections in the curve indicate that different processes must be effective in different spectral ranges. In the range of lowest energies ($E = 100$ ev to 1 kev) the spectral energy dependence follows E^{-1} to E^{-2}. The spectrum flattens to $E^{-0.4}$ from 1 to 10 kev and then bends progressively to a steeper dependence, approximately $E^{-0.75}$ from 20 to 40 kev and $E^{-1.3}$ from 40 kev to about 1 Mev. Considerable uncertainty still exists about the shape of the spectrum beyond 1 Mev. Several observers have claimed a flattening in the range 1 to 6 Mev, but instrumental effects may be responsible. At higher energies the spectrum follows E^{-2}.

From 1 to 10 kev, all the evidence from discrete sources reviewed above shows that the integral flux from galaxies and clusters may add up to the required background. However, the uncertainty is still an order of magnitude, and a truly diffuse cosmological source may also be operating throughout intergalactic space. Both thermal and nonthermal processes have been proposed to explain the spectrum above 10 kev. The earliest proposal to receive general support was based on inverse Compton scattering of the microwave background photons by cosmic-ray electrons (*41*). It would require 10^{-4} ev/cm^3 of ultrarelativistic electrons throughout intergalactic space to provide the observed background. Could powerful radio galaxies provide such copious sources of cosmic-ray electrons? The estimated mean life of radio galaxies is about 10^9 years (*42*). If each produced 10^{60} ergs of relativistic electrons, as deduced from synchrotron radio fluxes of the most active galaxies, the electron energy density still would average only 10^{-5} ev/cm^3. To compensate for the deficiency evolutionary effects can be invoked, for example by assuming a higher density of radio sources or greater luminosities in early epochs.

The diffuse x-ray background may have a thermal origin that involves the nature of the intergalactic medium and the universal distribution of cosmic rays. A critical average density of all matter and radiation in the universe is expressed by

$$\rho_c = \frac{3H_0^2}{8\pi G}$$

where H_0 is the Hubble constant and G is the gravitational constant. At this mean density, expansion of the universe approaches a halt as time approaches infinity. For densities less than ρ_c the universe is open and expands forever; if the density exceeds ρ_c the universe is closed and the expansion will stop and reverse after some finite time. A recent assessment (*43*) indicates a value for H_0 of approximately 50 km sec^{-1} Mpc^{-1}, which corresponds to $\rho_c \approx 4.7 \times 10^{-30}$ g/cm^3 (or a particle density of about 3×10^{-6} cm^{-3}). Estimates of the density of galactic matter averaged over all space out to a Hubble radius give about 7.5×10^{-32} g/cm^3, or about 2 percent of the critical density. Certainly there must be additional mass in the form of intergalactic gas, and a substantial number of subluminous objects such as white dwarfs, neutron stars, and black holes may contribute significantly to the mass budget. Attempts to detect cool intergalactic gas by virtue of its absorption or emission of electromagnetic radiation have all been negative; the indicated upper limit is about 10^{-11} cm^{-3} for the density of neutral gas. A hot, fully ionized medium could exist at much higher densities and would be detectable by its thermal x-ray emission. The identification of such diffuse emission is one of the great challenges to x-ray astronomy.

Recently, Cowsik and Kobetich (*44*) have performed a more precise calculation of the inverse Compton scattering process and shown that it cannot match the observed shape from 10 kev to 1 Mev. Instead, they find a close fit to bremsstrahlung at 3×10^8 K (Fig. 8), which could be produced by universal, hot, intergalactic gas at a density of 3×10^{-6} cm^{-3}. For $H_0 =$ 50 km sec^{-1} Mpc^{-1}, this density is close to that required for closure of the universe. At the very high temperature, the gas escapes freely from clusters and would be so uniformly dispersed throughout the universe as to satisfy the high degree of isotropy of the observed x-ray background. Underlying this thermal background at higher energies there would be an order of magnitude weaker inverse Compton flux. It would surpass the

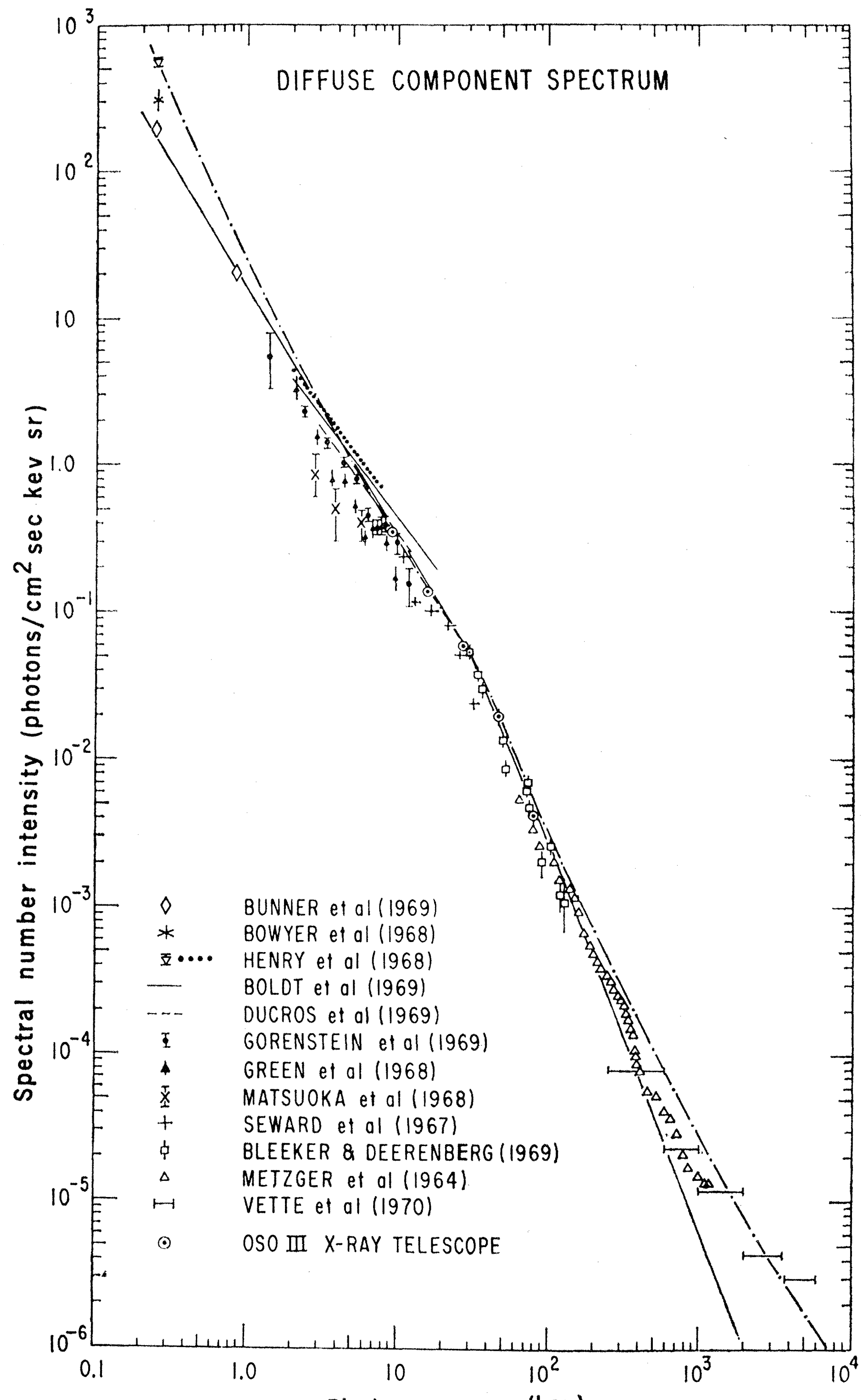

Fig. 7. Spectrum of diffuse x-ray background. The sources of the data are: Bunner *et al.* (*60*), Bowyer *et al.* (*70*), Henry *et al.* (*59*), Boldt *et al.* (*71*), Ducros *et al.* (*5, 72*), Gorenstein *et al.* (*73*), Green *et al.* (*74*), Matsuoka *et al.* (*75*), Seward *et al.* (*76*), Bleeker and Deerenberg (*77*), Metzger *et al.* (*78*), Vette *et al.* (*47*), and (OSO III) Schwartz *et al.* (*79*). [Courtesy of L. E. Peterson, University of California at San Diego]

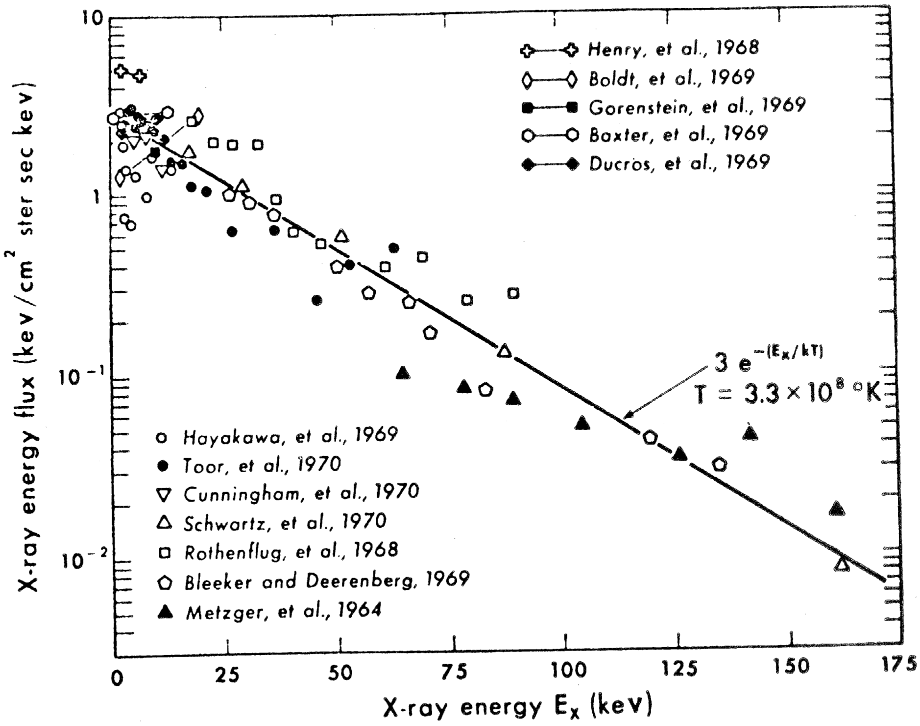

Fig. 8. Fit of observations of the diffuse background (10 to 175 kev) to a thermal spectrum (3.3×10^8 K). The sources of the data are: Henry *et al.* (*59*), Boldt *et al.* (*80*), Gorenstein *et al.* (*73*), Baxter *et al.* (*81*), Ducros *et al.* (*5*), Hayakawa *et al.* (*82*), Toor *et al.* (*83*), Cunningham *et al.* (*84*), Schwartz *et al.* (*79*), Rothenflug *et al.* (*85*), Bleeker and Deerenberg (*77*), Metzger *et al.* (*78*). [Courtesy of Cowsik and Kobetich (*44*)]

thermal flux at about 1 kev and account for the very soft x-ray background (100 ev to 1 kev). If the thermal model for 3×10^8 K fits the observations, it leaves unknown the source of energy for the hot gas. It is interesting to recall Gold and Hoyle's steady-state model of the hot universe (*45*), in which matter was created in the form of neutrons which quickly underwent beta decay (*46*), delivering about 300 kev of kinetic energy to the electron. When fully converted to thermal energy, this would raise the temperature of intergalactic gas to 10^9 K.

A semblance of a flattening in the diffuse background spectrum at 1 Mev was first reported on the basis of data obtained with the Ranger III and ERS-18 spacecraft. This feature implies an additional component of background flux in the range 1 to 6 Mev (*47*). Since the measurements were made from large distances above the earth, atmospheric background introduced no contamination. However, several authors have attributed the observed effect to locally produced radioactivity in the NaI(Tl) crystal detector and its surroundings. More recent measurements, including those made on the Apollo 15 and Apollo 16 missions and from Cosmos satellites and balloons, are contradictory, and the validity of the results is still uncertain (*48*). Several theoretical interpretations have been offered for the feature in the 1- to 6-Mev range, if it is real. Neutral pions (π^0) decay with the emission of a spectrum of gamma rays that peak at 70 Mev. If they are produced at red shifts of the order of 100, the observed gamma rays would concentrate in the range 1 to 6 Mev (*49*). Other proposed mechanisms are electron bremsstrahlung [either galactic (*50*) or extragalactic (*51*)]; proton bremsstrahlung (*52*); cosmological matter-antimatter annihilation (*53*); and nuclear line emission (*54*). But recent theoretical work discounts all but the hypotheses of π^0 decay with a high red shift and matter-antimatter annihilation.

Apollo 15 and Apollo 16 experimenters have extended the spectrum to 30 Mev, where the intensity obtained is 5×10^{-5} photon per square centimeter per second per steradian per million electron volts, in rough agreement with ballon results (*55*). Above 50 Mev one data point from the satellite OSO-3 is available (*56*), and it indicates a steepening of the spectrum, although not significantly in conflict with a power law extrapolation from lower energies. At these high energies, the contribution from the thermal model for 3×10^8 K is insignificant. Theorists suggest Compton scattering of a universal distribution of cosmic-ray electrons on the 2.7 K background (*57*), or interaction of relativistic electrons generated by rapidly spinning white dwarfs with the high photon densities near the stellar surfaces (*2*).

Consider finally the background of very soft x-rays below 1 kev. Observations are difficult in this range and there is considerable spread in the published results. However, there is general agreement that the flux near 44 Å exceeds any simple extrapolation of the spectrum from 1 to 10 kev. Most observers find an excess toward the galactic pole (*58–60*); and it is also well established that a substantial part of the soft flux originates in the galactic disk (*61, 62*). Figure 9 illustrates the results of a rocket survey of a large area of the sky at 44 Å and includes a map of the hydrogen column density for comparison (*62*). In general, the x-ray flux is highest where the hydrogen column density is smallest. About two-thirds of the x-ray flux at the poles can be considered extragalactic and the remainder appears to originate from discrete or diffuse sources within the disk.

Some discrete features seem to be present in these data and in the data of other observers, who have attempted to identify them with radio remnants of supernovas, such as the North Polar Spur and the Vela supernova remnant. However, other spurs, such as Loop III, were scanned in the rocket survey with negative results at x-ray limits well below that of the North Polar Spur. It does not appear, therefore, that all extended radio spurs are sources of soft x-rays or that they contribute substantially to the soft x-ray background.

A good fit to the observed soft x-ray flux is obtained if the sources in the disk are distributed with the same scale height as interstellar gas. The variation of flux from pole to plane then follows the expected attenuation of an extragalactic flux by a smooth distribution of hydrogen in the disk. Sources that scale with the neutral hydrogen in the disk include supernova remnants (*63*) and defunct pulsars (*64*). For a supernova remnant model, the density of sources is small and the average distance must therefore be great. Very large soft x-ray luminosities would be required to overcome interstellar absorption because the optical thickness of neutral hydrogen is only about 100 pc in the disk. The isotropy of the observed x-rays argues against the relatively small number of sources in a supernova remnant model. Defunct pulsars, however, should occur in relatively great densities. They would produce thermal x-rays by accretion of interstellar gas.

The soft x-ray background has been attributed by some authors (*58, 59*) to thermal bremsstrahlung from gas at a temperature of about 3×10^6 K. If the gas is intergalactic, its density would be of the order of that required for a "closed" universe; if it is condensed in clusters, a much smaller universal mass is indicated since the bremsstrahlung flux varies with the square of the density. However, it has not yet been established whether the gas is associated with the local cluster, is condensed in clusters of galaxies, or is smoothly distributed in extragalactic space.

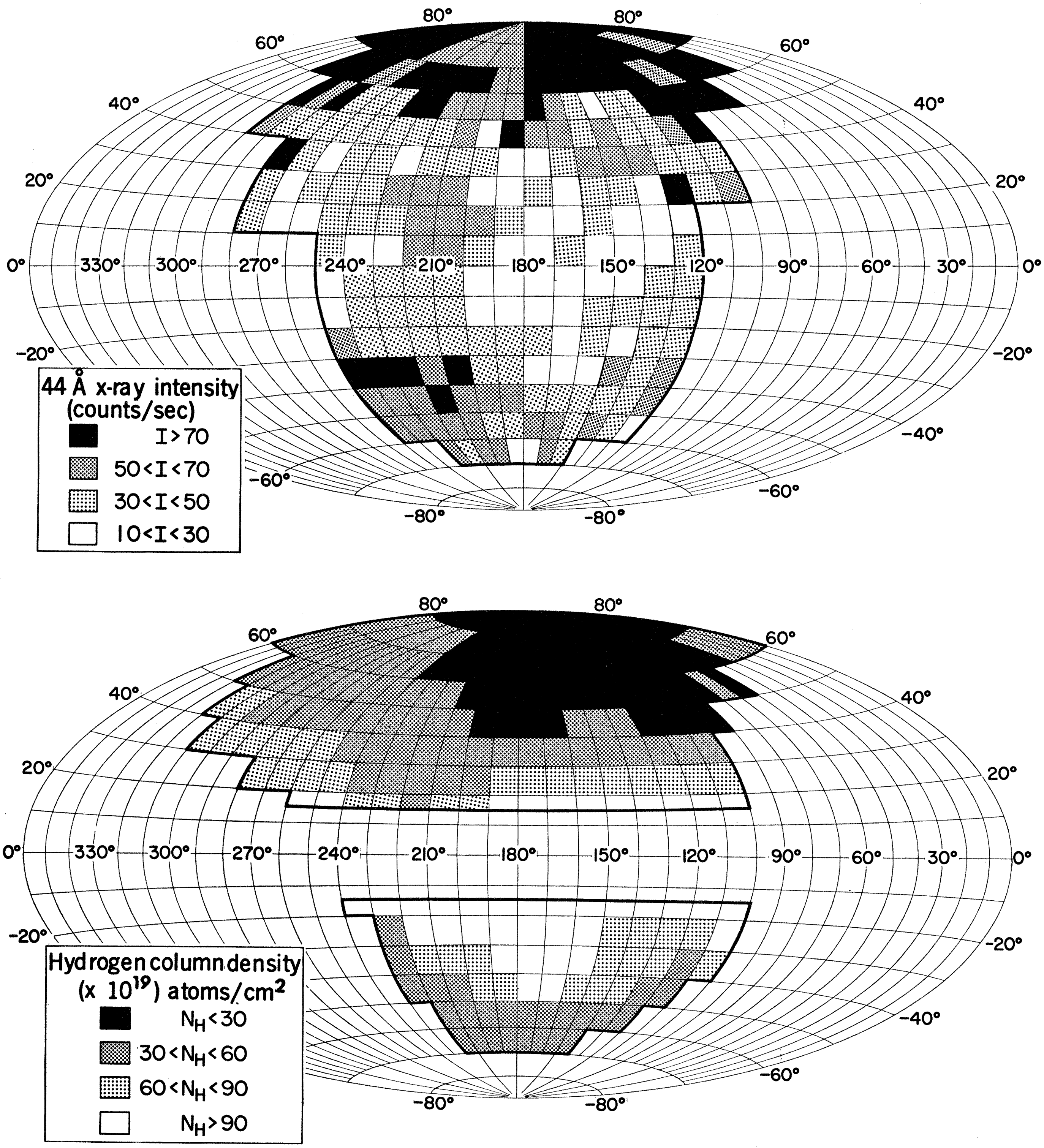

Fig. 9. Sky maps in 44-Å (0.28-kev) x-rays (top) and in hydrogen column density (bottom) (*62*). The maps are in new galactic coordinates. The portions of the sky surveyed are outlined by heavy lines.

Evidence against a cosmological source of the soft x-ray background (*65*) comes from a rocket scan across the Small Magellanic Cloud. If the origin of the background x-rays were more distant, the Cloud would be expected to mask the background. No such effect was found, and a limit of 25 percent was set on the fraction of the radiation in the band from 44 to 60 Å that could originate beyond the distance of the Cloud. The data of Fig. 9 led to the conclusion that 67 percent of the observed x-rays in the direction of the pole was extragalactic. The Small Magellanic Cloud is at a galactic latitude of about −40 degrees, where the hydrogen column density is much higher than at the poles and the expected extragalactic flux should be attenuated to 40 percent of the observed background—within a factor of 2 of the limit set by the observation of the Cloud. A further possibility is that soft x-ray emission from the Cloud itself fills in the shadow. The observation is certainly crucial and should be improved on.

If the source of the soft x-ray background is closer than the Small Magellanic Cloud it may be associated with a hot halo around the galaxy as had been proposed by Spitzer (*66*). His highest-temperature model (10^6 K) required a density of 5×10^{-4} cm^{-3} and a radius of 8 kpc. This amount of gas would not provide the x-ray background. The x-ray observations require a somewhat higher temperature, about 3×10^6 K, and an emission measure, $\int n_e^2 dl$ (*67*), of about 0.1 pc cm^{-6}. In order to avoid excess pressure from the halo at the interface with the neutral disk, the gas density there must not be greater than about 10^{-3} cm^{-3} and the radius of the halo must approach a megaparsec. The halo would therefore more correctly be described as an intracluster gas.

The x-ray emission from a regular cluster of galaxies such as Coma also provides evidence about the density of intergalactic gas if the x-rays are thermal bremsstrahlung from gas within the cluster (*68*). Where did this gas originate? It may be residual from the original cloud out of which the cluster formed, some of it may have been swept out of the galaxies, and some may have accreted from intergalactic space. If all the gas in Coma has fallen in from intergalactic space in the course of 10^9 years, the external gas density would not exceed 10^{-7} cm^{-3}. The intergalactic gas therefore contributes less than (or at most an amount comparable to) the mass in galaxies to the total mass budget of the universe. According to this argument the universe is open, unless a great deal of hidden mass is present in other forms such as black holes or dead galaxies.

Another interesting bit of evidence for the ratio of intracluster to extragalactic gas comes from studies of double radio sources (*69*). The sources within clusters have only about one-half the separation of those outside clusters. If the motions of the expanding clouds are opposed by the pressure of the ambient gas, the estimated intracluster densities are 15 times as great as those in intergalactic space.

In summary, the x-ray background data are not inconsistent with thermal models of an intergalactic gas at near-critical density. A very hot gas, about 3×10^8 K, fits the harder x-rays very well and accounts for the spectral bump at about 30 kev. Gas at about 4×10^6 K fits the soft x-ray spectrum below 1 kev. However, this soft x-ray component may originate within the local group.

Conclusion

X-ray astronomy has been carried on with balloons, rockets, and small satellites for the past decade. Great progress was expected from the HEAO program, which fell victim to budget limitations in 1973. With its 9000-kilogram payload capability in near-earth orbit, HEAO was designed to carry a new generation of instruments for detecting x-rays, gamma rays, and particles with very large gains in detection capability and speed of response. Large detectors with high sensitivities are required to characterize more precisely the physical properties of the wide variety of galactic and extragalactic sources. Higher sensitivity coupled with very fast response is essential for detecting the microsecond variations predicted by models of black holes and their associated gas disks. At the time of this writing, NASA is attempting to reconstruct the HEAO program with a lower budget, to begin flights in 1977. Although this observatory will be substantially reduced in capability from the original one, it will go a long way toward satisfying the urgent observational demands in high-energy astronomy.

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The Search for a Better Analgesic

After 75 years of research, solutions for morphine-type drug dependence are emerging.

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The accepted, standard analgesic has always been morphine, the medicament without which, until recently, no one could practice medicine effectively. Morphine not only relieves pain of any origin, whether due to illness or trauma, but it may relieve anxiety and the effects of mental or physical shock, promote sleep, and evoke a general feeling of peace and well-being. Its use for any of these benefits, however, demands that a price be paid. If the dose is only a little too great in the circumstances or if the patient is very young or debilitated, the breathing may be depressed to a degree which is life threatening. Frequently nausea, vomiting, sweating, dizziness, and sluggishness occur with routine doses; the heart rate is slowed and the blood pressure may fall. When the use of morphine is repeated, the effects wane and the dose must be increased and, worst of all, morphine causes addiction (drug dependence of the morphine type), an accommodation of the cells of the body to its presence so that its use must be continued or a particular, self-limited illness, the withdrawal or abstinence syndrome, makes its appearance. The search for a better analgesic then is a search for a better morphine, a substance with morphine's beneficial properties and with attenuated or no harmful side effects including tolerance and dependence.

Morphine, as morphine, has been known for less than 200 years, but the effects of opium are the effects of mor-

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