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X-RAY ASTRONOMICAL SPECTROSCOPY

S. S. HOLT

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Goddard Space Flight Center
Greenbelt, Maryland 20771

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S.S. Holt

Laboratory for High Energy Astrophysics
NASA/Goddard Space Flight Center
Greenbelt, Maryland 20771 USA

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1. INTRODUCTION

The ability to place scientific instrumentation outside the atmosphere of the Earth has been a crucial step forward in a variety of disciplines, but none so much as those for which the atmosphere is completely opaque. Astronomy from space platforms at wavelengths shortward of 912 A^{o} has been arbitrarily divided into XUV, X-ray and γ-ray nomenclature, but the relative convenience of the $\sim$ 1-10 keV ($\sim$ 10 - 1 A^{o}) energy band has made this the range in which the large fraction of X-ray astronomical research has been conducted.

The term "spectroscopy" has been used rather loosely in the X-ray context. Until quite recently, there has been no capability to study spectral features (such as emission lines) in X-rays; rather, the term was (and still is) used to describe the relatively gross measurements of continuum shapes over a dynamic range of about one order of magnitude. The basic problem, of course, is that the exposure obtainable with contemporary instrumentation precludes the effective utilization of dispersive techniques for all but the very brightest sources, so that proportional counters (with resolving power $E/\Delta E$ no better than 5) provide the bulk of the available spectroscopic data. Recently, the launch of the Einstein Observatory has increased the resolving power available with non-dispersive techniques for the entire pre-Einstein catalog to as much as 30 via the use of a cryogenically-cooled solid state spectrometer at the focus of the Einstein telescope, and has allowed the first focal-plane Bragg spectroscopy for the strongest of these (Giacconi et al. 1979).

This introductory section will sketch the elementary spectral signatures of the fundamental physical processes which might be operable in X-ray sources, and the basic instrumental limitations of the experimental techniques. In later sections, the specific contributions of spectroscopic measurements to our present understanding of the X-ray-emitting objects will be discussed, in rough order of increasing spectral complexity.

The simplest model spectra are expected from those astrophysical situations for which both atomic and transfer effects are minimal, i.e. from completely ionized low-density plasmas. In these cases, the X-ray production can be generally characterized as arising in a single interaction of an electron with an electromagnetic field. If the electrons can be approximately represented by a power-law spectrum:

$$\frac{d^2N}{dVd\gamma} \propto \gamma^{-\Gamma}\ \mathrm{cm}^{-3}, \tag{1}$$

where γ is the electron Lorentz factor, the rate at which the electron loses energy in interactions with the field is

$$-\frac{d\gamma}{dt} = \frac{4}{3}\ \frac{\sigma_0}{mc}\ \rho\ \gamma^2 \quad \mathrm{s}^{-1} \tag{2}$$

where σ_0 is the Thomson cross-section, m the electron mass, c the velocity of light, and ρ the energy density in the field. The characteristic cooling time is then simply

$$\tau = \left(\frac{1}{\gamma}\frac{d\gamma}{dt}\right)^{-1} = \frac{3mc}{4\sigma_0 \rho\gamma} \quad \mathrm{s}. \tag{3}$$

In the case of Compton interactions, the field energy density is that in soft target photons (e.g. infa-red or optical). For synchrotron (magnetobremsstrahlung) radiation, the appropriate energy density is that in the magnetic field, $B^2/8\pi$. Both these non-thermal processes yield power law X-ray spectra with energy index $\alpha = (\Gamma-1)/2$, where Γ is the spectral index from equation (1) in the energy range appropriate to the electrons responsible for the X-ray production. For Compton interactions, and X-ray of energy E will result from a single scattering of a photon of initial energy E_0 according to

$$\langle E\rangle = \frac{4}{3}\gamma^2 \langle E_0\rangle \tag{4}$$

while the analogous synchrotron case (in a field of magnitude B) will be

$$\langle E\rangle \approx 10^{-20}\ \gamma^2\ B \qquad \mathrm{ergs}. \tag{5}$$

The production of 10 keV photons from 1 eV photons or a 1 gauss field would require, therefore, γ of 10^2 or 10^6, respectively.

Coulomb collisions can also be formally accommodated by equations (2) and (3), but the X-ray yield is so low per collision ($\sim 10^{-4}$) that the appropriate distribution of electrons to consider is an equilibrium Maxwellian rather than a power law. The equilibrium X-ray spectral form is

$$E\frac{dq}{dE} \approx 10^{-19}\ gZ^2n^2\ (kT)^{-1/2}\ e^{-E/kT} \qquad \mathrm{erg\ cm^{-3}\ erg^{-1}\ s^{-1}} \tag{6}$$

which represents the volume emissivity for bremsstrahlung only, where T is the temperature, k the Boltzmann constant, n the density, Z the effective atomic number of the plasma (~ 1.3 for cosmic abundances) and g the Gaunt factor which, for temperatures in our range of interest, can be approximated by

$$g \approx \frac{E}{kT}^{-0.4}. \tag{7}$$

Unlike the non-thermal processes, bremsstrahlung X-rays are produced by electrons of comparable energies. The total bremsstrahlung luminosity per unit volume can be obtained by integrating equation (6) over energy, so that an effective cooling time can be defined as the ratio of the plasma kinetic energy density to the luminosity per unit volume

$$\tau \approx 10^{19}\sqrt{\frac{kT}{n}} \qquad \mathrm{s}. \tag{8}$$

Since bremsstrahlung cooling dominates above $\sim 10^7$ K, equation (8) is a good approximation at higher temperatures, but will underestimate the cooling at lower temperatures where it is dominated by line emission. Equation (6) is not good enough to satisfy the ability of contemporary instrumentation below about 10^8K, since line emission at the few percent level is presently detectable. This line emission, as well as other spectral features present as perturbations to the non-thermal as well as the thermal continua discussed here, will be treated as they arise in specific astrophysical contexts in succeeding sections.

It is interesting to note that Sco X-1, the brightest X-ray source in the sky, was optically identified by means of its gross continuum spectrum. The early measurements were consistent with a spectrum of the form of equation (6) which, when extrapolated back to the optical, suggested a blue star of approximately 16th magnitude. Just such a star was present in the spatial error box, and the identification has stood the test of time (Sandage et al. 1966). As we shall find in section 5 however, the assumption that equation (6) satisfactorily describes the continuum spectrum of the optical star with which Sco X-1 is identified is completely fortuitous.

The X-rays are detected by photoelectric devices which suffer from several fundamental difficulties. Firstly, they must observe through absorbing windows (including the interstellar medium) which reduce their efficiency and complicate (at least to some extent) their response. Secondly, the inherent response of the detectors is less than perfect in three respects: it has some irreducable background (which may vary in time), the photopeak corresponding to the deposited energy has finite resolution, and there is also some probability that the deposited energy will be incompletely collected. An input spectrum S(E), therefore, will give an experimental "spectrum" in approximate energy-equivalent space E' of the form

$$T(E') = \int_0^\infty S(E)R(E,E')dE + B(E'), \tag{9}$$

where B is the background and R(E,E') includes all the response function considerations described above. Since equation (9) cannot be uniquely inverted for S(E), the traditional means by which the "true" input spectrum is obtained is to assume a form for S(E) with a minimum number of free parameters, formally compute equation (9), and compare the set of trial T(E') with the experimental data via a χ^2 test using the experimental errors in both the data and the background. Data which have higher quality, either because the response function is more sharply peaked or because the errors are smaller, require more free parameters (i.e. a more detailed model) in order to achieve an acceptable fit. This, then, is the means by which spectral parameterization is accomplished, and the results are sensible only if the free parameters have been chosen to correspond to physically reasonable scenarios.

2. NON-DEGENERATE STELLAR SYSTEMS

The availability of dispersed X-ray spectroscopy from the sun has long required the detailed calculation of what have been termed "coronal" X-ray spectra. These calculations assume collisional equilibrium in the plasma and direct escape of the X-ray photons (Raymond and Smith 1977). Until quite recently, however, the data quality did not require even the presence of line components to the bremsstrahlung continuum, as the proportional counter response functions and the statistical quality of the data could be satisfied with bremsstrahlung continua from the few nearby stellar systems which were detectable in X-rays.

These stars (e.g. Capella) exhibited X-ray spectra consistent with such continua at temperatures of order 10^7K, which presented us with at least two fundamental difficulties. First, these temperatures suggest catastrophic mass loss, as the thermal velocities are comparable to the escape velocity. Second, traditional acoustic theories of coronal heating are hard-pressed to heat the coronae of late-type stars to such high temperatures. The problem was further complicated by the discovery of prolific X-ray emission from RSCVn stellar systems at even higher apparent temperatures with luminosities, in the X-ray band alone, which approached a solar constant.

The proof that the X-ray emission is, indeed, thermal in origin, and not some non-thermal effect which was indistinguishable with the relatively poor energy resolution of proportional counters, was given by the unambiguous detection of X-ray emission lines in virtually all of the main sequence dwarfs, of all spectral types, which are bright enough to study. Figure 1 illustrates raw X-ray spectra obtained with the Solid State Spectrometer (SSS) onboard the Einstein Observatory from Capella, indicating the necessity of such fits in accordance with the observed Si XIII, for example.

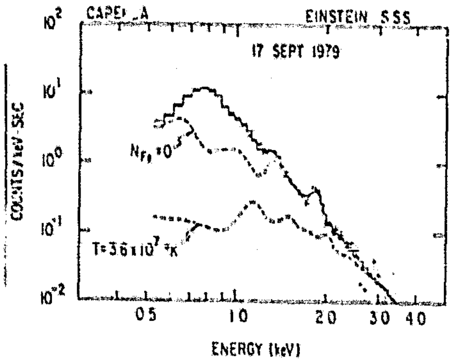

Fig. 1. SSS raw spectrum of Capella, fit with a two-component thermal model (solid histogram). In addition to the prominent Si XIII emission line just below 2 keV, most of the emission at low energies arises from Fe line components characteristic of temperatures < 10^7K (see dashed trace corresponding to setting the Fe abundance to zero). The high temperature component (lower dashed trace) is required only to replicate the positive detection $\geq$ 3 keV.

Very early stars have relatively soft spectra (few times 10^6K) which can be reconciled with turbulence in the radiation-driven stellar wind, but the late stars pose the twin difficulties of having apparently <u>higher</u> temperatures, and X-ray luminosity comparable to the earlier stars.

Rosner, Tucker and Vaiana (1978) suggested that a valuable lesson was available in the Skylab X-ray images of the Sun, wherein the X-ray emission was clearly restricted to magnetically confined loops with dimensions small compared to a solar radius. With the energy for X-ray emission deriving from electromagnetic rather than convective dissipation, the effective temperature T could be simply related to the loop size L and the pressure P:

$$LP \approx 5 \times 10^7 \, T^3 \,. \tag{10}$$

As the RSCVn systems are known to be starspot active, the generalization of equation (10) to late stars with either high rotation or deep convective layers (or both) could result in a dynamo and a geometry capable of satisfying the observed luminosities without catastrophic mass loss (Vaiana et al. 1980). The spectrum, however, still posed some difficulties.

The temperatures associated with the unambiguous emission line components, typically 5 - 10 x 10^6K, could not completely satisfy the spectral data. In all cases, an even higher temperature component ($\sim 5 \times 10^7$ K) was required, in addition. Interestingly, a continuum of temperature components did not provide a better fit than did two distinct temperature regimes coexisting in the stellar systems; three-temperature fits, for example, always resulted in an emission measure at the intermediate temperature which was less than at the two extremes. Swank et al. (1980) have provided a very natural explanation for the bimodal

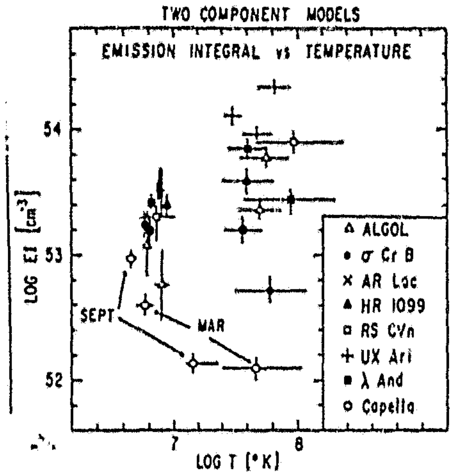

Fig. 2. SSS measurements of the emission integrals associated with RSCVn (and related) binary systems. Note the pronounced separation of the two temperature components, and the fact that in the close binaries (e.g. UX Ari) the high temperature EM exceeds the low temperature EM, while in the more widely separated systems (e.g. Capella) the reverse is true.

temperature distribution illustrated in Figure 2. For reasonable loop pressures (typically 1-10 dyne cm^{-2}), the low-temperature component implies a loop scale size, via equation (10), of the order of the stellar radius: such relatively large loops are consistent with the lack of reproducable eclipses in the X-ray emission in the equatorial binary systems RSCVn, UX Ari and AR Lac which are evident in the optical band. The same pressures imply loop sizes for the high temperature components which are of the order of the binary separation, so that we might suppose that this component alone is associated with the binarity of the stellar systems via connecting loops between them. Simon and Linsky (1980) have recently suggested such connecting loops in UX Ari for very different reasons.

The present capability of X-ray spectroscopy, therefore, has enabled us to verify the thermal nature of the intense soft coronal emission of early stars, to identify a higher temperature thermal component in later stars which could be sensibly associated with stellar magnetic loops, and to detect an even harder X-ray component in late binaries associated with mass exchange between them. This latter effect, unlike the stellar emission components, is not required to be thermal or quasi-thermal by the presence of detectable emission lines. Some sort of hard extension of the line-emitting thermal components is definitely required, but its identification with an equilibrium configuration consistent with the binary orbit scale size is, although physically reasonable, not unique.

3. CLUSTERS OF GALAXIES

Another example of an astrophysical setting in which we might expect a coronal equilibrium model to be an appropriate starting point is in clusters of galaxies. Known to be powerful (> 10^{44} erg s^{-1}) X-ray emitters, the poor spectral resolution of the early surveys could not distinguish among three possibilities for its origin: the integrated emission from individual galaxies, inverse Compton scattering from the 3^{o} background radiation, or thermal emission from a hot intergalactic gas.

The first crude spectra indicated a preference for the latter explanation, which became firmly established with the detection of thermal iron line emission at 6.7 keV from several clusters (Mitchell et al. 1976; Serlemitsos et al. 1977) with proportional counters. The detection of intergalactic iron in the clusters (at relative abundances no less than half-solar) did more than establish a thermal origin for the X-rays; it also demonstrated that the intergalactic gas was not primordial, as it must have been processed through stars in order that a respectable iron abundance be obtained.

Once the sample of proportional counter cluster spectra exceeded a dozen or so, it became possible to attempt correlations between the sample members and between the X-ray and morphological properties of the clusters (Mushotzky et al. 1978). Although the range of observed temperatures was less than an order of magnitude, with a typical value of order 10^8K, there was a pronounced correlation between apparent X-ray temperature and the velocity dispersion of the member galaxies; this argued that the galaxies and the intergalactic gas were in rough equilibrium in the overall gravitational potential of the cluster. The X-radiating gas comprises about 10% of the cluster virial mass, comparable to mass observed in the galaxies, so that we are still far short of observing the large fraction of the virial mass directly.

Cowie and Binney (1977) suggested that a fraction of the cluster mass comparable to that observed directly might be "disappearing" near the cluster center because material at higher density will cool more rapidly (recall from equation (8) that the cooling time for bremsstrahlung goes inversely with the density, and when the temperature decreases below 10^7 K the characteristic time will decrease even more rapidly as cooling via line emission becomes more important). A crude description of the evolution of cluster X-ray morphology begins with a patchy network of X-ray emission condensations around the more massive galaxies, which act as local gravitational centers for the gas entering the intergalactic medium (e.g. Virgo). The cluster then gradually develops spherical emission contours as the galaxies and the gas adjust themselves to the overall cluster potential. The emission may be peaked sharply at the center if a giant cD galaxy is present (e.g. A85), or more smoothly peaked if there is no dominant galaxy (e.g. Coma); see Jones et al. (1979) for graphic evidence of this scenario from the Einstein imaging experiments.

Clearly, the cooling suggested by Cowie and Binney should be most easily observable near the massive galaxies in either the patchy or the cD morphologies, and should manifest itself in the appearance of emission lines of lower ionization states than those characteristic of the bremsstrahlung continuum. The SSS has, in fact, observed just such lower ionization lines in more than a dozen such clusters. In most cases, a two-temperature parameterization satisfies the statistical precision of the data, even though a continuum of temperatures should be more appropriate. In the case of the emission around M87 in Virgo, where the statistical precision is better than in most cases, at least 4 temperature components are required.

4. SUPERNOVA REMNANTS

The situation in supernova remnants is a bit more complicated than in the preceding. In bare outline, the post-impulsive history of supernovae may be characterized by three distinct phases. In the first phase, the ejecta move supersonically out through the interstellar medium, with the attendant shock accumulating material in its path (but not so much as to effectively brake the outflow, i.e. the SNR radius increases linearly with time). When the accumulated mass becomes comparable to the ejected mass, the shock slows down because of its increased inertia. It is during this phase that the X-ray emission becomes important, because of both the increasing mass and the lowering temperature associated with the decreasing shock velocity. When X-ray cooling becomes so large that the expanding remnant loses a significant fraction of its energy, it rapidly slows down (third phase) and eventually breaks up in the interstellar medium.

The second phase is often called the "adiabatic" phase because the X-ray cooling is not yet high enough to have dissipated a significant fraction of the initial energy. The Sedov similarity solution yields the following relations between the remnant radius R, the initial energy in the ejecta ε_0, the interstellar mass density in front of the shock ρ_0, the age of the remnant τ, and the temperature T of the material which has equilibrated with the shock (the present velocity of which is V):

$$R \approx \left(\frac{\varepsilon_0}{\rho_0}\right)^{1/5} \tau^{2/5} \approx \frac{5}{2} V\tau, \tag{11}$$

$$T \approx 2 \times 10^{-9} V^2 . \tag{12}$$

We might expect, therefore, that the apparent X-ray temperatures we measure should be consistent with the observed expansion velocities, as suggested by equation (12). In no cases, however, is this straightforward supposition supported by the data.

Instead, we find that those remnants which appear to be in their adiabatic phase are best characterized by temperatures which are an order of magnitude lower. There can be no doubt about the identification of the best "temperature" to assign to the X-rays, as the preponderance of the observed photons are in emission lines (fully half the measured X-ray photons from the Tycho remnant, for example, are directly attributable to Si XIII and S XV emission).

Although the prominent line components require temperatures below 10^7K, the continua are not consistent with a single temperature regime. In order to fit the data of Figure 3, which extend out to 4.5 keV, Becker et al. (1979) used temperatures of .6 keV and 4 keV. Pravdo and Smith (1979) pointed out that HEAO A-2 proportional counter data from the same remnant required even higher temperature components as the low energy threshold of the analyzed data is raised, indicating that the electrons exhibit a range of temperatures extending beyond 10^8 K (i.e. to the temperature characteristic of the shock velocity). It is clear that the simple picture of a spherically symmetric shock propagating through a homogeneous medium will fail to replicate the details of the emission from SNRs (in much the same way as the assumption of homogeneity in any cosmological model will fail to replicate the presence of galaxies), and the Einstein images of Cas A in X-rays (Murray et al. 1979) indicate the presence of intense knots of emission interior to the shock, which demonstrates the necessity for departures from homogeneity. The variety of possible perturbations from a true equilibrium spectrum will not be discussed here.

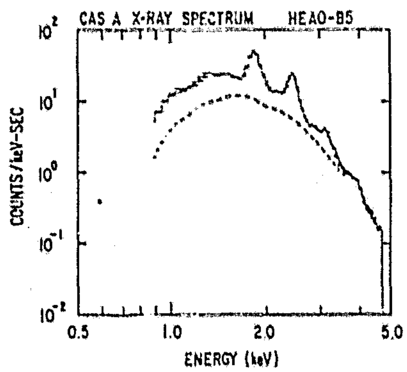

Fig. 3. SSS raw spectrum of Cas A, integrated over the entire remnant. The pronounced emission features are identified with Si XIII and S XV, but features associated with magnesium, argon, calcium and iron are required for an adequate fit to the data. The dashed trace is the bremsstrahlung component of the best thermal fit (the solid histogram), with the difference between the two arising from emission lines.

Rather, we note that Itoh (1979) has calculated the evolution of the X-ray spectra which should be observed from SNRs in the adiabatic phase, assuming that the electron temperature behind the shock front is much lower than the ion temperature. He finds that the two-temperature fits which the SSS requires for adequately fitting about a dozen such remnants (with ages ranging between a few hundred and tens of thousands of years) can be adequately described by a two-temperature fit, and, most important, that the abundances inferred from line strengths are not seriously in error as a result of applying this approximation. Some evidence that this approach is viable is afforded by the focal-plane-crystal-spectrometer (FPCS) onboard the Einstein Observatory, which has resolution sufficient to resolve the helium-like analog of L_α in Si XIII, for example, into its three components: the $1s^2$ - 1s2p resonance transition, and the forbidden and intercombination transitions. In those remnants which have sufficient intensity for study by the FPCS (Cas A, Pup A) the domination of the resonance transition illustrates that the lines do not have their origin in recombination, but arise instead from collisional, or thermal, excitation (Winckler et al. 1980).

The elemental abundances which are typically deduced from the X-ray spectra are not very different from solar, for those elements (Mg, Si, S, A, Ca, Fe) which can be measured directly from their line intensities. The young remnants (Cas A, Tycho) exhibit factor-of-two-or-three excesses above solar abundances (while the older ones, such as Pup A, do not), but we must be observing the dilution effects of a considerable amount of swept-up material in even the younger remnants. Surprisingly, we do not observe significant overabundance of Fe in the Type I remnants. If the characteristic Type I light curve of Tycho, for example, has its origin in the radioactive decay of iron-group material, we might expect to observe very large (factors in excess of 10) overabundance in Fe line emission; it is difficult to avoid this expectation because the Rayleigh-Taylor plasma instability should effectively mix the iron-group material with the other ejecta even if there was original stratification. It would appear, therefore, that the X-ray spectral measurements of Type I SNRs present an imposing constraint to the iron-group radioactive decay hypothesis for their early light curves.

While most SNRs exhibit the thermal appearance described above, there are some which are distinctly non-thermal. The Crab nebula is, of course, the prime example of such a system. As the density of the interstellar medium in the neighborhood of the Crab is much lower than that near the younger remnants Cas A, Tycho and Kepler, there is no indication of the shell-like structure because not enough material has been swept up at the shock front. Instead, the X-ray morphology (like the morphology at lower photon energies) is better described as a filled sphere rather than a hollow one. The discovery of the radio pulsar in the Crab was the key to understanding the fundamental difference between the thermal SNR sources (which derive their energy from the mechanical energy in the original ejecta) and the Crab (which derives its energy from the residual rotational energy in the central pulsar). The virtual identity between the total luminosity of the nebula and the measurable rotational energy loss rate of the pulsar (obtained from the slowing-down rate of the pulses and an estimate of the neutron-star moment of inertia) has removed the historical difficulty of accounting for emission via non-thermal processes with electron lifetimes of the order of a year. We are now certain that the nebular emission in all energy bands is dominated by synchrotron radiation from relativistic electrons which are constantly replenished by the action of the pulsar. The spectroscopic verification of this conclusion is the smooth, featureless power-law spectrum observed from the Crab.

Some other remnants (e.g. 3C58) exhibit the same "filled-center" radio morphology as does the Crab, and their X-ray spectra are similarly featureless. For these, we can assume the implicit presence of a central pulsar, even though the pulsations may not be detected directly. Even if the pulsations are not detectable owing to beaming effects which may hide them from us, it may be possible to observe the thermal emission from the neutron star surface (see Tsuruta 1979), as the Einstein Observatory imaging experiments should be quite sensitive to the presence of such objects if their temperatures exceed $\sim 10^6$ K. The lack of remnant neutron stars in the early Einstein data is a bit disconcerting. The very young remnants Cas A, Tycho and Kepler have column densities through the interstellar medium too large to detect 10^6 K objects, but the general deficiency of point-like soft sources in somewhat older remnants with much smaller columns (e.g. Pup A) is not promising. Very much older neutron stars (i.e. radio pulsars) are also not detectable in general, but here the surface temperatures are expected to be too cool even without the invocation of any exotic cooling mechanisms. In order to account for the observed radio pulsar production rate, such exotic cooling (e.g. pion condensation) is almost certainly required to account for the lack of observable neutron stars in SNRs; either that, or we are faced with the necessity of producing neutron stars "quietly" with higher efficiency than we can "noisily" (i.e. with the attendant SNR which is a testament to at least some fraction of the stellar binding energy released in the neutron star production).

5. DEGENERATE STELLAR SYSTEMS

With the exception of a few supernova remnants and some superluminous early stars, all of the X-ray sources in our galaxy with X-ray luminosity in excess of a solar constant arise in binary systems, one member of which is a degenerate dwarf, a neutron star, or a black hole. Unlike the supernova remnants which derive their energy from the mechanical energy created at the time of the implosion, or the stars which derive their energy from contemporary nuclear burning, these X-ray emitters derive their energy from the gravitational energy liberated when mass is transferred to the surface of the degenerate member of the system:

$$L_X = \eta G \frac{\dot{M}_X M_X}{R_X} \quad , \tag{13}$$

where R_X and M_X are the radius and mass of the compact X-ray star, $\dot{M}_X$ is the rate at which mass is accreting onto it, and η is the efficiency with which the gravitational potential energy may be converted to X-radiation (a typical value might be ~ 0.1).

Of the catalogued varieties of degenerate X-ray binaries, we are certain that white dwarfs are the compact objects in cataclysmic variables, and that neutron stars are present in the X-ray "pulsars". Note that the latter have unfortunately been given the same name as the central source in the Crab nebula; while it is true that both types are rotating neutron stars, the fact that those in binary systems are acquiring rotational kinetic energy rather than expending it represents a fundamental difference between the two. There are many historical classifications of sources (e.g. "soft transients, bursters, bulge sources, halo sources) for which arguments have been made for both dwarf and neutron star compact objects. In addition, there is strong circumstantial evidence (based on mass estimates) that at least one source, Cyg X-1, must contain a black hole.

Spectroscopically, the prime characteristic which distinguishes galactic binaries from the sources discussed previously is that photon transport in the source can no longer be ignored. In those sources, the assumption of direct transmittal of the freshly created X-ray photons to our detectors, with only photoelectric absorption in the interstellar material intervening, was a good one. Here, however, the X-ray photons are expected to suffer a considerable number of inelastic collisions before escaping the source region, so that we cannot measure the production spectrum directly.

In most accretion scenarios, the infalling material cannot fall directly to the surface of the neutron star because of the angular momentum that it carries. The material must, therefore, spiral into the star, so that the probability of an accretion disk forming around the object is quite high (e.g. Pringle and Rees 1972). X-radiation produced by viscosity in the disk will not be characteristic of a single temperature, and the optical depth for Thomson scattering will greatly exceed unity. Even if the emission arises close to the stellar surface rather than from deep within the disk (as we might expect near the magnetic poles of X-ray pulsars), obscuration by material in the disk or at the Alven surface will almost certainly result in high Thomson optical depths for most geometries. In fact, the very condition which limits the luminosity of compact sources is based upon the balance between Thomson-scattered radiation pressure and gravitation, i.e.

$$L_x \lesssim 10^{38} \frac{M_x}{M_\odot} \quad \text{erg s}^{-1} \tag{14}$$

is the Eddington condition which imposes an upper limit on spherically symmetric emission from an object of mass M_x. The same compactness which allows degenerate stars to be powerful X-ray sources often prevents the direct observation of the initially-produced X-radiation, via electron scattering in the source region itself. Emission signatures, such as thermal emission lines, will be largely smeared by the transport of the photons out of the source (see Sunyaev and Titarchuk 1979, for a recent treatment of this effect). Typically, smooth power-law spectra are expected to emerge from the source over limited dynamic ranges, with the power law indices determined primarily from the Thomson optical depth and the scattering-electron temperature, and only secondarily from the input X-ray spectrum, if the scattering depth is high.

Cataclysmic variables, which include all varieties of novae, are binary systems in which one member is a white dwarf. They appear to suffer considerably less from Thomson scattering than do most other degenerate X-ray sources, possibly because they radiate well below their Eddington-limited luminosities. They possess accretion disks from which most of the optical variation is observed (in particular, that associated with the "hot spot" where the accreting material is channelled into the disk), but the disk temperatures are too cool to be responsible for the X-ray emission. The X-rays are presumed to arise, instead, from material which is falling directly to the stellar surface. Fabian, Pringle and Rees (1976) have calculated that effective temperatures of $\sim 10^8$ K should be observed from material which is being spherically accreted onto white dwarfs, and the spectra of cataclysmic variables observed with proportional counter experiments have detected just such thermal components from U Gem, SS Cygni, EX Hydrae, and the polar system AM Her. It is important to note that only in the latter is there direct evidence for X-ray production at the stellar surface; the hard X-radiation from AM Her exhibits modulation consistent with self-eclipsing of the magnetic poles, with subsequent reflection and fluorescence from adjacent regions of the system. The other cataclysmics have spectra consistent with optically thin bremsstrahlung, and the presumption of spherical accretion is based only upon consistency with the observed temperature.

Outbursts from the cataclysmics are characterized by very soft ($kT \lesssim 100$ eV) emission that may be related to episodic nuclear burning on the stellar surface, which is the traditional explanation for their classification as novae. The total luminosity in this softer emission is considerably in excess of the steadier 10^8 K emission, and recent evidence from the SSS indicates the presence of an even weaker "coronal" (i.e. $\sim 10^7$ K) emission component; the origin of the latter is not well-understood.

Kylafis and Lamb (1979) have generalized the problem of accretion onto a white dwarf, and have concluded that a peculiar relation between apparent X-ray temperature and the X-ray luminosity can uniquely determine the stellar mass, luminosity and distance. Luminosity-temperature variations from the source Cyg X-2, observed with the Copernicus satellite, appeared to exactly reproduce the calculations; this is a rare instance in which the correlation of a spectral parameter (the apparent temperature) with the apparent luminosity is capable of yielding detailed information about the fundamental stellar parameters. Unfortunately, the prototype for the application of the model, Cyg X-2, is almost certainly a neutron star rather than a white dwarf (Cowley, Crampton and Hutchings 1979), so that the model cannot uniquely identify the nature of the degenerate stars and, therefore, cannot unambiguously determine the system parameters.

Those sources which exhibit periodic modulation of their X-ray emission on timescales $\lesssim$ 1000s have been termed "X-ray pulsars", and all of these must certainly be neutron stars. Spectroscopically, these sources exhibit several characteristics which are not shared by the bulk of the galactic X-ray catalog. Perhaps the most obvious of these is the very hard ($0 \lesssim \alpha \lesssim 0.5$) energy index of the phase-averaged power law spectrum at energies below about 20 keV, at which energy the spectrum sharpens dramatically so that little or no continuum emission is observed above 30 or 40 keV. Fully half the sample of such X-ray pulsars, it should be noted, are associated with recurrent episodes of enhanced ($> 10^3$) emission which are believed to arise from increased accretion onto the neutron star surfaces.

Other spectral characteristics of the X-ray pulsars are variable low energy absorption (i.e. the effects of apparently cold material in the line of sight), spectral variations as a function of pulse phase, fluorescent Fe emission, and the possibility of cyclotron emission or absorption characteristic of intense magnetic fields ($B > 10^{12}$ gauss) in at least two (and possibly all) of the pulsar sources.

If we assume that the X-ray emission originates close to the neutron star from material which is funnelled into the polar regions by the magnetic field, all the characteristics of the X-radiation (many of which are illustrated in Figure 4) may further be assumed to arise from geometrical considerations, i.e. "beaming" of some sort in the production process itself and/or transport of the X-radiation through the infalling material. The detailed models are quite complicated and will not be discussed in detail here, but they generally relate the sharp cutoff near 20 keV to the high magnetic field at the stellar surface, which also can explain the reemergent emission near 50 keV as a cyclotron line component. The variations in spectrum with phase are tied to both the opacity of the material which is held out at the Alven

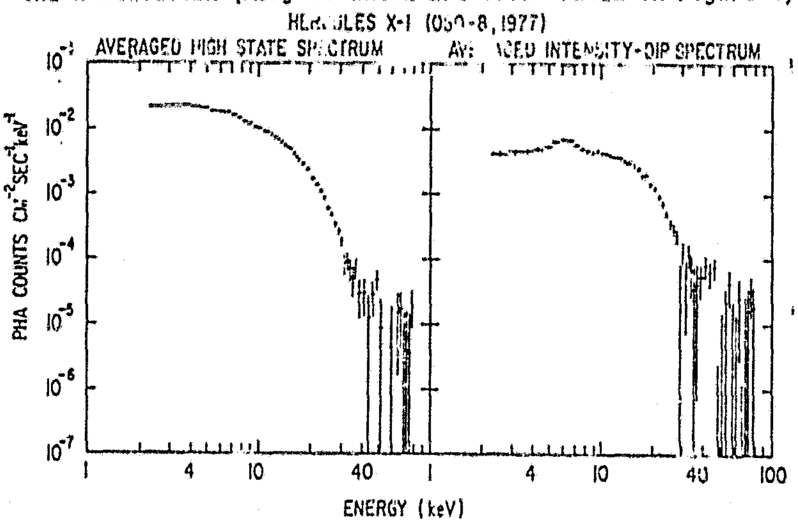

Fig. 4. Two raw proportional-counter spectra of Her X-1 averaged over the pulse period. Note that the severe attenuation in the second panel reveals the Fe fluorescence feature at 6.4 keV which is not obvious when our view to the central source is less obscured. Note also the positive detection $\gtrsim$ 50 keV which may represent a cyclotron line component.

surface and the fundamental beaming process, while the Fe fluorescent emission near 6 keV (which is most evident in the second panel of Figure 4, where a non-fluorescing component of the emission is suppressed) arises from irradiation from the central source. Spectral measurements are providing a wealth of detailed input to the very elaborate computer models which are presently being generated to replicate the emission from these sources.

In contrast, the large fraction of galactic X-ray sources have no pronounced spectral features (e.g. emission lines or sharp spectral breaks). They can generally be fit with a bremsstrahlung continuum at a temperature of several keV; deep exposures from satellite experiments may require deviations from a single-temperature continuum, but the required deviations are non-unique. The spectra are generally consistent with the presence of Fe K-emission features which are broadened by Thomson scattering, and are usually spectrally harder when the intensity is higher. Without additional information, such as we might obtain from the determination of binary periods for example, we have no real handles on the nature of the compact objects, or on the binary system masses or separations. Most of the galactic X-ray sources, which include the types historically called "bulge", "soft transient" and "bursters", fall into this category. It is likely that most of them have a common origin in a neutron star accreting mass from a binary companion.

While the so-called "burst" sources exhibit these featureless spectra in their quiescent states, it is interesting to note the implications of the spectra of the individual bursts (i.e. intense increases in the emission on timescales of seconds). The ones which have been designated Type II, i.e. those which are repetitive with relative intensities proportional to the time since the previous burst, are not spectrally distinct from the quiescent source; this is consistent with their reconciliation in terms of storage and release to the neutron-star surface, with the X-radiation arising in the conversion of gravitational potential energy. Type I bursts, on the other hand, have a distinct black-body spectral character which differs considerably from the quiescent source spectrum. Furthermore, the Type I burst spectrum appears to cool like a black-body of constant radius, where that radius is of the order of that of a neutron star. This fact, first noted by Swank et al. (1977), has been used by van Paradijs et al. (1979) to argue that the burst sources are neutron stars, as the Type I bursts appear to be consistent in all respects of He-burning flashes on neutron star surface, as calculated by Joss (1979).

There are, of course, several anomalous source spectra which do not fit neatly into any of the categories discussed above. The prime black hole candidate Cyg X-1, for example, exhibits a power law spectrum which is remarkably constant in both index and intensity with time over the energy range 1-100 keV, at least during the extended low states which constitute the large fraction of the source history. Even though Cyg X-1 exhibits considerable micro-structure on timescales < 1 sec, on timescales > 1 hour it is one of the most stable sources in the galactic catalog. This must clearly represent a true steady-state condition, and Sunyaev and Trumper (1979) have modelled the emission as arising from the superposition of Thomson-scattered components of an accretion disk around a black hole.

Finally, no discussion of the spectra of galactic X-ray sources can be complete without at least a mention of Cyg X-3. Like Cyg X-1, it appears to have a long-term intensity history which is roughly bimodal. In its high state it appears to exhibit a black-body spectrum, and its low state is characterized by a much harder spectrum extending out to higher energies (interestingly, the total X-ray luminosity in both cases is about the same, and consistent with the Eddington-limited luminosity for a unit solar mass). It exhibits a very high column density, so that virtually no emission below 1 keV can be observed, and features the most pronounced Fe-K-emission line observed in any X-ray source (Serlemitsos et al. 1975); the Fe-K line alone is among the 50 brightest (in apparent magnitude) sources in the sky. This line arises from fluorescence of the material responsible for the large column density around the hot source, and the SSS has detected S-fluorescence, as well. The X-ray emission is modulated with a period of about 5 hours, comparable with the binary period of the cataclysmics discussed earlier in this section, but the X-ray luminosity is more than 10^3 times that of any of the cataclysmics. With all these clues, however, we still cannot unambiguously define the source geometry (i.e. whether the thick material is a stationary shell or a wind from the companion), or even the nature of the compact object with certainty. The lesson to be learned from Cyg X-3 is that we can always achieve consistency with a variety of potential models if the data base at our disposal is limited: higher quality data are bound to elicit unexpected differences in sources which we assumed were generically similar. These differences may be minor, in which case the generic similarities may be preserved, or point to basic differences which were unanticipated. We should be cautious, therefore, about the characterization of the large fraction of the galactic sources which, at present, have minimal spectral restrictions on their detailed modelling.

6. ACTIVE GALACTIC NUCLEI

Quasars have been found to be prolific X-ray emitters with the Einstein Observatory (e.g. Tananbaum et al. 1979), as had the less luminous (but less distant) Seyfert I galaxies which were previously observable with lesser sensitivity. Current prevailing opinion places the energy source for quasars, BL Lacs and Seyfert galaxies in a central black hole (or equivalent) of mass $\sim 10^{6-8}$ M_o. The X-ray emission must ultimately have its energy input arising from the conversion of gravitational potential energy, and measurements of the timescale for variability indicate that the large fraction of the X-ray emission must emanate from a central source with a characteristic dimension which is smaller than a light-day.

Both quasars and Seyfert I galaxies exhibit very broad emission lines. A variety of arguments (e.g. Davidson and Netzer 1979) place the origin for this emission in cool clouds or filaments at a radius of about 0.1 pc from the central source. The UV continuum which excites this cool material is presumed to arise coincidently with the X-ray emission. Still further out, at distances approaching 1 Kpc, is additional cool material responsible for the narrow lines observed from such active galactic nuclei. BL Lacs are quite similar to quasars in luminosity, but do not exhibit the line emission. It is likely that the core region within the central light-day of all three types of systems is quite similar.

The X-ray emission from the core regions, as in the case of binary X-ray sources, cannot be assumed to emerge without substantial Compton scattering. Fabian (1979) has recently reviewed the possible mechanisms which might be most directly responsible for the X-rays observed. If there exists very hot plasma ($T > 10^8$ K), as might be expected from shock heating or accretion onto the central object, there will be a direct bremsstrahlung component emanating from the nucleus. The presence of the non-thermal continuum responsible for exciting the broad-line clouds will result in X-ray production via Compton scattering from the high temperature electrons, however, so that the emergent spectrum would not be easily interpretable even if these were the only possibilities. The presence of ultrarelativistic electrons complicates the story further, as X-rays may be produced via direct synchrotron radiation, or from Compton interactions with the far infared synchrotron radiation which the same electrons produce in the ambient magnetic field. Clearly, the possibilities are almost limitless, and the emergent spectra are invariably featureless, so that it is unreasonable to expect that X-ray spectra obtained over a limited dynamic range will uniquely specify the model details. Nevertheless, some clear consistencies are beginning to emerge.

The Seyfert I nuclei provide the largest sample of extragalactic nuclei for which we have spectral data, and they exhibit remarkable uniformity over two orders of magnitude in luminosity. For about two dozen Seyferts for which we have spectral data from proportional counters in the energy range $\sim$ 2-40 keV, all are well-fit power-law approximations with $\alpha \sim 0.7$ (the rms deviation in the index for the sample is 0.1, which is about a factor of three smaller than the one-sigma error on most of the individual fits). All are better-fit by power-laws than by high-temperature thermal continua, but the latter approximations cannot be formally excluded in most cases.

The SSS has measured the .5-5 keV spectra of about one-third of this sample, all of which are consistent with the power-laws measured at higher energy (for these, thermal continua fits to the combination of proportional counter and SSS data can be formally excluded). In almost all instances, there is no evidence for a low-energy turnover which would be suggestive of absorption in the source itself. One notable exception, NGC 4151, exhibits such a large column density at 2 keV that its positive detection at 1 keV implies "holes" in the absorbing column. Holt et al. (1980) have shown that clouds with dimensions smaller than the central X-ray source can plausibly be associated with the X-ray absorption as well as the broad emission lines if their covering factor over the NGC 4151 X-ray source is about 90%. If this covering factor decreases with luminosity (i.e. if the clouds move out from the central source with luminosity without increasing their number fast enough to maintain the same covering factor), the lack of absorption in Seyferts and quasars with much higher luminosity than NGC 4151 can be understood without altering the geometry.

The sample of true quasars for which we have spectral information is considerably more sparse. Only 3C273 and 4U0241+62 have well-measured spectra with proportional counters in the energy range 2-40 keV, and their best-fit values are mutually exclusive. The former has $\alpha = 0.41 \pm .02$ and the latter $\alpha = 1.0 \pm .3$ (Worrall et al. 1980), so that their slopes bracket the mean value for the Seyferts. The SSS data for these two are consistent with the proportional counter data, as are the results for a few extreme Seyfert I or N galaxies which are sometimes classified as quasars (e.g. IC4329A and Fairall 9 each have $\alpha \gtrsim 0.8$, so that these near-quasars appear to have, like 4U0241+62, spectra which are slightly steeper than the average Seyfert I galaxies).

The five BL Lac objects for which we have both proportional counter and SSS data exhibit extreme variations in their spectra (as well as their intensities: they can be variable by more than an order of magnitude, in contrast to the factor-of-a-few in the quasars and the < 50% in the Seyferts). A characterization of their spectral variability can be attempted in terms of two spectral components, as follows. At the lowest energies measured, their spectra appear quite steep ($\alpha > 1$ always, with $\alpha \gtrsim 3$ at times). Occasionally (in approximately 20% of the observations which have been made of all five objects taken as a whole) a distinct flattening of the spectrum is observed at higher energies, implying a second component with characteristic $\alpha \lesssim 0$.

There are some qualitative differences among the active galactic nuclei which might shed some light on the differences in the X-ray spectra observed. Seyfert I nuclei and BL Lac objects appear to have at least two sharply contrasting differences: the latter are extremely radio "loud" (and variable) and are generally associated with elliptical galactic

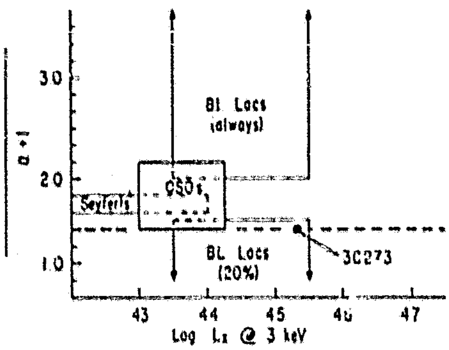

Fig. 5. Spectral indices of compact extragalactic sources, by type, as determined from the Einstein SSS and the HEAO A-2 experiments.

geometries, while the former are typically radio "quiet" and almost invariably associated with spirals. The quasars form a quite inhomogeneous sample, ranging from the intense radio loud objects like 3C273 to the much more common (> 90%) radio quiet sources; IC4329A, the extreme Seyfert I which has also been labelled a quasar, is both radio quiet and near enough for the spiral galactic structure to be clearly observed in the optical.

It is conceivable, therefore, that the typical Seyfert I power law ($\alpha \sim .7$) and the slightly steeper spectra observed from the radio quiet quasars ($\alpha \sim 1$) are manifestations of the same X-ray production process(es), where the limits of the sample suggest slight spectral softening with luminosity. This could be consistent with Compton scattering being responsible for the output spectral form.

The BL Lac spectra imply a different interpretation for the radio loud sources. In these cases, we might assume that the soft spectral component is largely synchrotron in nature, and that the even more variable hard component is the Compton scattering of the infa-red or radio synchrotron photons with the same electrons responsible for those photons. We might expect radio loud quasars to exhibit either the hard component (3C273?) or, more often, the soft synchrotron component, or a combination of the two.

While the above is largely conjectural, it may have important implications with respect to the extent to which quasars contribute to the "diffuse X-ray background". Marshall et al. (1980) have carefully fit this "XRB" above 3 keV and at high galactic latitudes (to minimize possible galactic contamination) to a bremsstrahlung spectrum at a characteristic temperature of 45 keV; the fit is excellent over a dynamic range of 20 from 3 keV to 60 keV, and excludes a single power-law over that range. If modelled with a homogeneous hot intergalactic medium, the intensity of the XRB would require about 1/3 the critical closure density of the universe! Theoretical arguments demand that such a hot IGM must be clumped, in which case the average density would be much lower, but the more fundamental issue is to what extent any hot IGM is required, at all.

The recent Einstein imaging data have been interpreted as being consistent with quasars being responsible for the totality of the XRB (e.g. Giacconi et al. 1979b; Tananbaum et al. 1979). The present results can explain approximately 25% of the XRB at about 1 keV (assuming that the 45 keV spectrum can be extrapolated down to there), so that the generally accepted assumption of pronounced quasar evolution might explain the totality of the XRB if we extrapolate past the present Einstein sensitivity. In fact, the extrapolation need not extend much past a visual magnitude of 21 or so, in order that the XRB not be exceeded by the quasar contribution (e.g. Setti and Woltjer 1979).

The spectroscopic constraint on this hypothesis is interesting, if not as definitive as we might hope it could be. The XRB cannot be dominated by an average spectral form as steep as that of the Seyfert I galaxies, or the radio-quiet QSO's which are slightly steeper. In fact, the only compact extragalactic sources with spectral components as flat as the XRB are the occasional flat components of the BL Lacs and the radio loud quasar 3C273. If the integrated contribution from all QSO's is dominated by the radio quiet objects (which are so much more numerous), why is there this glaring spectral inconsistency? And is there any significance to the excellent fit to a thermal spectrum?

It has been argued that the latter coincidence is no more than accidental. Since the Einstein imaging data indicate that at least 25% of the XRB near 1 keV arises from discrete sources with distinctly non-thermal spectra, the possibility of synthesizing a thermal-appearing net spectrum with a substantial thermal component appears to be problematic, as the sum of thermal and non-thermal components can never appear thermal. In fact, the available data do not deny this possibility, since the thermal-appearing spectrum is a fit to the 3-60 keV data, and the Einstein imaging data is concentrated $\lesssim$ 1 keV (and the 25% is based upon an extrapolation of the 3-60 keV spectrum). One can construct a scenario where the radio-quiet quasars can replicate the Einstein imaging results, and can combine with the Seyferts to match the > 100 keV XRB (which far exceeds the extension of the 45 keV thermal spectrum), while ~ 80% of the 3-60 keV XRB can still arise from a true thermal component (Holt 1980). This is not to suggest that a substantial true thermal component is indicated, but only that the available data can not rule it out. The extent to which it might represent emission from an intergalactic gas is quite another matter, however.

Bookbinder et al. (1980) have recently proposed a rather natural explanation for the apparently thermal main contribution to the XRB. Young galaxies, with lots of supernovae and pulsars, may produce intense galactic winds with temperatures on the order of 100 keV. If such galaxies are common at epochs earlier than Z ~ 1, it may be these which are responsible for the intense 45 keV component. Interestingly, quasars can still dominate the XRB $\lesssim$ 1 keV because their spectra are steeper, and $\gtrsim$ 100 keV because their spectra are harder. Unfortunately, the ability to determine, with certainty, the origin of the large fraction of the energy density in the XRB may have to wait until such time as we are capable of measuring X-rays, with sensitivity comparable to Einstein, at wavelengths where this energy density peaks. Until then, the difficulty associated with reconciling the XRB with active galactic nuclei which have spectra apparently inconsistent with the XRB will remain a formidable obstacle.

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