

X-RAY SPECTROSCOPIC OBSERVATIONS AND MODELING
OF SUPERNOVA REMNANTS

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ABSTRACT

X-ray spectroscopy can be a valuable tool in interpreting the temperatures, densities, and elemental abundances in young supernova remnants. Because of the large enrichment of the remnant ejecta in nucleosynthetic products of the stellar explosion, emission lines from He-like and H-like ionization stages of many heavy elements are prominent in HEAO-2 spectra. Precise abundance determinations, however, remain elusive because of the need for non-ionization equilibrium spectral modeling.

This review describes the recent x-ray observations of young remnants and their theoretical interpretation. A number of questions remain, concerning the nature of the blast wave interaction with the interstellar gas and grains and of atomic processes in these hot plasmas. Future x-ray spectrometers with high collecting area (10^3 cm^2), moderate spectral resolution ($E/\Delta E \sim 100$) and good spatial resolution (5-10") can make important contributions to our understanding of supernova remnants in the Milky Way and neighboring galaxies and of their role in the global chemical and dynamical evolution of the interstellar medium.

I. INTRODUCTION

If X-ray spectroscopy is to be used as a diagnostic tool for astrophysical plasmas outside the solar system, it will most likely prove itself in observations of young supernova remnants (SNRs). Heated to temperatures of 1-10 keV and enriched with the heavy element products of nucleosynthesis, the gas in these remnants emits prodigiously in X-ray lines (Holt 1980). Models of the emission from elements with atomic number $6 \leq Z \leq 28$ provide measures of plasma temperature, elemental abundances, and the degree of approach to ionization equilibrium. These observations yield valuable information on the type and structure of stellar explosion, the nucleosynthetic products, and the subsequent interaction of the blast wave with interstellar gas and grains.

Future X-ray spectrometers can make further contributions to our knowledge of SNRs in the Milky Way and neighboring galaxies. This review presents a brief summary of the past observations, the theoretical modeling, the primary unanswered questions, and the requirements for future instruments.

II. OBSERVATIONS

Most young remnants ($t < 1000$ years) have been observed by the HEAO-2 Imaging Proportional Counter (IPC) or by the High Resolution Imager (HRI). Shell-like emission was found in the remnants Tycho, Cas A, Kepler, and others; in a few cases such as the Crab Nebula and Vela, the remnant shells are filled. Although the spherical morphology is reassuring evidence for the blast wave model of SNRs, it is yet unclear whether the detailed emission structure is best described by the Sedov adiabatic similarity solution (Sedov 1959; Taylor 1950), or by reverse-shocked ejecta (McKee 1974; Gull 1975; Kirschner and Chevalier 1977).

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Two of the HEAO-2 spectrometers have resolved prominent emission lines from heavy elements in young SNRs. The Solid State Spectrometer (SSS), with effective area $\sim 100 \text{ cm}^2$, observed remnants in our galaxy and the Large Magellanic Cloud with an energy resolution $\Delta E \cong 160 \text{ eV}$ from 0.6 to 4.5 keV (Becker *et al.* 1980ab). The strongest lines (Figure 1) arise from He-like ionization stages of Ne, Mg, Si, S, Ar, and Ca, as well as from blended L-shell lines of Fe near 1 keV.

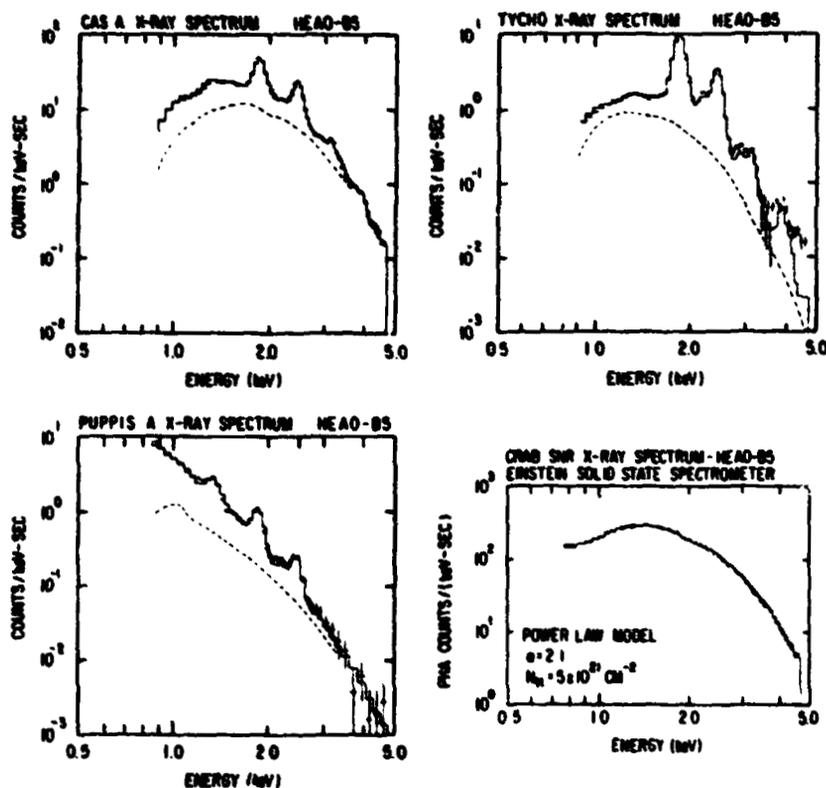


Figure 1. Einstein SSS experimental spectra from four young SNRs (Holt 1980).

The Focal Plane Crystal Spectrometer (FPCS), with effective area $\sim 2\text{-}3 \text{ cm}^2$, pushed X-ray spectroscopy even further, separating the He-like "triplet" lines (resonance, forbidden, and intercombination) of O VII and Ne IX in Puppis A

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(Winkler *et al.* 1981) and resolving the H-like $L\alpha$ and $L\beta$ lines of O VIII and Ne X and several lines of Fe XVII (Figure 2).

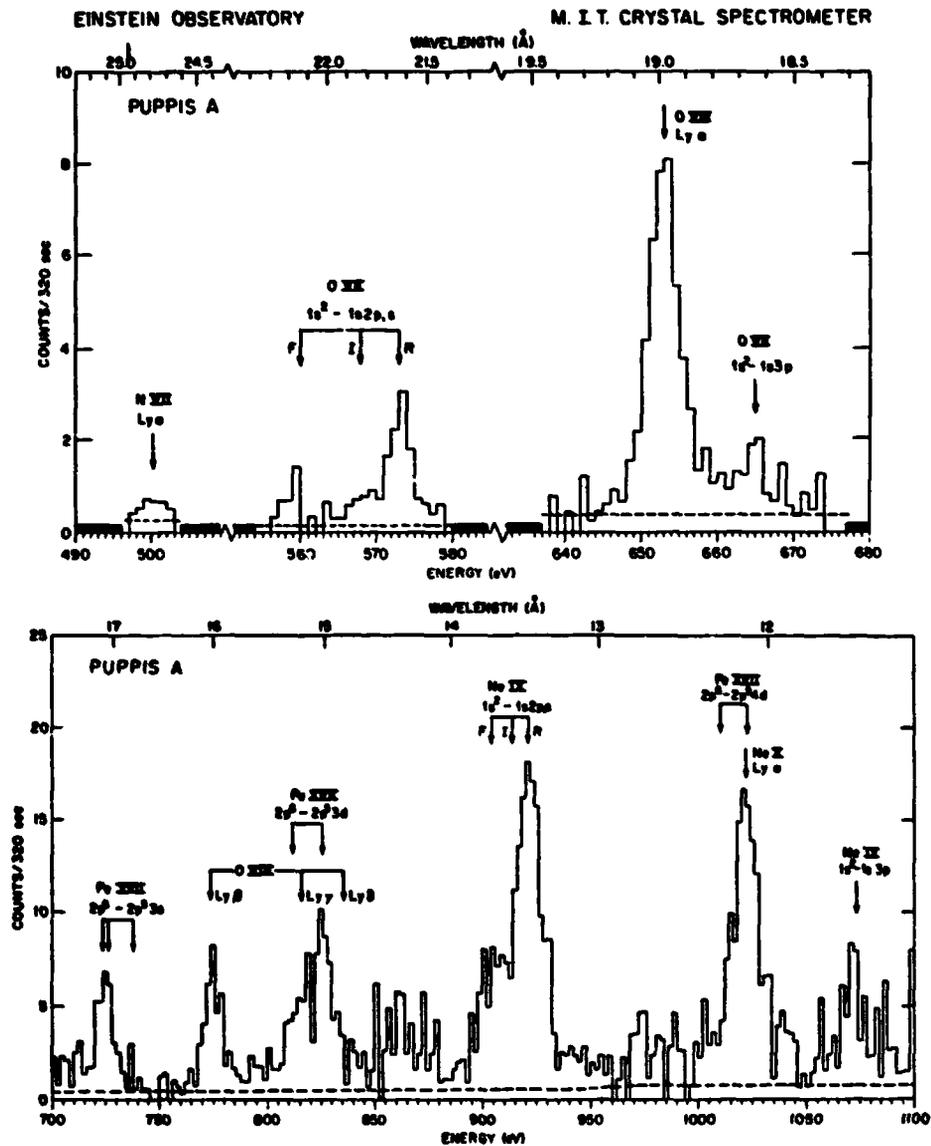


Figure 2. HEAO-2 (FPCS) spectra of the Puppis A SNR (Winkler *et al.* 1981), showing He-like "triplet" lines (marked F, I, R), H-like $L\alpha$ and $L\beta$ lines of O VIII and Ne X, and several L-shell lines of Fe XVII. Dashed lines indicate background.

Preliminary coronal equilibrium analyses of the SSS data (Becker et al 1980ab) required two temperature components to fit the spectra: a "hard" component with $kT \sim 5-10$ keV to fit the continuum and a "soft" component with $kT \sim 0.5$ keV to fit the H-like to He-like line ratios. These equilibrium models for Tycho suggested that Si and S were enhanced by factors ~ 10 over their cosmic abundances, but that Fe was underabundant by a factor 0.15. Even stranger were the derived abundance enhancements of Ca (x 76) and Ar (x 35). All of these abundances are suspect, however, because of the possibility of substantial departures from ionization equilibrium.

III. THEORETICAL MODELING

Spectral emission models of hot, optically-thin, low-density plasmas (Shapiro and Moore 1976; Raymond and Smith 1977; Shull 1981a) are now a familiar tool in x-ray astronomy for deriving the temperatures, densities, and abundances in solar flares, stellar coronae, and intracluster gas. Using the most accurate available rates for collisional ionization and recombination to compute the equilibrium ionization fractions of the abundant elements, these models then generate the spectral emissivity of the hot plasma in the x-ray continuum and emission lines. Coupled with a χ -square fitting program, these spectral codes yield the plasma temperature and elemental abundances.

The application of ionization equilibrium (IE) models to young SNRs is questionable for three major reasons:

1. The SNR ages are often comparable to the characteristic collisional ionization time for He-like and H-like ions.
2. The dramatically different temperature components (~ 5 keV and ~ 0.5 keV) required to fit the continuum and lines, respectively, suggest an ionizing plasma in a transient stage.
3. The ratio of the resonance line to forbidden plus intercombination line of He-like O VII and Ne IX (Winkler et al. 1981) is too high for ionization equilibrium (Pradhan and Shull 1981).

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As shown by Itoh (1977), non-ionization-equilibrium (NIE) effects may have a significant effect on the emissivity of young remnants. If the shocked plasma has not had sufficient time to ionize Si or S to their equilibrium state at temperature $kT \sim 5$ keV, the He-like stages (and the resulting emission line strengths) may far exceed their values in equilibrium.

NIE models of X-ray emission from a hot plasma are far more complicated than IE models, because they involve the calculation of the time-dependent ionization history of every parcel of emitting plasma. For young SNRs, NIE modeling requires the coupling of gas hydrodynamics with a time-dependent ionization code and a spectral emission code (Shull 1981b). Recently computed NIE models of young remnants have been used (Shull and Szymkowiak 1981) to derive elemental abundances from the SSS data (Figure 3).

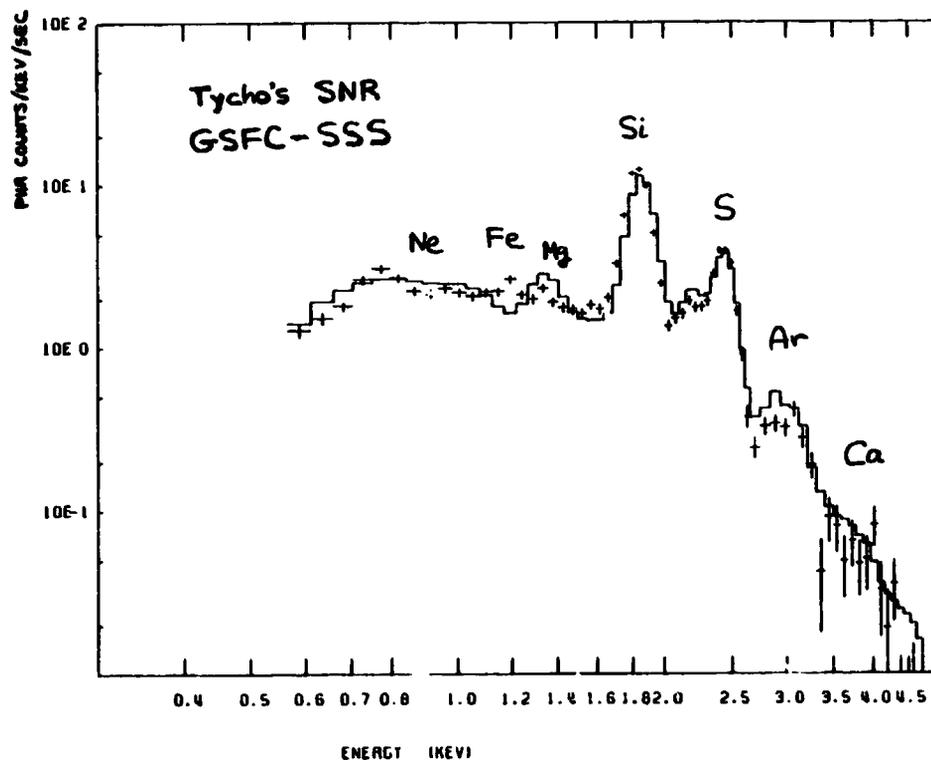


Figure 3. Einstein SSS data (crosses) and NIE model (solid lines) for Tycho's SNR (Shull and Szymkowiak 1981). Emitting elements are marked near their strongest lines.

Table 1 compares the abundances for Tycho derived from a single-velocity NIE blast wave model with those derived from a 2-temperature IE model. Although Si and S are still enhanced in the NIE model, Fe is no longer underabundant, and Ca and Ar have more realistic abundance enhancements. Although a great deal of further work remains in this area, it appears that NIE models with a single velocity can achieve nearly as good a fit to the Tycho spectrum as 2-temperature IE models. The Ca, Ar, and Fe abundances appear more realistic, and the single velocity parameter is physically simpler than the multi-component IE fit.

Several theoretical questions remain to be answered.

1. What is the ratio, T_i/T_e , of ion to electron temperatures behind the blast wave? (Pravdo and Smith 1979).
2. Do NIE effects fully explain the low ratio of He-like forbidden and intercombination lines to the resonance line?
3. What fractions of emission come from the blast wave and from reverse-shocked ejecta? What are the ejecta masses?
4. How sensitive are the derived NIE abundances to the assumed dynamical model (the range of densities and temperatures) of the remnant?

IV. FUTURE STUDIES

Further observational advances in answering the four questions posed in Section III will undoubtedly require x-ray instruments with higher sensitivity, greater spatial resolution, and better spectral resolution. However, in designing such instruments, one must decide which of these requirements are essential and which are only advantageous. Let us examine the four questions in order.

The degree of ion-electron temperature equilibration may be studied by measuring the hard x-ray (5 - 30 keV) continuum in SNRs (Pravdo and Smith 1979; McKee and Hollenbach 1980). At the low densities characteristic of remnants, the Coulomb equilibration time (Spitzer 1962) may be quite long. Plasma instabilities behind collisionless shock fronts may equilibrate T_i and T_e on a

faster scale (McKee 1974). To study these effects observationally, one requires high spatial resolution to identify the location of the hard continuum emission relative to the blast wave.

An observational study of He-like line ratios requires substantially greater spectral resolution than that afforded by the SSS. While the FPCS had the needed resolution, it was only capable of studying the brightest remnants. Therefore, these observations probably require a different type of spectrograph with both good energy resolution and high effective area. Table 1 presents the energies of the He-like resonance lines and the energy resolutions necessary to separate the forbidden and intercombination lines. Although O VII and Ne IX require the lowest resolution (~ 100), the Si XIII and S XV lines are far stronger in most remnants. A study of line ratios for a range of elements should show a progressive departure from equilibrium with increasing atomic number Z . However, it is probably most fruitful to study the O and Ne lines with a sensitive instrument having good spatial resolution in order to identify variations in ratios from specific regions in a large number of remnants.

The answer to the third question--that of the relative contribution of "blast wave" and "ejecta" x-ray emission--is the most dependent of the four on high spatial resolution. The ejecta appear to be unresolved on the HRI images (Seward 1981). Therefore, in order to measure the heavy element abundances in the true "blast wave" and distinguish them from the metal enriched ejecta, one must be able to obtain moderate energy resolution spectra of small regions of the remnant. The mass determinations of these ejecta require accurate abundances, since the emissivity of the plasma is greatly enhanced by metal enrichment and NIE effects. Because the x-ray intensity from these small regions will be less than that from the large-field SSS data, a high collecting area is required.

Question four may be the most important scientific issue concerning SNRs for the overall astrophysical community. If the x-ray spectra of young remnants are to be used as diagnostics of stellar evolution, stellar explosions, and nucleosynthesis, x-ray astronomers must increase the accuracy of the spectral data as well as refine the theoretical models. The HEAO-2 SSS provided remarkably good line determinations, considering its moderate energy resolution, $E/\Delta E \sim 10-20$. That this was possible was due primarily to its large effective area ($\sim 100 \text{ cm}^2$). Because the major uncertainties in the modeling of SNR x-ray spectra involve the effects of non-equilibrium ionization (i.e. time-dependent temperature and density history of the plasma), future observations can best help by providing high spectral resolution and a large collecting area. Resolving the Fe L-complex near 1 keV, as well as higher excitation lines of He-like and H-like ions of Ne, Mg, Si, and S, or determining the energy centroid of the Fe K-line complex near 7 keV can better constrain the model fits. Until this is done, further refinements in the theoretical modeling are probably unwarranted.

The conclusion drawn from the assessment of the four scientific questions appears to be that large collecting area ($\sim 10^3 \text{ cm}^2$) and moderate spectral resolution ($E/\Delta E \sim 10^2$) are needed to make further progress in spectral studies of SNRs. Moderate spatial resolution, of order 5", would be advantageous for some specific problems in individual remnants. However, unless one achieves the high effective area and spectral resolution, SNR studies will be limited to only a few bright sources. While detailed studies of these sources at high spatial resolution will yield useful information on the masses and remnant structure, the scientific topic of greatest general interest--an abundance analysis of a large sample of remnants in our galaxy and the Magellanic Clouds--will almost certainly require the sacrifice of spatial resolution to achieve the required spectral resolution and sensitivity.

TABLE 1. MODEL ELEMENTAL ABUNDANCES FOR TYCHO*

ELEMENT	EQUILIBRIUM ¹	NON-EQUILIBRIUM ²
Ne	1	0.37
Mg	0.1	2.0
Si	6.0	7.6
S	13.5	6.5
Ar	34.6	3.2
Ca	76	2.6
Fe	0.15	2.1

*Abundances relative to Solar Values, determined from χ^2 -fitting to HEAO-2 SSS data. H, He, and CNO are assumed to be in solar abundance.

¹Becker et al. (1980a), 2-temperature component, ionization equilibrium model.

²Shull and Szymkowiak (1981), single-velocity, non-ionization-equilibrium model of SNR blast wave with immediate post-shock temperature, $kT_s = 7.2$ keV, explosion energy 10^{51} ergs, and ambient H-density $n_0 = 1 \text{ cm}^{-3}$.

TABLE 2. HE-LIKE LINES

ELEMENT	E_R^*	$\Delta E(R-F)^*$	$\Delta E(R-I)^*$	RESOLUTION*
O	574 eV	13 eV	5.4 eV	110
Ne	922	17	6.8	140
Si	1865	25	11	170
S	2461	30	13	150
Fe	6702	64	26	260

*Energy E_R of the He-like resonance line (R); energy separations, $\Delta E(R-F)$ and $\Delta E(R-I)$, between R and the forbidden line (F) and intercombination line (I); and resolution, $E_R/\Delta E(R-I)$, required to analyze He-like line ratios.

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