NON-EQUILIBRIUM IONIZATION X-RAY EMISSION FROM SUPERNOVA REMNANTS

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I. INTRODUCTION

X-ray spectra of young supernova remnants (SNR's) are perhaps the most spectacular examples of hot, line-emitting astrophysical plasmas. Heated to temperatures of 1 to 10 keV and enriched with the heavy element products of stellar nucleosynthesis, the plasma inside these SNR's emits prodigiously in lines of O, Ne, Mg, Si, S, Ar, Ca, and Fe. Theoretical models of this emission provide measures of the plasma temperature and density, elemental abundances, and the degree of approach to ionization equilibrium. Thus, astrophysicists are offered the opportunity to test their understanding of the supernova explosion, its interaction with the interstellar medium, and the nucleosynthetic processes which enrich our galaxy with heavy elements.

However, the practical task of modelling the SNR X-ray spectra is fraught with technical difficulties, primarily questions of the internal hydrodynamics and ionization state of the SNR. In this review, I will describe recent X-ray spectral observations of young remnants and will summarize the current state of non-equilibrium ionization modelling.

II. OBSERVATIONAL SUMMARY

Many young remnants (t < 1000 years) observed by HEAO-2 exhibit the shell-like morphology predicted for SNR's in the adiabatic (Sedov) phase. However, the existence of filled-shells such as the Crab Nebula and Vela, and the patchiness of the emission in otherwise spherical remnants suggests that departures from pure Sedov structure are important. For example, a physically plausible case has been made for the contribution of reverse-shocked ejecta to the X-ray emission (McKee 1974; Gull 1975; Chevalier 1982).

The HEAO-2 spectrometers (SSS = Solid State Spectrometer, FPCS = Focal Plane Crystal Spectrometer) observed prominent emission lines

J. Danziger and P. Gorenstein (eds.), Supernova Remnants and their X-Ray Emission, 99–107.

from He-like ionization stages of many heavy elements, as well as other lines of Fe, O, and Ne. The SSS, with effective area 100 cm^{-2} and energy resolution 160 eV from 0.6 to 4.5 keV (Becker et al. 1980a,b), demonstrated that the strongest lines arise from Si and S (see Fig. 1). However, Ne, Mg, Ar, and Ca are also detected, together with a blend of Fe L-shell lines between 0.8 and 1.4 keV. The FPCS, with effective area 2-3 cm^{-2}, resolved the He-like "triplet" lines (R = resonance, F = forbidden, and I = intercombination) of O VII and Ne IX, provided important measurements of the H-like Lα and Lβ, and resolved several lines of Fe XVII in Puppis A (Winkler et al. 1981).

Preliminary coronal ionization equilibrium analyses of the SSS data (Becker et al. 1980a,b) required two temperature components to fit the spectra: a hard component with kT = 5-10 keV to fit the continuum, and a soft component with kT ≈ 0.5 keV to fit the H-like to He-like line ratios. These ionization equilibrium models for Tycho suggested that Si and S were overabundant by factors of 10, but that Fe was underabundant by a factor 0.15. Even stranger were the derived abundance enhancements of Ar (×35) and Ca (×76). However, all of these abundances are suspect because of the possibility of substantial departures from ionization equilibrium.

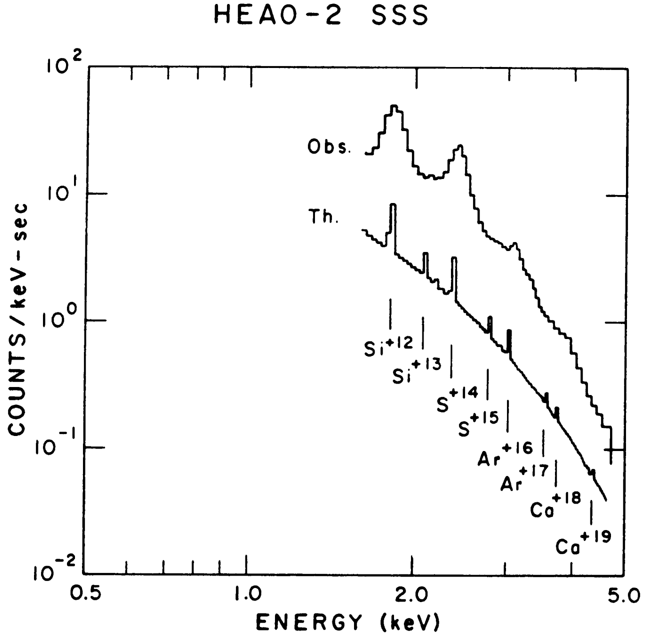

Fig. 1. HEAO-2 SSS spectrum of Cas A (marked Obs.), plus theoretical spectrum for plasma in ionization equilibrium at 3×10^6 K (marked Th.). Positions of He-like and H-like emission lines of various heavy elements are marked. The observational line widths are instrumental; theoretical lines are binned in 46 eV intervals.

https://doi.org/10.1017/S0074180900033726 Published online by Cambridge University Press

III. THEORETICAL MODELS OF NON-EQUILIBRIUM EMISSION

The application of ionization equilibrium (IE) models to young SNR X-ray spectra is questionable for four major reasons: (1) the SNR ages (400 to 1000 years) are comparable to the collisional ionization times for He-like and H-like ions in low-density plasma; (2) the dramatically different temperatures (4 keV and 0.5 keV) required to fit the continuum and lines, respectively, suggest that the plasma may be in a transient, ionizing state; (3) the observed ratio G = (F + I)/R of forbidden plus intercombination to resonance line intensity of He-like O VII and Ne IX in Puppis A (Winkler et al. 1981) is lower than that predicted for IE and characteristic of an underionized plasma (Pradhan and Shull 1981); and (4) a comparison of S-line equivalent widths to the Fe Kα line energy in Tycho (Pravdo et al. 1980) suggests departures from equilibrium.

Itoh (1977, 1979) showed that non-ionization equilibrium (NIE) may have a significant effect on the emissivity of young remnants. The physical effect is easy to understand: if the shocked plasma has had insufficient time to ionize Si and S to their equilibrium state at kT = 3-8 keV, then the fractional abundance in He-like stages and the resulting emission line strengths will far exceed their values in equilibrium. (The elements ionize "up the ladder" until they encounter the large ionization barrier from Li-like to He-like stages, at which point they accumulate and radiate strongly in the He-like triplet lines.) In terms of the plasma emissivity, the situation is very much like dropping an ice cube into a bath of hot water!

Ionization equilibrium models of hot, optically thin, low density plasmas (Raymond and Smith 1977; Shull 1981a) are relatively straightforward to construct. One simply solves for the steady-state ionization balance among competing rates of collisional ionization and radiative plus dielectronic recombination, then computes the plasma emission in the continuum and lines. The dominant processes which contribute to this emission are:

Continuum:
1) bremsstrahlung (free-free emission)
2) radiative recombination continua
3) two-photon continua (from H- and He-like ions)

Lines:
1) electron collisional excitation (bound states)
2) radiative recombination cascade
3) dielectronic recombination satellite lines

Of these processes, heavy elements dominate the line emission while H and He normally dominate the free-free emission. The electrons which radiate are donated either by H and He, or in metal-enriched plasmas from C, N, O, etc. Because the HEAO-2 SSS is not sensitive to CNO line emission below 0.6 keV, the absolute abundances of heavy elements are ambiguously determined. If CNO are enhanced in the ejecta relative to H and He by a factor greater than about 100, then the continuum emission is metal-dominated. Thus, in practice, the quoted abundances of Si, S, etc. are actually determined relative to an assumed cosmic abundance of CNO.

Non-equilibrium ionization models are far more complicated, because they require the specification of the past ionization history of every parcel of emitting plasma. While this ionization history has little effect on the free-free continuum, the emission line strengths are quite sensitive to the dominant ion stage at a given temperature. For young SNR's, non-equilibrium modelling involves the coupling of the gas hydrodynamics (density n and temperature T as a function of radius r) to a time-dependent ionization code and a spectral emissivity code. As a first step, most modellers have assumed an adiabatic Sedov interior solution to specify n and T. Only later have the effects of reverse shocked ejecta been considered.

In the Sedov solution (Sedov 1959; Taylor 1950), the radius, velocity, and temperature of the outer periphery are given by

$$R_s(t) = (4.97\ \mathrm{pc})(E_{51}/n_o)^{1/5}\ t_3^{2/5} \quad (1)$$

$$V_s(t) = (1950\ \mathrm{km\ s^{-1}})(E_{51}/n_o)^{1/5}\ t_3^{-3/5} \quad (2)$$

$$kT_s(t) = (4.54\ \mathrm{keV})(E_{51}/n_o)^{2/5}\ t_3^{-6/5} \quad , \quad (3)$$

where E_{51} is the explosion energy in units 10^{51} ergs, n_o ($\mathrm{cm^{-3}}$) is the ambient hydrogen number density assuming $\rho_o = 1.4\ m_H n_o$, and t_3 is the remnant age in units 10^3 years. By dividing the remnant into 100 shells, one may follow the thermal and ionization history of each parcel of the remnant interior by integrating rate equations for ionization, recombination, and the first law of thermodynamics (Shull 1982). Once the temperature, density, and ionization structure are known, one may compute the emergent X-ray spectrum by summing the shell emissivities, using a spectral code such as that described by Raymond and Smith (1977). The calculations to be described here used a recent spectral code (Shull 1981a) which incorporates the most accurate available collision strengths, particularly for ions in the He-like isosequence (Pradhan, Norcross, and Hummer 1981). Similar non-equilibrium ionization calculations have been made by Gronenschild (1979) and Hamilton, Sarazin, and Chevalier (1983).

The parameters of the non-equilibrium Sedov models may be expressed in a number of equivalent forms. In perhaps the simplest version, one specifies the ambient hydrogen number density (n_o), the explosion energy (E_{51}), the remnant age (t), and the metal abundances. The first three parameters determine the remnant's outer radius, velocity, and temperature. The metal abundance set is varied to fit the observed X-ray emission. Although it would be valuable to treat all parameters as free variables, we have fixed $E_{51} = n_o = 1$ for our standard models and varied only t and the metal abundances

(Hamilton, Sarazin, and Chevalier 1983 have computed a grid of models in which the scaling parameter, $E_{51}\ n_o^2$, is allowed to vary as well). For ease in comparing with equilibrium models of constant temperature, we will designate the non-equilibrium models by their immediate post-shock temperature T_s [see eq. (3)] rather than t.

Consider Sedov models with $kT_s = 7.2$ keV. The ionization structure and X-ray emission differ markedly in equilibrium and non-equilibrium. Because of the significant time for Si and S to ionize up to their equilibrium state, the He-like ion fractions are far greater in the non-equilibrium case. The overabundance of He-like ions in this hot plasma results in strong emission in the $n = 2 \rightarrow 1$ lines, as well as a decrease in the ratio $G = (F + I)/R$ of forbidden plus intercombination to resonance lines (Pradhan and Shull 1981) dictated by the increase in the relative importance of collisional excitation over recombination.

These non-equilibrium ionization enhancements in line emissivity affect both the derived metal abundances and ejecta masses. Figure 2 compares equilibrium and non-equilibrium X-ray spectra for a remnant with $kT_s = 7.2$ keV. The differences in He-like line strengths and He-like to H-like line ratios are apparent in the non-equilibrium case, as are the differences in Fe L-shell emission lines near 1 keV. A fit of SSS data on Tycho's remnant to this illustrative model (Shull 1981b, 1982) yielded the abundances in Table 1. In comparison with two-component ionization equilibrium models (Becker et al. 1980a), the "one component" non-equilibrium ionization model gave slightly higher chi-square per degree of freedom, but resulted in perhaps more believable abundance enhancements for Ar, Ca, and Fe. Iron is no longer underabundant, while the Ca and Ar enhancements are more in agreement with those of other elements. The Si and S abundances are affected by less than a factor of 2. More elaborate fitting will be described by Szymkowiak et al. (1983).

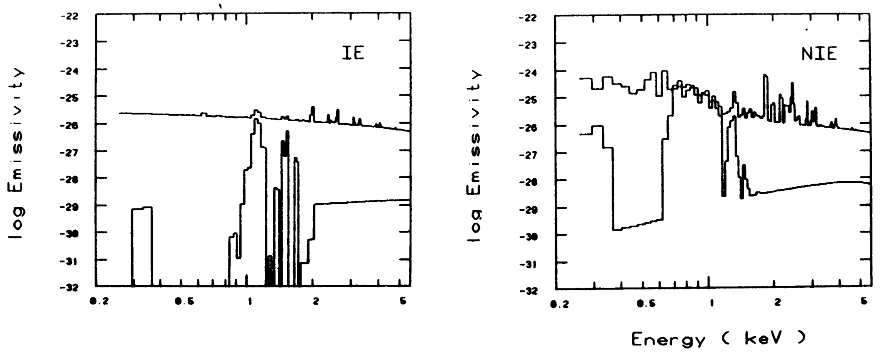

Fig. 2. X-ray emissivities (ergs $cm^3\ s^{-1}\ eV^{-1}$) of Sedov remnant in ionization equilibrium (IE) and non-ionization equilibrium (NIE) at time t = 680 yr ($kT_s = 7.2$ keV, $E_{51} = n_o = 1$). Abundances are those in Table 1. The two curves in each plot represent total emissivity and emissivity of Fe.

Table 1. Model Elemental Abundances for Tycho[a]

Element	Equilibrium[b]	Non-Equilibrium[c]
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

[a]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.

[b]Becker et al. (1980a), two-temperature component, ionization equilibrium model.

[c]Shull (1981b), 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 $n_o = 1\ \mathrm{cm}^{-3}$.

Figure 3 illustrates the changes in broadband X-ray emissivities produced by non-equilibrium ionization. The overabundance in He-like ion stages results in an enhanced emissivity in the 1-3 keV range. Supernova ejecta masses determined from equilibrium emissivities may therefore overestimate the amount of emitting plasma by significant factors (see Gorenstein, Seward, and Tucker 1983 for an explicit example of the application of these non-equilibrium emissivities to ejecta masses in Tycho).

IV. SUMMARY

Preliminary Sedov models indicate that Ar, Ca, and Fe abundances are strongly affected by non-equilibrium ionization. The fact that Fe, while not glaringly overabundant in Tycho, is at least present in significant amounts is satisfying. Silicon and sulfur remain the dominant contributors by mass to the X-ray emitting plasma. Likewise, the ejecta masses inferred for Tycho are lower in non-equilibrium models. Each of these inferences is important for ascertaining the nature of the progenitor of the supernova.

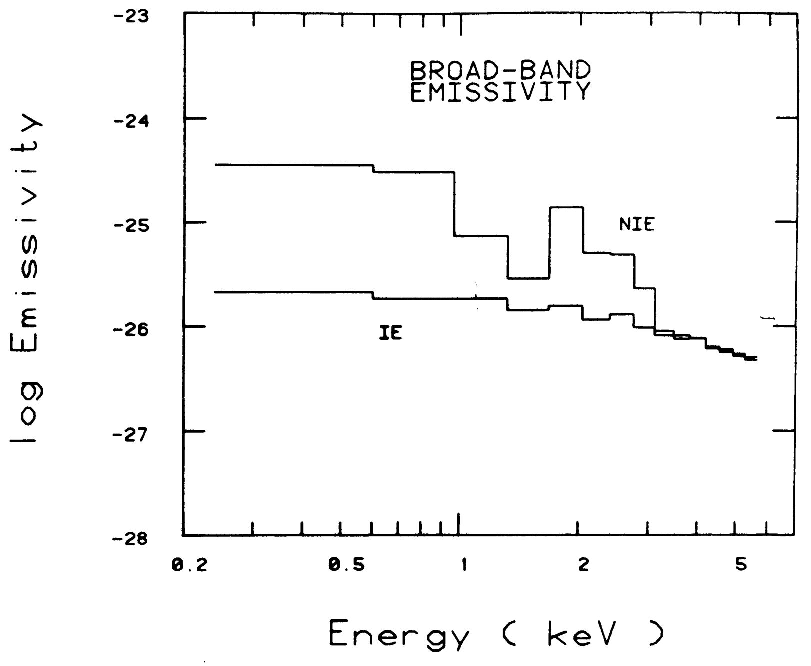

Fig. 3. Broadband spectral emissivities (ergs cm^3 s^{-1} eV^{-1}) in ionization equilibrium and non-ionization equilibrium, averaged over 360 eV wide binds. Model parameters same as in Fig. 2.

These abundances, however, should still be regarded with some skepticism, since a number of questions remain to be answered concerning the nature of the SNR hydrodynamics and plasma:

1. What is the degree of ion-electron temperature equilibration?

2. How far does the SNR depart from the idealized Sedov structure?

3. How much mixing has occurred between ejecta and shocked interstellar gas?

4. How certain are the atomic rates that go into the modelling?

5. Can one exclude the possibility of heavy element depletion into grains (or cold clumps)?

Some work has been done in these areas (see Sarazin, Hamilton, and Chevalier 1983). The real answers, however, will most likely await future X-ray spectrometers with higher spectral and spatial resolution.

This work was supported by National Science Foundation grant AST80-19960 through the University of Colorado.

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DISCUSSION

COX: Shouldn't we be calling these models NEI rather than NIE? Also, when you model remnants, do you fix E_{51} or derive it?

SHULL: NEI is probably appropriate, but NIE is analogous to non-LTE. I fix the SNR energy at 10^{51} ergs to avoid many model calculations. Hamilton et al. (1983) have let the scaling parameter $E_{51}n_o^2$ vary.

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DICKEL: What is the physical basis for the prominence of He-like and even-Z ionization stages?

SHULL: The odd-even variation in Z is just cosmic abundances (nuclear binding). The prevalence of He-like stages results from the "hang up" in the ionization at the large barrier between Li-like and (closed shell) He-like stages.

BISNOVATYI-KOGAN: Did you take into account excited states of different elements in the calculations?

SHULL: No. At the low interstellar densities, all ions are in their ground state.

PRAVDO: Can you comment on our finding that your model for Tycho violates the high-energy data by a large factor, while our fit (which is consistent with all the data) results in elemental abundances higher by a factor of 10.

SHULL: In your fit, you must lower the continuum temperature to about 4.6 keV, which then raises the line fluxes and metal abundances. I assumed kT_s = 7.2 keV for the post-shock temperature (quoting your published HEAO-1 results). Evidently you have changed your mind about the temperature needed to fit the high energy data. Perhaps the Maxwellian tail of the electron energy distribution is depleted, or perhaps the relative normalization between the two data sets is uncertain.

CANIZARES: A plea to modellers: could you produce a table of a dozen or so line emissivities for various temperatures in ionization equilibrium? These could be used to compare the various models and separate effects due to atomic physics from those due to astrophysics.

SHULL: I agree with your idea. However, the strong He-like lines on which many of the SSS abundance fits are based, probably have the best-determined collision strengths (20%) -- Pradhan, Norcross, and Hummer (1981). The Fe L-shell lines near 1 keV are more uncertain.

GRINDLAY: Can you comment on the relative importance of a cloud-filled ambient medium for non-ionization equilibrium effects?

SHULL: I suspect that high-density clouds would be nearer to ionization equilibrium. Separating clouds from intercloud matter might be difficult without both spatial and spectral resolution. Also, the importance of the cloud component might not appear until the remnants were older and larger, owing to the delayed effect of evaporation.