THE HIGH ENERGY X-RAY SPECTRA OF SUPERNOVA REMNANTS[1]

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ABSTRACT

We present the results of fitting an ionization nonequilibrium (NIE) model to the high energy (> 5 keV) X-ray spectra of the young supernova remnants Cas A and Tycho. As an additional constraint, we demand that the models simultaneously fit lower energy, higher resolution data. For Cas A, a single NIE component can not adequately reproduce the features for the entire X-ray spectrum because 1) the ionization structure of iron ions responsible for the K emission is inconsistent with that of the ions responsible for the lower energy lines, and 2) the flux of the highest energy X-rays is underestimated. The iron K line and the high energy continuum could arise from the same NIE component but the identification of this component with either the blast wave or the ejecta in the "standard" model is difficult. In Tycho, the high energy data rule out a class of models for the lower energy data which have too large a continuum contribution.

1. INTRODUCTION

The high energy X-ray spectrum of a young supernova remnant provides a measure of the X-ray continuum temperature and intensity, the most direct determinations of the electron temperature and emissivity. Also present is the iron K line, the only prominent line with so high an ionization energy. The most sensitive measurements to date of several high energy spectra were performed with the HEAO 1 A2 spectrometers[2] (HED). Previous analyses of the continua have indicated the presence of electron-ion temperature equilibirium (Pravdo and Smith 1979, Nugent 1982), but quantitative analyses of the line emission (Mason et al. 1979, Pravdo et al. 1980, and Winkler 1979) have been hampered by the absence of general theoretical models which go beyond "simple" collisional ionization equilibrium (CIE; e.g. Raymond and Smith 1977). Indeed, the conclusion from many of the above references was that a CIE model was not adequate and that

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an ionization nonequilibirum (NIE) model such as described by Itoh (1977) was needed.

A number of workers have now rushed to fill this need. We will discuss herein a reanalysis of the Cas A and Tycho spectral data using the NIE model developed by Nugent (1982). A recurring problem with complex models such as these, is that there are too many free parameters to uniquely fit the data. In order to further constrain the class of possible good fits, we have simultaneously fit both the A2 data and lower energy, higher resolution data obtained with the Solid State Spectrometer (SSS) onboard the Einstein Observatory. The SSS data were also previously analyzed in the context of the CIE model (Becker _et al_. 1979, 1980).

The NIE models described below are in the Sedov limit; i.e., the X-ray emission generated by interstellar material swept up by the blast wave dominates that from the ejecta. However, little generality is lost in this approach since a blast wave component can mimic an ejecta component if the parameters have a free rein (Hamilton and Sarazin, 1982, this Symposium). In addition, electron-ion temperature equilibrium is assumed.

2. PARAMETERS OF THE MODELS

This section will not attempt to describe the NIE model. For this the interested reader must see Nugent (1982). Instead we will list and give mnemonics for the parameters which are discussed in later sections.

Three "reduced" parameters describe the continuum spectrum in the Sedov limit. The first is C_{ev}, which is given in units of 10^{13} cm^{-5}, and can be thought of as a measure of the X-ray surface brightness. The second is η, a density-like parameter, and the last is τ, a time-like or inverse temperature-like parameter. Their product, $\eta\tau$, is proportional to the evolutionary progress of the ionization structure. Higher values of this quantity result in heavy element ionization structures which are closer to CIE, because the density is higher, the time is longer, or both. Similar parameters in the recent NIE model of Hamilton, Sarazin, and Chevalier (1982; HSC) can be obtained through the relations $\eta_{HSC} = 10^{51} \eta^3$ ergs cm^{-6} and T_s (the "post-shock" temperature) = $6 \times 10^7 \tau^{-6/5}$ K. The fitted quantities C_{ev}, η, and τ can be inverted to yield the following familiar quantities (plus an undetermined filling factor f): the initial ambient interstellar density (divided by f); the remnant age (times f); the distance (times f); and the total blast wave energy (times f^2).

Another set of free parameters is the elemental abundances. These are represented as A_Z, the abundance relative to hydrogen of the element with atomic number Z, normalized to the solar values

(Allen 1973). The elements included are Ar+Ca, Mg, Si, S, and Fe. As we are not primarily concerned in this work with determinations of elemental abundances except, perhaps, of iron, we only present the Si and S value as representative of the fits, in addition to the Fe.

A final, somewhat diverse set of free parameters is unrelated to the NIE model. First, is the interstellar, neutral hydrogen column density (Fireman 1974), N_H, in units of 10^{22} cm^{-2}. Next, in some cases, an additional thermal bremmstrahlung continuum component is added. Lastly, the relative normalization between the A2 and SSS data sets is left as a free parameter and afterwards compared to an initial estimate.

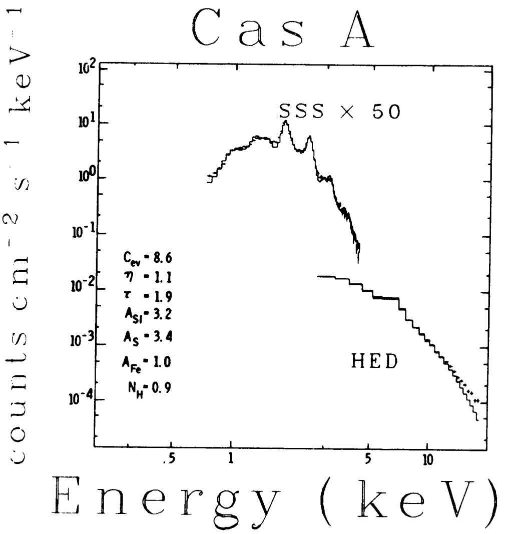

Fig. 1. $\mathrm{NIE}_{\mathrm{ALL}}$ model histogram.

Acceptable values of chi squared (χ^2) are never achieved for these fits. This is in part because the systematic uncertainties in the detector response functions can exceed the statistical uncertainties in many energy channels. Moreover the atomic physics used to calculate the relative line strengths is significantly uncertain in some cases. Nevertheless, comparisons between χ^2 values are meaningful.

3. CAS A

Figure 1 shows a histogram of the best-fit NIE model superposed on the spectral data from Cas A. The relative normalization between these A2 and SSS data is expected to be unity since both detectors contain the entire remnant within their respective fields of view. The best-fit value of 1.1 indicates that the detector normalizatins have been adequately evaluated. Three comments can be made about this model fit. First, the 0.7-20. keV spectrum is grossly approximated by a single component model. This is in contrast with CIE models which require two components at different temperatures (e.g., Davison, Culhane, and Mitchell, 1976). Much of this difference is due to the enhanced low energy line emission in the NIE compared to the CIE model.

Second, the high energy continuum emission is underestimated. This reflects the fact that the low energy line emission drives the spectral fitting, and is inconsistent with a high enough continuum "temperature" to match the data.

Last, a major contribution to the χ^2 comes from the Fe K line fit. From a total χ^2 of 1581 for 103 energy channels, the 7 Fe K channels contribute 481. This is illustrated in Figure 2a where this model and the data in the region near 6.8 keV are magnified. The observed line energy is clearly too high to be consistent with the rest of the data and indicates that the iron is more highly ionized than this model would predict.

The fact that both aspects of the high energy data, the continuum and the Fe K line, are inconsistent with the overall best fit suggests an attempt to fit a comparison NIE model to the A2 data alone. In this case the only free parameters are the three NIE parameters, the iron abundance, and a normalization and temperature for a low temperature continuum component. This last component is designed to account for the anticipated excess at the low energy end of the A2 data (near 3 keV). The resultant temperature is 2 x 10^7K, an <u>a posteriori</u> confirmation that this component performs the desired function and no more.

The NIE model fit to the A2 data alone ($\mathrm{NIE}_{\mathrm{FE}}$) succeeds where the overall best-fit model ($\mathrm{NIE}_{\mathrm{ALL}}$) fails. Figure 2b illustrates the fit to the Fe K line. The contribution to χ^2 from the 7 Fe K channels is now 48, a reduction by a factor of 10. In addition, the high energy continuum is well represented by the model. For this model the NIE parameters are $C_{ev} = 1.5$, $\eta = 7.5$, and $\tau = 0.8$, where the units are as described in Section 2.

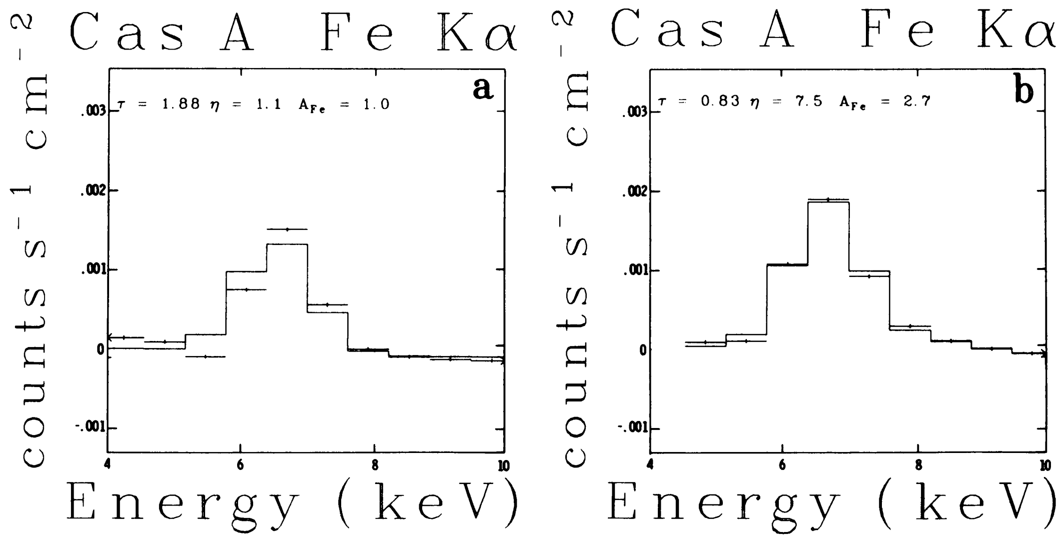

Fig. 2.a. $\mathrm{NIE}_{\mathrm{ALL}}$ model histogram. b. $\mathrm{NIE}_{\mathrm{Fe}}$ model histogram.

A comparison between the NIE_{Fe} and the NIE_{ALL} models is instructive. The product, $\eta\tau$, is three times larger in the former. This indicates that the ionization structure of the iron K line has effectively evolved three times longer than the lower energy lines. The age derived from the NIE_{ALL} model is 190 f years. Since f cannot be larger than unity and the age of Cas A is about 300 years, this model is already in trouble. However, it is evident that the NIE_{Fe} model requies a high filling factor. In contrast, the age derived from the NIE_{Fe} model is 17000 f, implying a filling factor closer to 0.02. Similarly, in order for the derived distances and blast wave energies to approach typical estimates, the NIE_{Fe} model requires a high f and the NIE_{ALL} model requires a low f. The densities derived from these values of f are 11 cm^{-3} (NIE_{ALL}) and 21 cm^{-3} (NIE_{Fe}). The iron abundance is similar in both models and close to the solar value.

The NIE_{Fe} component can produce the Fe K line and the high energy X-ray continuum, and has a low filling factor. Its longer effective ionization time makes it closer to CIE than the NIE_{ALL} model. The latter is more characteristic of the low energy continuum. In the standard interpretation for the Cas A X-ray spectrum the high energy emission is associated with the blast wave and the low energy emission with ejecta. Unfortunately for this scenario the NIE_{Fe} component does not look like a blast wave, which is instead expected to have a large f and a low density. Ejecta is present in high density clumps with a low filling factor, but cannot be heated to a high enough temperature to create the highly ionized iron without, for example, significant heat conduction between the blast wave and the ejecta (Chevalier, 1975). A mechanism of this sort appears necessary to create an X-ray component with these properties.

The X-ray spectrum of the supernova remnant RCW 86 (MSH 14-63) exhibits many of the same properties as Cas A, although it is not as extreme a case. Nugent (1982) discusses the NIE analysis of RCW 86.

4. TYCHO

We know from previous results that the high energy X-ray spectrum of Tycho differs from that of Cas A in one important respect: the Fe K line energy is significantly lower (Pravdo et al. 1980).[3] Our NIE modelling for Tycho reflects this fact with the result that there is no significant difference between the effective ionization times of the corresponding NIE_{Fe} and NIE_{ALL} models.

The Tycho data and best-fit NIE_{ALL} model are illustrated in Figure 3. The high energy continuum intensity is adequately reproduced. For Tycho the SSS data must be scaled by a relative normalization factor larger than unity because the remnant is larger than the SSS field of view, but still smaller than the A2 field of view. A maximum of 50% of remnant is in the SSS field of view at any one time, but the average value from different pointing positions must be less. The averaged SSS data from two positions is used here. A simple scaling of the SSS data relative to the A2 data is approximately correct since there is no significant spectral variability in SSS spectra from a number of positions in Tycho (Becker et al. 1980). The best-fit value for the relative normalization (the inverse of the fraction of the remnant viewed) is 3.5 in good agreement with the estimate.

Using the same procedure as above, this model implies a filling factor of 0.1-0.3 and a density of 1-3 cm^{-3}. In contrast with Cas A, the abundances of Si and S are significantly enhanced over the solar values.

In a recent model of Shull (1982) a fit to the Tycho SSS data gives Si and S abundances a factor of three lower than these. The ambiguity of the continuum level in the SSS energy range allows a tradeoff between the abundances and the continuum. The Shull model was accurately reproduced by fixing η, τ, and A_Z at the published values and allowing only the scale factor, C_{ev}, to vary. However, an extrapolation of this model into the A2 energy range reveals that the model continuum level is, in fact, too high. This is shown in Figure 4. A fixed relative normalization factor of 2.8 is chosen for this model so that consistency is obtained in the data overlap region of the two detectors, ~2.5 to 3 keV. If the factor is treated as a free parameter, an unreasonably low value of 1.6 is obtained and the fit underestimates the low energy A2 data while still overestimating the high energy data. This does not constitute a proof that the elemental abundances must be as high as those derived herein, multi-component models have more flexibility, but it is a caveat against seemingly good models which cover a limited energy range.

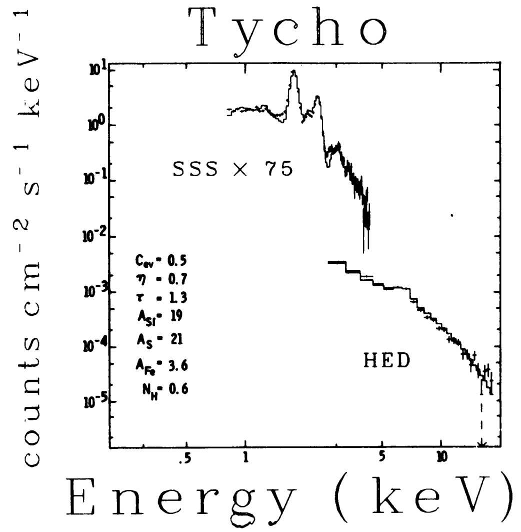

Fig. 3. NIE_{ALL} model histogram.

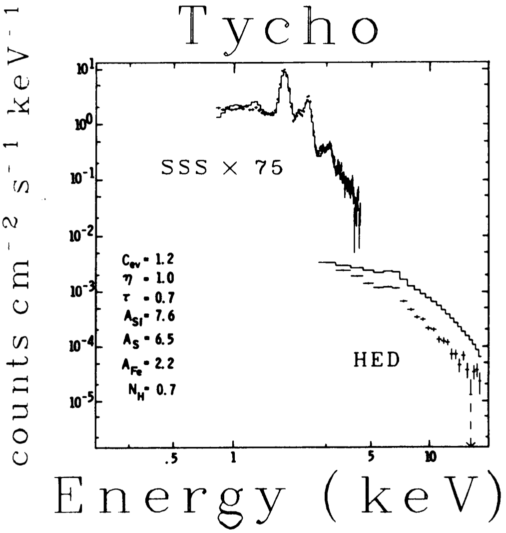

Fig. 4. Shull (1982) model.

As with Cas A, although the single-component NIE_{ALL} model apporoximately fits the Tycho data, it does not do so in detail. Again, the Fe K line region is poorly fit, although not for the same reason as in Cas A. For Tycho, the model is not inconsistent with the line energy, but rather with the continuum shape near the line. The reason that the iron line in Tycho is at a lower energy than in Cas A is still not clear, but may be related to the lower densitites derived for Tycho.

5. SUMMARY AND CONCLUSIONS

The high energy X-ray spectra of Cas A and Tycho have been reanalyzed in the context of an NIE model for supernova remnant emission. Single-component NIE models cannot reproduce all the features of either spectra. The component responsible for the Fe K line (and perhaps the high energy continuum) in Cas A has some properties which are not consistent with either the standard blast wave or ejecta model. In general, the high energy continuum data is a crucial constraint for a determination of the continuum contribution over the entire X-ray spectrum.

One could proceed by fitting multi-component NIE models to the spectral data and, without doubt, improved fits would be obtained. However, the number of free parameters is then so large that equally good fits with widely varying parameter sets are possible. Unique, and therefore, meaningful, values for the parameters could not be specified. The problem may be that because the detector fields of view are large compared to the remnant size scales, the contemporary data contain contributions from several spectral components. Spectral data from a next-generation, high spatial resolution, broadband detector will be a sufficient challenge for future analysts.

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[2] The A2 experiment on HEAO-1 is a collaborative effort led by E. Boldt of GSFC and G. Garmire of CIT (now PSU), with collaborators at GSFC, CIT, JPL, and UCB.

[3] Please note that in this reference the intensity units on page L10, second paragraph, should be 10^{-10} ergs cm^{-2} s^{-1}.

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