EINSTEIN BRAGG CRYSTAL SPECTROMETER OBSERVATIONS OF CAS A - A NONEQUILIBRIUM IONIZATION INTERPRETATION

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Abstract: We use *Einstein* FPCS observations of lines of highly ionized neon, silicon and sulfur to constrain the parameters of the supernova remnant Cas A.

We observed the supernova remnant Cas A on several occasions in 1979 - 1981 with the Focal Plane Crystal Spectrometer (FPCS) on the *Einstein* Observatory (Canizares *et al.* 1979). The FPCS uses Bragg crystals to obtain high spectral resolutions ($E/\Delta E > 100$) over the energy range 500 - 3500 eV. We used the FPCS to study features in the Cas A spectrum in the range 800 - 1250 eV (where the dominant lines are from highly ionized iron and neon) and around the energies of the lines of helium- and hydrogen-like silicon (1800 - 2100 eV) and sulfur (2400 - 2700 eV).

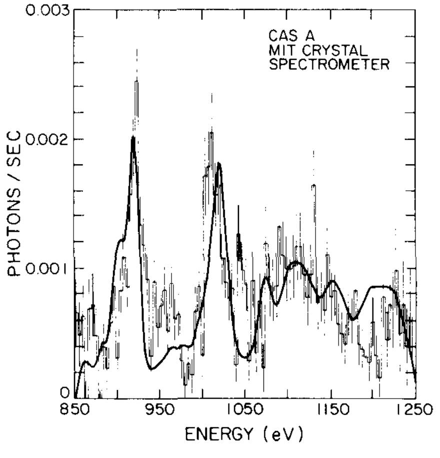

Figure 1

Figure 1 shows the spectrum we observed in the range 850 - 1250eV. Overlaid on the data is a model spectrum based on the observations of the sun compiled by Doschek and Cowan (1984). We have been unable to "fit" any simple model to the data, but show this result to illustrate that many of the lines and temperatures are known approximately although a detailed understanding of Cas A is not yet available.

It is not surprising that not all of the high resolution spectral data can be explained in terms of any simple model. The data contain a great deal of information and Cas A is known to be a complex object. For example, there are at least two regions in Cas A which are undergoing shock heating (the primary and reverse shocks). There are undoubtedly non-cosmic abundances in the X-ray emitting matter (because Cas A is a supernova remnant). It is a young object (about 300 years) so it is unlikely that ionization equilibrium has been established. The material is expanding at several thousand km s^{-1} so the lines are Doppler broadened. Finally, Cas A is clumpy - the irregular spatial appearance is probably indicative of spectral complexities as well.

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In order to learn something about this object without attempting to explain every feature of the spectrum, we developed a straightforward and relatively simple non-equilibrium model which we applied to a few of the brighter and less ambiguous spectral features. In this model we assume that the X-ray emission from Cas A arises from a thin plasma which is instantaneously shock-heated to an X-ray emitting temperature T_e, (the electron temperature).

The first step in the model is to solve the ionization balance equations for each of the elements of interest, i.e.

$$\frac{dF_i}{dt} = n_e \times \{\alpha_{i-1}F_{i-1} - [\alpha_i + R_{i-1}]F_i + R_iF_{i+1}\} \qquad [1]$$

where F_i is the fraction of a given atomic species in the i<u>th</u> ionization state, α_i is the ionization rate by electron collision from state i (into state i + 1) and R_i is the recombination rate <u>to</u> state i (from state i + 1). The equations were solved using the method of Hughes and Helfand (1985). The rate coefficients are those used by Hughes and Helfand (which were taken from Raymond and Smith 1977 and subsequent revisions).

The ion structure in this model is a function of T_e and the ionization time parameter τ (≡ n_e [electron density] × t [time]). For a given ionization structure (corresponding to a particular value of T_e and τ) we then computed the expected emissivity for the X-ray lines of interest. The emissivity formulae were taken from Mewe and Gronenschild (1981) and included rate coefficients for processes of inner-shell ionization, electron-impact excitation, radiative recombination and dielectronic recombination. Once the emissivities are computed, the flux in a particular line is given by

$$f_i = V/4\pi d^2 \times \exp(-\sigma n_H) \times n_Z n_e \varepsilon_i(T_e,\tau) \quad \text{photons cm}^{-2}\ \text{s}^{-1} \qquad [2]$$

where d = distance to the object, V = volume of emitting plasma, σ = cross-section at energy E_i for absorption of the X-rays by intervening matter (Morrison and McCammon 1983), N_H = hydrogen column density, n_Z = density of element Z, and ε_i = the emissivity of line i (photons cm³ s⁻¹).

Ideally, we would like to measure precise fluxes for a large number of lines and use the information to compute the various parameters on the right side of equation [2]. Since we only have a few flux measurements, however, we have chosen to take ratios of the measured values. If chosen wisely, many of the unknown parameters will cancel and the resulting ratio will be a function of only two uncertain parameters.

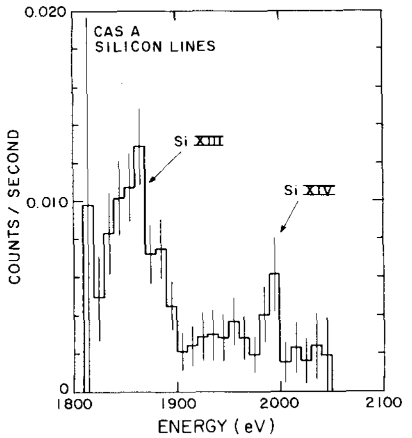

Figure 2

This technique is illustrated by our results for observations of the silicon lines. The portion of the Cas A spectrum between 1800 and 2100 eV is shown in Figure 2. The helium-like silicon (actually, a blend of the three n=2 to n=1 transitions of Si XIII) and the hydrogen-like silicon (Si XIV Lyman α) are indicated. We measured the flux of the two lines and computed the ratio.

We found $$\frac{f_{\mathrm{Si\ XIV}}}{f_{\mathrm{Si\ XIII}}} = 0.42 \pm 0.13$$

$$= \exp((\sigma(2006\ \mathrm{eV}) - \sigma(1860\ \mathrm{eV}))\ N_H)\ \frac{\varepsilon_{\mathrm{Si\ XIV}}(T_e,\ \tau)}{\varepsilon_{\mathrm{Si\ XIII}}(T_e,\tau)} \qquad [3]$$

For most plausible values of N_H, the first term in the ratio is nearly unity, so that the ratio is essentially a function only of T_e and τ. We generated a table of values of the Si ratios as predicted by our model for ranges of the parameters T_e and τ. Figure 3(a) shows a contour plot of the table generated for a large region of T_e and τ space. The contours are the 1σ and 2σ uncertainty intervals of the silicon line ratios. It is clear that the observations constrain the values of the plasma parameters. Note that at equilibrium (τ large), the electron temperature is in the range $6.8 < \log T_e < 7.4$.

We performed a similar analysis using observations of the sulfur lines (SXVI at 2521 eV and SXV at 2460 eV). The ratio of observed fluxes constrained the (T_e, τ) space to a region nearly identical to that of the silicon line ratio.

In figure 3(a) we show a small rectangle that overlaps our silicon-sulfur contours. This is the result obtained by Tsunemi *et al.* (1986) using the gas scintillation proportional counter (sensitive above about 1.5 keV) on *Tenma*. The *Tenma* group analyzed their data using a technique quite similar to the FPCS method presented here and were thus able to determine an allowed region of the (T_e,τ) parameter space. By using their measurement of the X-ray continuum above about 2 keV to find T_e directly, they were able to obtain a still smaller parameter region, as shown in the figure.

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In Figure 3(b) we show a (T_e,τ) contour plot obtained from the ratio of fluxes of hydrogen-like to helium-like neon (Ne X at 1022 eV and the Ne IX complex in the range 905-922 eV). It is clear from figures 3(a) and (b) that the low-energy (neon) and the higher energy (silicon, sulfur, *Tenma*) results are inconsistent. We interpret the higher-energy (and, for most values of τ, the higher temperature) region as resulting from the primary shock moving into the interstellar medium. The lower-energy region we then interpret as resulting from the reverse shock propagating backward into the ejecta.

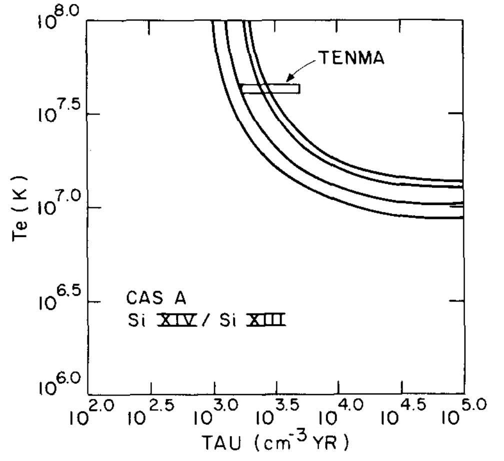

Figure 3 *Contours are 1 and 2σ regions of the non-equilibrium parameter space constrained by the observations of silicon lines (figure 3(a) on the left) and neon lines (figure 3(b) on the right). Observations of sulfur lines (not shown) are consistent with the silicon results. The results obtained with the Tenma satellite are shown in figure 3(a).*

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