AN X-RAY HALO AROUND CASSIOPEIA A

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ABSTRACT

We report on evidence for weak large scale (r $\gtrsim$ 6 arcmin) X-ray emission from Cassiopeia A. We investigate several mechanisms for producing such an X-ray halo. Further observations will be required to determine which mechanism is operative.

INTRODUCTION

Most previous analyses of the X-ray image of the Cassiopeia A supernova remnant have concentrated on the double shell structure associated with the blast wave and reverse shock. This has a radius of $\sim$ 2 arcmin, similar to the size of the radio source and the optical system of fast moving knots.

We report here on evidence for weak X-ray emission from Cas A which is detectable to a radius of $\sim$ 6 arcmin, comparable in size to the optical HII region known to exist around the remnant (Minkowski 1968, Van den Bergh 1971). We discuss several mechanisms for producing such an X-ray halo.

OBSERVATIONAL EVIDENCE

Plate 1 shows the Einstein HRI (High Resolution Imager) X-ray image of Cas A (Murray *et al.* 1979) binned into 16 arcsec pixels. This was displayed on a television monitor using a non-linear conversion of intensity-to-brightness. An extensive halo is observed around the easily discernible inner shell structure.

Despite the nominal high resolution of the HRI (the full width half maximum (FWHM) of the point spread function (PSF) is $\sim$ 4 arcsec), the telescope mirror contributes large scattering wings to the PSF. Clearly, an accurate estimate of the instrumental contribution to the observed halo is required before any astrophysical explanation is sought.

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Deconvolution of the effects of the PSF from the data by Fourier on Maximum Entropy techniques is not practical as the data have insufficient signal to noise ratio. We have therefore attempted to model the intrinsic emission of Cas A folded through the PSF and compared it with the data.

As the PSF of the telescope-instrument combination varies with energy we had to construct a PSF appropriate to Cas A. We used the pre-flight calibration PSFs made at various energies and weighted these according to the overall spectrum of Cas A modified by the HRI efficiency at the appropriate energy. The resultant PSF proved to be similar to that measured using the Zirconium monochromatic source with an energy of 2.04 keV. Consequently, we used that measured PSF throughout the analysis.

Two different models were used:-

a) a spherical shell of outer radius 110" and thickness 15"
b) a series of circularly symmetric rings of emission.

Both models gave essentially equivalent results, so here we shall discuss only the results given by method b.

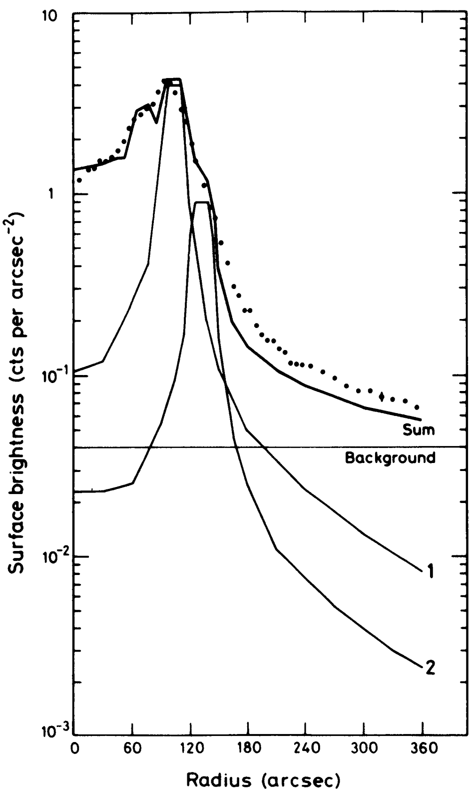

Figure 1 shows the azimuthally binned surface brightness distribution of the Cas A image, together with the predicted surface brightness profile. Two of the individual ring contributions are also shown.

Fig. 1. Surface brightness distribution of Cas A. Dots are data points. The thick solid line represents the fit to data using method b. Curves for two of the emission rings are labelled 1 and 2 and the background level is shown.

A statistically significant excess is apparent out to a radius of ∿ 6 arcmin. We stress that while the excess is statistically significant, possible systematic effects are largely unknown. However, a number of tests have been made and in none of these was the instrumental contribution sufficient to completely explain the halo. This could only be done by assuming a mean photon energy of ∿ 3 keV in the image, clearly unreasonable in view of the HRI efficiency at these energies, or by postulating a degradation of the mirror since the calibration tests. Post launch trials appear to rule out this latter effect.

DISCUSSION

The difference between the observed and predicted surface brightness profiles is shown in figure 2. The total luminosity (0.5 - 3 keV) of the halo is ∿ 5 x 10^{34} erg s^{-1} (∿ 2% of the total Cas A luminosity) assuming a distance of 3 kpc for Cas A. Three mechanisms which might give rise to the halo emission are thermal, non-thermal emission and scattering of the intrinsic shell emission by dust along the line of sight.

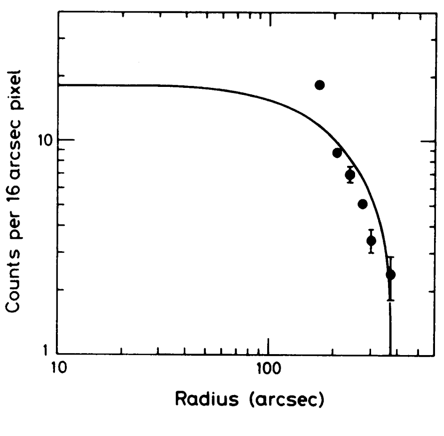

Fig. 2. The excess surface brightness of the Cas A data compared to model b is shown by the dots. The solid line represents the fit to these points of the dust halo model discussed in the text.

The density of the ISM currently being encountered by the outer shock is ∿ 1 - 2 cm^{-3} (Pravdo & Smith 1980, Fabian *et al.* 1980). A sphere of radius 6 pc has a thermal bremsstrahlung luminosity of ∿ 10^{35} $nT_7^{\frac{1}{2}}$ erg s^{-1} which with line emission is sufficient to explain that observed. It is not clear how this gas may have been heated as the total thermal energy is ∿ 5 x 10^{49} ergs.

Supernova events may produce more than 10^{49} ergs in soft X-rays (Klein & Chevalier 1978, Canizares *et al.* 1982). However, the column density through the halo region of ∿ 10^{19} cm^{-2} is insufficient to absorb much of this energy.

Kinetic heating of the material is also possible. High velocity material ($v \gtrsim 10^4$ km s^{-1}) is seen in the optical jet extending 2 arcmin to the NE of the main shell. A distribution of fragments with high densities and velocities sprayed out through action of the Rayleigh-Taylor instability in the explosion (Bychkov 1974, Falk & Arnett 1973, Chevalier & Klein 1978) could shock heat the matter ahead of the bulk ejecta to $\sim 10^9$ K. This gas may adiabatically expand and cool. This requires $\gtrsim$ 1% of the energy of the supernova event to be processed efficiently from the kinetic energy of the high velocity fragments to heat. Cooler, higher density gas could explain the optical HII region.

Fast moving thermal electrons could propagate ahead of the shock (Chevalier 1975) and produce bremsstrahlung X-rays. Consideration of the relative volume emissitivities shows that approximately equal numbers of electrons are ahead of and behind the shock front. It remains to be shown that the plasma processes operative in a collisionless shock (see e.g. McKee & Hollenbach 1980) are sufficiently "leaky".

A more efficient process than thermal bremsstrahlung, where the cooling time of the gas is $\sim 10^7$ yrs, is synchroton radiation. The synchroton cooling time to produce 1 keV X-rays is $\approx 10^4 B_5^{-3/2}$ yr, where B_5 is the magnetic held strength in units of 2.10^{-6} G. To explain the X-ray observations 10^{46} ergs is the total energy in electrons with $\gamma \sim 10^8$. Hard X-ray observations by Pravdo and Smith (1980) require that the energy spectral index of the halo, α, be greater than ~ 0.6 (unless the emission they observe is from the halo). Assuming that cosmic ray electrons produce synchroton X-rays with $\alpha = 0.7$ and radio waves from the same power law, the 408 MHz radio flux from the source is 15 Jy. The total energy in relativistic electrons above $10^2 \gamma_2$ is then $4.10^{49} \gamma_2^{-0.4} B_5^{1.7}$ ergs which may not be unreasonable. Detection of the halo at other wavelengths would help determine whether synchroton is the relevant mechanism.

This interpretation requires that cosmic-ray electrons are accelerated to 's $\sim 10^8$ in supernova remnants and leak ahead 3 times faster than the shock velocity, a velocity much greater than the local Alfven speed. A more uniform (radial) field structure allowing rapid streaming to take place may have been created by a stellar wind. An accompanying flux of cosmic ray protons and nuclei would imply a local cosmic ray energy density enhancement of $\sim 10^3$. This would lead to heating of the surrounding gas to $\gtrsim 10^4$ K (see Dalgarno & McCray 1972) and explain the HII region.

Scattering of the main shell emission by dust may also produce an X-ray halo. For a monochromatic point source it has been shown (e.g. Hayakawa 1970) that simple single scattering from spherical grains produces a halo with radius, $\theta \simeq 8 E_{keV}^{-1} a^{-1}$ arcmin, where a is the grain radius in units of 0.1 μ. The form of the halo is given by $(j_1(x)/x)^2$ where $x = 4\pi a/\lambda \sin(\theta/2)$ and j_1 is the first order Bessel function. The total intensity of the halo, I , is given by I $= \sigma_{sc} n_g L$ where σ_{sc} is the scattering cross-section and $n_g L$ is the grain column density to the source.

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Convolving such a profile with the emission within 2 arcmin detected from CasA results in the halo profile shown in figure 2. From the normalisations to the observed halo we derive values for $a \approx .03\ \mu$ and $\sigma_{sc}\, n_g \doteq .006\ \mathrm{kpc}^{-1}$ which are not unreasonable for graphite or silicon grains.

CONCLUSION

We believe the extended emission detected to be real and not to be purely an instrumental effect. While we have insufficient information to determine which of the physical processes we discuss is at work the data do already provide useful upper limits to all the processes. Further observations of the halo at different energies, both in X-rays and in other wavebands may provide the solution.

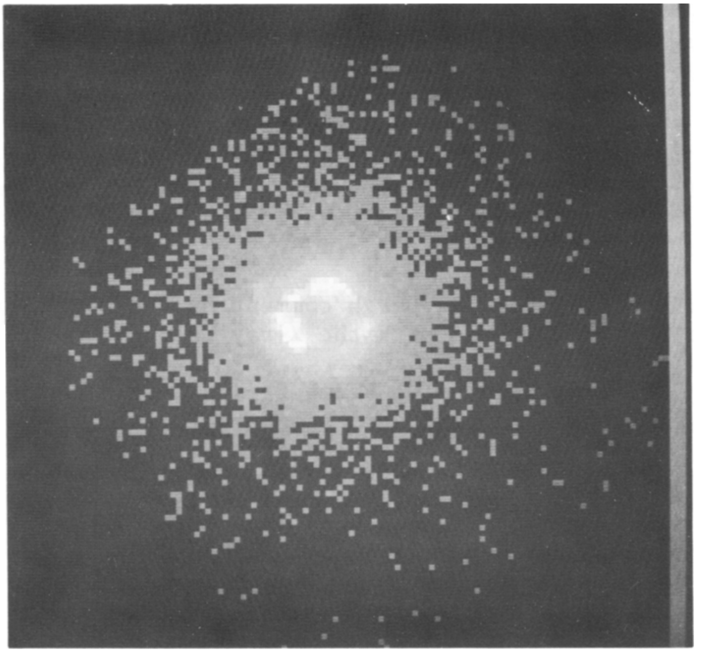

Plate 1 : HRI X-ray image of CasA binned in 16 arcsec pixels and displayed as discussed in the text.

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DISCUSSION

GORENSTEIN: As the effect has a scale of 6 arcmin, why did you not use the IPC data? You would have obtained information on the energy dependence of the effect and reduced the number of possibilities.

STEWART: Analysis of the IPC data is in progress but is as yet unfinished. Preliminary results show the existence of the halo in two energy bands, but we have no information on the energy dependence of the halo so far.

GRINDLAY: Could Sidney van den Bergh comment on the morphology of the HII region and how it compares with the X-ray halo.

VAN DEN BERGH: Observations by M. Peimbert and myself show evidence for some very faint patches of Hα emission nebulosity in the vicinity of Cas A. In our 1971 paper we speculated that the HII region might have been excited by a burst of UV radiation produced by the supernova.