X-ray Studies of SS433

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Results of Einstein Observations of SS433 are discussed which address both the nature of the diffuse X-ray lobes and the relationships between SS433 and W50 as well as the time variability and nature of the central X-ray source. The diffuse X-ray lobes extend out to the quasi-spherical shell seen in the radio maps of W50 and suggest that the X-ray lobes are powered by the interaction of shock-heating from the SS433 jets and the denser material in the W50 shell. The central X-ray source in SS433 is time variable but only on timescales $\gtrsim$ 500-1000 sec. Flares, in which the non-thermal spectrum hardens, are detected at two preferred phases in the 13.08 day binary orbit. Constraints on the central X-ray source size as well as a possible eclipse by the companion star suggest the compact object in SS433 may be an ~10 $M_\odot$ black hole.

1. Introduction

The peculiar object SS433 was observed in some 37 separate pointings with the Einstein X-ray Observatory (Giacconi et al. 1979) between March 1979 and October 1980. Observations were made with the two imaging instruments, the HRI and IPC, which showed the previously known X-ray source (Seward et al. 1976, Marshall et al. 1979) was surrounded by diffuse X-ray emission in two lobes (Seward et al. 1980, Watson et al. 1983). The MPC data from all the Einstein observations have been used to study the spectrum and variability of the central source (Grindlay et al. 1983). We shall describe both the diffuse and compact source results here and discuss a common model.

2. Diffuse X-ray Lobes

A ~1° x 2° field was mapped out around SS433 in three separate IPC exposures, each with ~15 ksec exposure time. The common X-ray image is shown in contour form in Figure 1. The X-ray lobes are striking direct confirmation of the existence of the relativistic jets in SS433. They define the same position angle (99°) on the sky as the jets and they have brightened "ends" at angular distances (from SS433) of 35-40 arcmin where they intersect the bright radio shell of W50 (Watson et al. 1983).

J. Danziger and P. Gorenstein (eds.), Supernova Remnants and their X-Ray Emission, 459–463.

The luminosity in each lobe is ~6 x 10^{34} erg sec^{-1} in the 0.5-4.5 keV band, and the spectra can be fit with thermal bremsstrahlung models with kT ≃ 1.5 keV. There is some evidence that the diffuse emission becomes harder towards the central source.

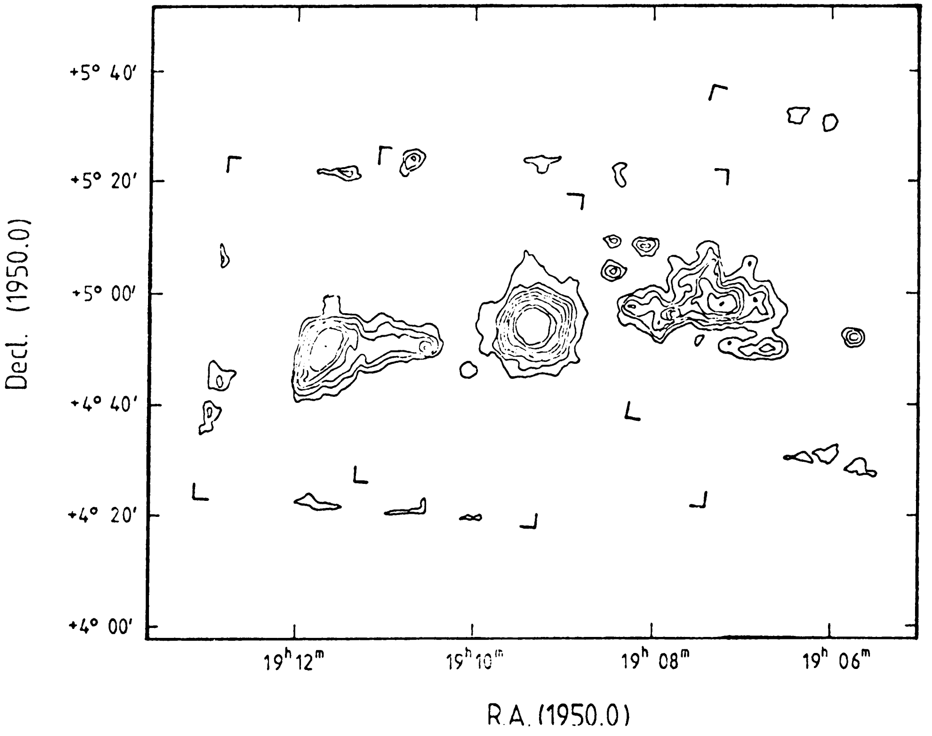

Figure 1 - Contour map of the (three) combined IPC images of SS433 in the ~0.7-4 keV band. The lowest contour is at ~7σ above background and corresponds to 2.3 x 10^{-3} IPC cts sec^{-1} $arcmin^{-2}$; subsequent contours are in steps of ~2.5σ (from Watson et al. 1983).

Perhaps the most striking feature of the lobes is their axial symmetry and center-filled morphology. The angular width subtended by the lobes is only ~15° (FWHM) although faint diffuse emission extends out from the lobe axis with full widths of ≳50°. The angular width of the lobe is significantly narrower in the hard X-ray band (1-2.5 keV) than in the soft band (0.5-1.0 keV) of the IPC. However, even in the soft band the FWHM is significantly narrower than the ±40° cone expected from the precession cone angle of the jets as inferred from the optical data and kinematic model (Margon 1982). If the X-ray lobes are due to the direct interaction of the beams with the material in W50 limb-brightened X-ray lobes would be expected. The lobe morphology may be used to distinguish between non-thermal and thermal models for the emission.

In a non-thermal model, the diffuse X-rays could be due to synchrotron radiation from electrons with energy ~6×10^4 GeV in a (equipartition) magnetic field of B ~4 μg. These electrons with lifetimes of ~10^4 year, could be produced by a first-order Fermi acceleration process in which ~40 collisions of an electron with material in the relativistic beams would boost the energies by the factor ~10^4 required from the initial ~5 GeV radio-emitting electrons. The center-filled morphology of the lobes would require the diffusion timescale (limited by the Alfven speed) for particles be less than the radiation lifetime. This is not possible for reasonable combinations of B and particle density, and so the precessing jets would have to fill the entire cone.

A thermal emission model is consistent with the lobe surface brightness and approximate spectrum profiles. The lobe spectra are fit by bremsstrahlung spectra with kT ≃ 1-3 keV, increasing towards the cone axis and central object. The particle densities required range from ~0.2 cm^{-3} in the faint emission plateau at $\gtrsim$ 45 arcmin from SS433 to ~0.7 cm^{-3} in emission peak at radius ~35 arcmin. The emission peak in the lobes is probably due to the density peak in the shell (at ~35 arcmin) of W50 as evident in both the radio (Geldzahler et al. 1980) and optical (Zealey et al. 1980) maps. The center-filled lobe morphology and possible temperature gradient suggests the actual heating mechanism of the gas is by shocks propagating perpendicular to the beams and intersecting along the cone axis. This requires heating timescales long enough (~10^4 yr) for shock propagation (at ~300 km sec^{-1}) to the cone axis.

The total thermal energy content of the lobe is 1.2×10^{51} ergs and the cooling time is ~3×10^8 years. This requires a rate of energy supply (from the beams) of $L_{beams} \simeq 4 \times 10^{40}/(\varepsilon\, T_3)$ erg s^{-1}, where ε is the conversion efficiency from beam kinetic energy to thermal energy and T_3 is the timescale for energy supply in units of 10^3 years. Thus, for $T_3 \gtrsim 1$ (corresponding to the minimum propagation times at 0.26 c of the material in the beams out to the lobes), then $L_b \lesssim 10^{41}$ erg s^{-1}.

3. X-ray Emission from the Central Region of SS433

The central object in SS433 is, of course, especially interesting. Its X-ray emission is apparently non-thermal and characterized by flares with ~1 day timescales (Seaquist et al. 1982, Grindlay et al. 1983). In the latter study, we have shown that since there is no evidence for variability on timescales $\lesssim$500-1000 sec, a plausible lower limit on the source size is ~10^{12}-10^{13} cm. The central source appears to have a relatively hard power law spectrum which may be eclipsed briefly once per 13.08 day orbit. The possible eclipse is evident at phase 0.3 in the X-ray light curve plotted in Figure 2. The spectral index, as measured in both the MPC and SSS instruments, steepens significantly in the dip, and there is a marginal increase in the low energy absorption. The X-ray luminosity plotted in Figure 2 also shows two phases (~0.1 and ~0.6) of the 13.08 day period where flares occur. These are

https://doi.org/10.1017/S0074180900034276 Published online by Cambridge University Press

characterized by pronounced hardening of the power law spectrum, with even positive (energy) spectral indices observed in some flares.

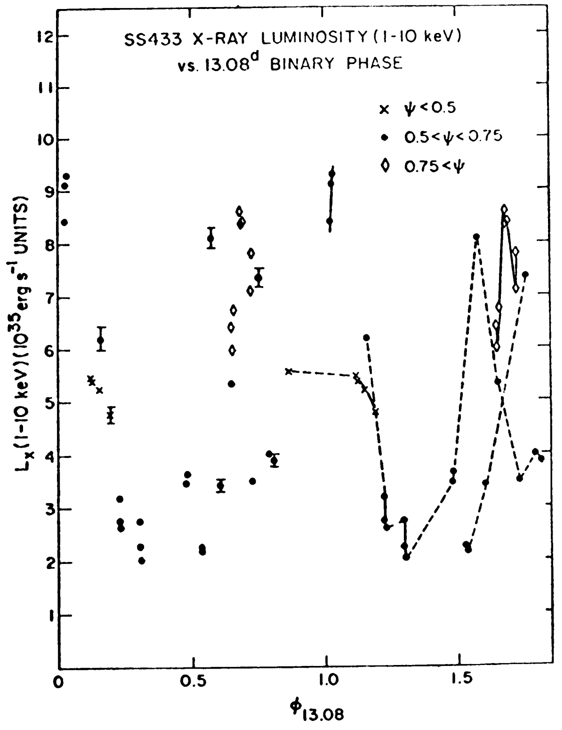

Figure 2 - Apparent modulation of the ~1-10 keV X-ray luminosity of SS433 at the 13.08 day binary period (plotted twice, for clarity). Three different intervals of 164 day phase, Ψ, are indicated. Solid lines connect adjacent observations (within 0.75 day) and dashed lines connect points observed in the same sequence by Einstein. A possible partial eclipse is evident at phase ~0.3, while flares are evident primarily at phases ~0.1 and ~0.6 (from Grindlay et al. 1983).

The flare modulation is approximately synchronous with both the velocity maxima/minima in the "stationary" HeII λ4686 line emission (Crampton and Hutchings 1981) as well as the photometric (continuum) variations in a similar range of 164 day phase, $0.5 < \Psi < 0.6$ (Kemp et al. 1980). The X-ray and optical maxima at quadrature phases suggest the accretion disk is comparable in optical brightness to the companion star and that the flares are triggered by enhanced accretion into the disk plane. If the companion star also has inclined spin, as in the slaved disk models of Katz et al. 1982 which give rise to the nodding motions of the disk, then the Roche lobe radius of the companion star will undergo two maxima/minima per orbit provided the orbit is nearly circular (Avni and Schiller 1982). This could provide the required modulation of the accretion rate. Alternatively, if internal damping has aligned the companion star (Papaloizou and Pringle 1982), the precessing disk may still undergo enhanced accretion twice per orbit when its mid-plane crosses the orbital plane. In either case the phase of the X-ray maxima is expected to advance with 164 day phase if the disk precesses with the beams.

The possible X-ray eclipse and yet finite X-ray source size can constrain the source mass. To (partially) eclipse the X-ray source (with radius $\sim 10^{12}$–10^{13} cm), the stellar companion must have a comparable radius. A ~ 20–$30\ M_\odot$ B giant (with radius $\sim 2 \times 10^{12}$cm) would be consistent as has been suggested (Zealey et al. 1980) on the basis of the inferred mass loss in the system. The mass function of SS433 derived by Crampton and Hutchings (1981) would then require the compact object to be $\sim 10\ M_\odot$ and thus presumably a black hole.

4. Conclusions

X-ray studies of SS433 constrain both the nature of the jets (with age $\gtrsim 10^3$–10^4 years and total kinetic energy $\lesssim 10^{41}$ erg s^{-2}) and ISM into which they expand (which appears to be consistent with a SNR). They constrain also the nature of the central binary system, which appears to contain a B giant, a massive ($\sim 10\ M_\odot$) compact object (black hole) and tilted accretion disk in which variable accretion occurs. Particle acceleration (to $\gamma \gtrsim 10^2$–10^4) must occur in the disk or disk corona to explain the central non-thermal X-ray source which is eclipsed. The acceleration region may be in the inner ends of the beams, with blobs of relativistic plasma then entrained in the jets and moving out to give the synchrotron radio emission (and an additional inverse Compton X-ray component) at distances of $\sim 10^{14}$–10^{15} cm as envisioned in the model of Seaquist et al. (1982).

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