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X-Ray Observations of SS 433: Review and Recent Results

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Abstract. The X-ray characteristics of SS 433 are reviewed together with results of recent multi-wavelength observing campaigns.

1. Introduction

SS 433 is the enigmatic binary system with a bipolar jet emanating at 0.26 c (see Chakrabarti on page 5 and references therein). The Doppler-shifted emission lines move in the spectrum as the jet axis precesses with a period of 162.5 days (Margon 1984 and references therein). The jet blobs successively ejected from the central core draw a "cork screw" in the radio sky (Hjellming & Han 1997 and references therein). The historical activity of the jet over 10^4 yr and 10^{51} erg is visible as the spectacular X-ray jet lobes around SS 433 (Brinkmann, Aschenbach, & Kawai 1996). Such an outstanding jet has never been discovered from any other sources in the universe. SS 433 is truly one of a few exotic stars we know.

Although the system has been studied for more than 20 years, some fundamental questions remain unanswered: how the bipolar jet is accelerated and collimated, why the jet axis is precessing, and whether the compact object in the central engine is a black hole or a neutron star. Because X-rays are emitted from the highly energetic region of the system, e.g., the vicinity or the surface of

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the accreting compact object, the inner-most region of the super-critical accretion disk and the hot base of the jet, X-ray observations are suitable to explore the nature of the system and answer the questions above. SS 433 has been one of the most important targets of X-ray astronomy missions, and numerous observations have been performed, leading to some key findings. We review the X-ray observations of some past and on-going missions and their discoveries, and show how conclusions were often found inconsistent with the data of successor missions. This review is not intended to be comprehensive, and not all of the previous missions are mentioned: Chandra, ROSAT, Ginga and several others are omitted, although their results are of no less importance.

2. History of X-Ray Observations

Results obtained with Einstein, EXOSAT and ASCA are presented. Their discoveries about SS 433 had an impact on the field and results of other missions were influenced or based on them. The ASCA results are described in more detail in Section 3.

2.1. Einstein (1978–1981)

Just after its discovery, SS 433 was observed with Einstein, the advanced X-ray observatory at the time. The X-ray spectra from 1 to 10 keV taken with Einstein are shown in Fig. 1. No significant spectral features were found with the detector, and it was concluded that the spectrum of SS 433 is non-thermal, of synchrotron or inverse-Compton nature, and that high-energy electrons in the jet account for both the X-ray and radio emissions. It should be noted that the last bin in the spectra was always higher than the best-fit power-law model. That might be a statistical fluctuation or a sign of what EXOSAT later found.

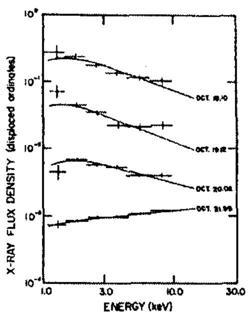

Figure 1. X-ray spectra taken with Einstein (Seaquist et al. 1982, reproduced with permission of the Astrophysical Journal Editors).

2.2. EXOSAT (1983–1986)

Fig. 2 (Watson et al. 1986) is the famous spectrum obtained with EXOSAT, which had a finer spectral resolution and larger effective area than Einstein. The spectrum clearly shows a blue-shifted iron line. This was evidence that the

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X-ray emission mechanism was not synchrotron or inverse-Compton, as argued earlier based on Einstein data, but thermal. The X-rays are emitted from the thin-thermal plasma in the jet. Stewart et al. (1987) argued that the red-shifted emission line is not visible because it is hidden behind an accretion disk. It was concluded that the X-ray emitting part of the jet is shorter than 10^{12} cm. This conclusion is widely accepted and cited in text books (e.g., Charles & Seward 1995). It should be noted that in Fig. 2 there is a marginal hump at 5 keV where a red-shifted counter part of the emission line is expected to be. This might be a statistical fluctuation or a sign of what ASCA later found.

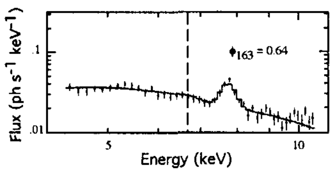

Figure 2. A spectrum taken with EXOSAT (Watson et al. 1986, reproduced with permission of the Monthly Notices of the Royal Astronomical Society Editors).

2.3. ASCA (1993–2001)

The SIS (Solid-state Imaging Spectrometer) on-board ASCA had a finer spectral resolution and larger effective area than EXOSAT. The spectrum (Fig. 3) clearly shows various emission line pairs from both the jets (Kotani et al. 1994). It is evidence that the X-ray jet is longer than estimated, probably $\sim 10^{13}$ cm. A longer jet implicates a larger kinetic energy. The study based on ASCA data is described in the following section.

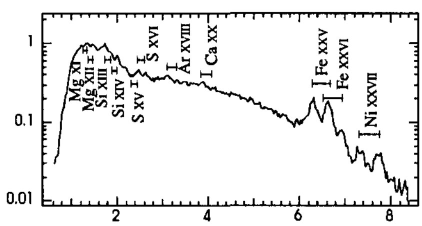

Figure 3. A spectrum taken with ASCA.

3. ASCA Observations

The Doppler-shifted emission lines of highly ionized nickel, iron, calcium, sulfur, silicon and magnesium from both the jets were resolved by ASCA/SIS. Information of the system can be extracted from the technique of line diagnostics: the precession and nodding motion of the bipolar jet from the Doppler shifts, the

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temperature structure from the ion species, the geometry of the system from the line flux ratios, and so on. The line diagnostics has been developed to analyze the ASCA data, which were sampled during the life time of the satellite, accumulated over 500 ks and more than 30 pointing observations (e.g., Kotani et al. 1996; Kotani 1997). The technique is briefly reviewed in this section. For more detail, see Kotani (1997).

3.1. Spectral Model

In the line diagnostics, the thin-thermal multi-temperature Doppler-shifted spectrum from the jets is numerically calculated for quantitative analysis of the observed spectrum. The jet is modeled as a conical plasma flow cooling via radiation and expansion. The input parameters are the initial electron density, the opening angle of the cone, the mass outflow rate, the initial temperature, and the abundance of the plasma. The emission from each part of the jet is integrated considering Doppler shift and Doppler boost. When the plasma is cooled down to a few eV, the plasma collapses within milliseconds due to a thermal instability This point is defined as the end of the X-ray jet and the calculation is terminated. The resultant spectra are compared with observations, and the parameters of the jet are determined.

3.2. Eclipse

SS 433 is an eclipsing binary with a period of 13.01 days. In eclipse, the companion star occults the accretion disk and the base of the jet. Since the emission lines from both jets are resolved, we can tell how and when each jet is occulted during eclipse. The depth of the eclipse tells us how much of the jet is occulted, and the duration of eclipse tells us the size of the companion star. An observation campaign covering an eclipse was performed, and the relative size of the jet, the accretion disk and the companion star were determined (Kotani 1997).

3.3. Toy Model

To explain the eclipsed light curves quantitatively, a simple geometrical model consisting of a bipolar jet, a companion star, and an accretion disk is adopted. The multi-temperature bipolar jet is occulted by both the companion star and the accretion disk. The companion star has an ellipsoidal shape, and the disk has a thickness and an opening angle. The companion star goes around the compact object as the eclipse progresses.

We calculated the emission line light curves according to this toy model, and searched the parameter space for a point best describing the data. As a result, the orbital separation was found to be 1/10 of the X-ray jet length. The companion star's radius is roughly half of the orbital separation. A thin plane like disk model can not explain the data. The disk must have a thickness of one tenth of the radius. The resultant disk radius is puzzling. It must be larger than the orbital separation to explain the observations. Either something is wrong with the assumptions, or the optically thick gas extends over the orbital separation from the rim of the disk.

4. RXTE Observations

4.1. Multi-wavelength Observing Campaigns

RXTE observed SS 433 many times, often as a part of multi-wavelength observation campaigns. Participating observatories included the VLA (Band et al., in preparation), the Nobeyama millimeter array (Kotani et al., in preparation), and other space observatories such as ASCA, etc.

In a 1997 campaign, in which ASCA and the Nobeyama millimeter array participated, a spectrum over 10 orders of magnitude including millimeter-wave data has been simultaneously sampled. SS 433 was in its quiescent state at that time. The overall spectrum consists of three components. The synchrotron radio emission from the high-energy electrons in the jet, the thick-thermal optical emission from the disk and the companion star, and the thin-thermal X-ray emission from the hot part of the jet.

4.2. A Massive Radio Flare

The archival radio light curve obtained with the Green Bank Interferometer is shown in Fig. 4. The Green Bank Interferometer was running a monitoring program of various radio and X-ray sources at that time, and very important data like these were obtained. Unfortunately, the program was terminated two years ago due to funding problems. The radio light curve obtained over three years shows the activity of SS 433. Sometimes SS 433 experiences massive radio flares exceeding 1 Jy. In these massive radio flares, a massive jet blob is formed and ejected. Such massive jet ejection events are rare, a few times a year, and short, within days, and thus difficult to detect. So we have planned to catch the

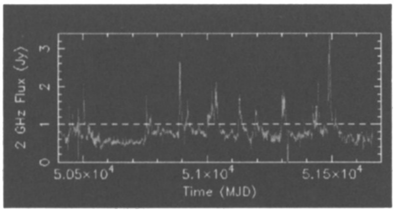

Figure 4. A radio light curve taken with the Green Bank Interferometer (GBI Monitoring Program 2000).

moment of a massive radio flare with RXTE. Because these flares are clustered, we have coordinated long term RXTE observations triggered by radio flares.

The RATAN-600 radio telescope has performed long monitoring observations. In November 2001, the RATAN-600 detected a massive radio flare, and we triggered a RXTE monitoring observation. Twenty days later, a second massive radio flare was detected. A few days before the radio flare, the RXTE data showed a scattering. This is the first massive jet ejection event covered with an X-ray mission. The radio and X-ray light curves are shown in Figs. 5 and 6, respectively.

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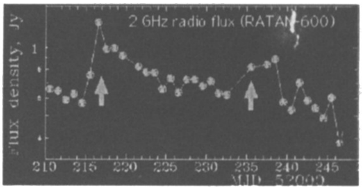

Figure 5. The radio light curve taken with RATAN-600 in November 2001.

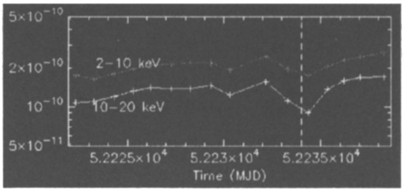

Figure 6. The X-ray light curve taken with RXTE in November 2001.

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