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A recent multi-wavelength campaign to observe the microquasar SS433

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Abstract. We present a summary of the recent multiwavelength campaign made in September-October, 2002, to observe SS 433. We used the Giant Meter Radio Telescope (GMRT) for radio observation, 1.2 meter Physical Research Laboratory Infra-red telescope at Mt Abu for IR, 1 meter Telescope at the State Observatory, Nainital for Optical photometry, 2.3 meter optical telescope at the Vainu Bappu observatory for spectrum and Rossi X-ray Timing Explorer (RXTE) Target of Opportunity (TOO) for X-ray observations. Sharp variations in intensity in time-scales of a few minutes in X-rays, IR and radio wavelengths have been discovered. We also discover a delay of about two days between IR and Radio. Double Fe line profiles which corresponded to red and blue components of the relativistic jet have been found in X-ray data. We present the broadband spectrum averaged over the campaign duration.

Keywords : SS 433 — X-ray, Infra-red and radio sources — stars: individual (SS 433)

1. Introduction

The enigmatic compact star SS 433 is a well studied bright emission line object which is known to have a companion with an orbital period of 13.1d, a large disk and two highly collimated relativistic jets moving at $v \sim 0.26$c. Disk axis makes an angle of $\sim 78°$ with the line of sight, while the jet precesses with the axis at an angle of $\sim 19°$ (Margon, 1984) with a periodicity of about 162.15d. Several observations have been carried out over the last three decades, and yet, the object alluded a proper identification. Most

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recent estimate (Hillwig et al., 2004) suggest that the central object could be a low mass black hole ($2.9 \pm 0.7 M_\odot$) with a high mass ($10.9 \pm 3.1 M_\odot$) companion.

The aim of our campaign was (a) to carry out observations in as many wavelengths as possible, (b) to detect the nature of the short time-scale variabilities in all the wavelengths, (c) to obtain a broad band spectrum of this enigmatic system in order to model the emission processes in future. We carried out the campaign in Radio (1.28 GHz), in IR (J, H, and K$'$ bands), in optical (B and V bands) and in X-ray (3-30 keV) wavelengths in September-October, 2002, when the jet is more or less normal to the line of sight and the X-ray intensity is statistically in its minimum. Our radio observations were carried out during 26th September to 6th of October, 2002. The IR observations were made during 25th to 29th of September, 2002. The optical photometry was made during 27th September to 3rd October, 2002, while X-ray observation was taken only on the 27th of September, 2002. Optical spectra were taken on the 27th and 28th of September, 2002. A brief report on the variabilities in radio, IR and X-rays, observed on the 27th of September, 2002 has already been published in Chakrabarti et al., (2003) and a detailed paper with major observational results is in Chakrabarti et al., (2005, hereafter referred to as Paper 1).

Among the major results we find that (a) The short time-scale variations are present ($2-8$ minutes) on all the days in all the wavelengths; (b) The optical and X-ray spectra contain the blue and red-shifted lines which are compatible with the kinematic model (Abell and Margon, 1979); (c) For the first time, we obtained the broadband spectrum over ten decades of frequency range based on the contemporaneous data and (d) We found a lag of two days between overall variation of intensities in IR and Radio wavelengths.

2. Observations

Radio observations were carried out with the GMRT near Pune, India which has 30 antennas each of 45m diameter in a Y-shaped array with the longest baseline being over 25km (Swarup et al., 1991). The observations were carried out at 1.280 GHz (bandwidth 16 MHz) during September 26th, 2002 to October 1st, 2002 and at 610 MHz (bandwidth 16 MHz) during 2nd-6th October, 2002. However, results of 3rd-4th October were full of scintillations. The data were binned at every 16 seconds. AIPS package was used to reduce the data. Bad data was flagged using tasks UVFLG and TVFLG and the standard deviation at each time bin using UVPLT package was computed. Generally, 3C48 and 3C286 were used as the flux calibrators whenever available.

Infrared observation was made using the Physical Research Laboratory (PRL) 1.2m Mt. Abu infrared telescope equipped with the Near-Infrared Camera and Spectrograph (NICMOS) having 256 $\times$ 256 HgCdTe detector array cooled to the liquid nitrogen temperature 77K. One pixel corresponds to 0.47 arcsec on the sky, giving a field of view of 2×2 arcmin^2. The filters used were standard J (λ=1.25 μm, $\Delta\lambda$= 0.30 μm), H (λ=1.65

μm, $\Delta\lambda$= 0.29 μm) and K$'$ (λ=2.12 μm, $\Delta\lambda$= 0.36 μm) bands. Short exposures were taken in immediate succession in all the three bands. Single-frame exposure time during whole observations in the J and H filters were 10 seconds. Observations in K$'$ filter were taken with 2 sec exposure and 5 successive frames were binned to obtain 10 sec for a better signal to noise ratio. On the 26th of September only J band observation could be made before clouds covered the sky. At each dithered position ten frames were taken with each integration time of 10 seconds. The nearby infrared bright standard star GL748 (Elias et al., 1982) was used as the flux calibrator and it was observed for 50 frames with exposure time of 10 sec in each filter during each night. Data reduction of JHK$'$ images were performed in a standard way using the DAOPHOT task of IRAF package. All the objects and standard star frames were de-biased, sky-subtracted and flat fielded. The sky frames were created by usual practice of median combining of at least five position-dithered images where the source was kept within the field of NICMOS of $2' \times 2'$. At each dithered position at least 10 frames of 10 sec exposure were taken for J and H bands while 20 frames of 2 sec exposure were taken for K$'$ band. The zero point of the instrument was taken from the standard star observations. The stellar magnitudes were measured using the aperture photometry task (APPHOT) in IRAF. The derived mean JHK$'$ magnitudes on September 25th, 27th and 29th are 9.51±0.04, 8.48±0.03 and 8.49±0.08; 9.47±0.02, 8.48±0.02 and 8.32±0.02; 9.51±0.01, 8.49±0.04 and 8.38±0.03 respectively. On the 26th of September J magnitude was 9.52±0.02. The magnitudes are converted to flux density (Jansky) using the zero-magnitude flux scale of Bessell, Castelli and Plez (1998) for plotting purpose. The differential magnitudes are determined using two brightest stars in the same frame of the object. Photometric errors ϵ are calculated for individual frame of every star and for the subtracted differential magnitude, the final error was calculated as $\sqrt{\epsilon_1^2 + \epsilon_2^2}$, where ϵ_1 and ϵ_2 are the error-bars of the individual stars.

The optical photometry was carried out at the State Observatory (currently known as ARIES), Nainital, India using its 1m reflector. The optical spectroscopic study of SS 433 was carried out with the 2.3 meter Vainu Bappu Telescope (VBT) at the Vainu Bappu Observatory (VBO), Kavalur, India. Details of the observations are in Paper 1.

X-ray observations were carried out using the Proportional Counter Array (PCA) aboard RXTE satellite. The data reduction and analysis was performed using software (LHEASOFT) FTOOLS 5.1 and XSPEC 11.1. We extracted light curves from the RXTE/PCA Science Data of GoodXenon mode. We combined the two event analyzers (EAs) of 2s readout time to reduce the Good Xenon data using the perl script *m*ake_se. Once *m*ake_se script was run on the Good_Xenon_1 and Good_Xenon_2 pairs, the resulting file was reduced as Event files using *s*eextrct script to extract light curves. Good time intervals were selected to exclude the occultations by the earth and South Atlantic Anomaly (SAA) passage and also to ensure the stable pointing. We also extracted energy spectra with an integration time of 16s from PCA Standard2 data in the energy range 3 - 30 keV (out of the five PCUs only data from No. 2 and No. 3 PCUs are added together). For each spectrum, we subtracted the background data that are generated using PCABACKEST v4.0. PCA detector response matrices are created using

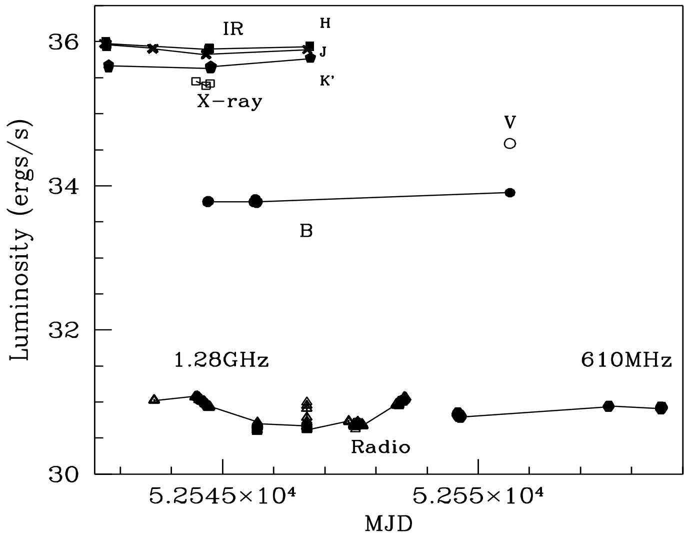

Figure 1. Multi-wavelength observation of SS 433 at 1.28 GHz (triangles) band and at 610 MHz (filled hexagons) in radio, at J (crosses), H (filled boxes), K$'$ (filled pentagons) bands in IR, B (filled circles) and V (open circle) bands in optical, and $3-25$ keV (open squares) in X-ray during the campaign. There seems to be a lag of minimum intensity region in radio (MJD 52545.5 to MJD 52547.5) with respect to the Infra-red minimum region ($\sim$ MJD 52544-52545) by about 1.7 days.

PCARSP v7.10. We perform fits to the energy spectra in the energy range 3-27 keV with the so-called 'traditional model' for SS 433, consisting of the super-position of thermal bremsstrahlung and Gaussian lines due to the emission from the iron atoms, modified by the interstellar absorption.

3. Results and discussion

Figure 1 shows the lightcurves of our multi-wavelength observation at 1.28 GHz (triangles) band and at 610 MHz (filled hexagons) in radio, at J (crosses), H (filled boxes), K$'$ (filled pentagons) bands in IR, B (filled circles) and V (open circle) bands in optical, and $3-25$ keV (open squares) in X-ray during the campaign. There seems to be a minimum in IR data on $\sim$ MJD 52544.674 (see Paper 1) while the radio shows minimum at $\sim$ MJD 52546.7, almost two days later. If the IR data could be taken as the pre-cursor of the radio data, one would infer that IR was also in a state of minimum intensity during the campaign. However, it is to be noted that this IR intensity is the sum of the components coming from the companion and the jet. From the IR observation of Kodaira, Nakada and Backman (1985), one notices that at the precessional and orbital phases of SS 433 corresponding to our campaign, the relative K magnitude was expected

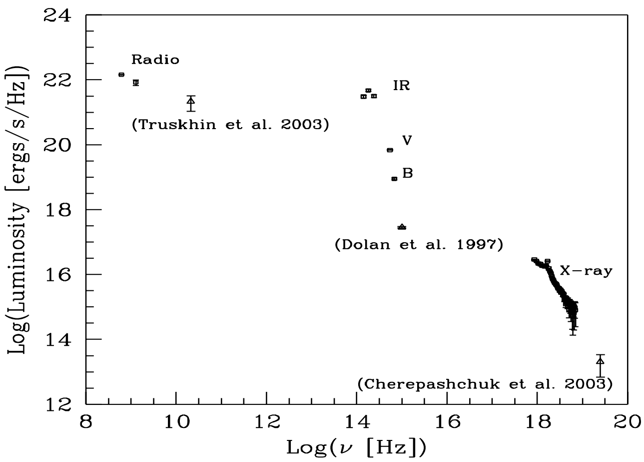

Figure 2. The multi-wavelength spectrum of SS 433 as obtained by our campaign. Here, average luminosity (open boxes) over our available data has been plotted and the wavebands are marked. For comparison, we included three points, marked by open triangles with error bars, from literature (marked) which are not contemporaneous with our observation.

to remain almost constant ($\sim 0 \pm 0.05$Jy), while in our observation we find it to be highly variable (~ 0.225Jy) which suggests that there are intrinsic variation in IR band which may have been reflected in the Radio band two days later. The H-band intensity was found to be higher compared to the J and K$'$ band results during the whole period.

Figure 2 gives the broadband spectrum of SS 433 that we obtained using our multi-wavelength campaign. Campaign average data has been used for simplicity and no correction has been made for extinction. In radio, results of 610 MHz and 1.28 GHz data have been put, while in infra-red, the results of I,J, K' bands have been put. We included V and B band observations which clearly show heavy extinction and the luminosity drops dramatically. X-ray spectrum in $3-27$ keV is also shown. To compare with the results of others, we have included three observations at wavelengths which were not covered during our campaign (triangles). Thus, 21.7GHz observation of Trushkin et al., (2003), ultra-violet observation of Dolan et al., (1997) and gamma-ray observation of Cherepashchuk et al., (2003) have been included. These three points were not contemporaneous to our campaign, but yet, they generally fall at reasonable values in the overall spectrum.

In this paper, we presented some results of a recent multi-wavelength campaign on SS 433 carried out during 25th September, 2002 till 6th of October, 2002 using radio, IR, optical and X-ray instruments. We found that there is a tendency for the radio intensity variation to lag the IR variation by about two days. The broadband spectrum clearly showed evidence of very high extinction in optical region, possibly due to large scale obscuration of the central object by matter coming from the companion wind (Paragi et al., 1999). The X-ray data could be fitted with two Fe lines, both of which appear to

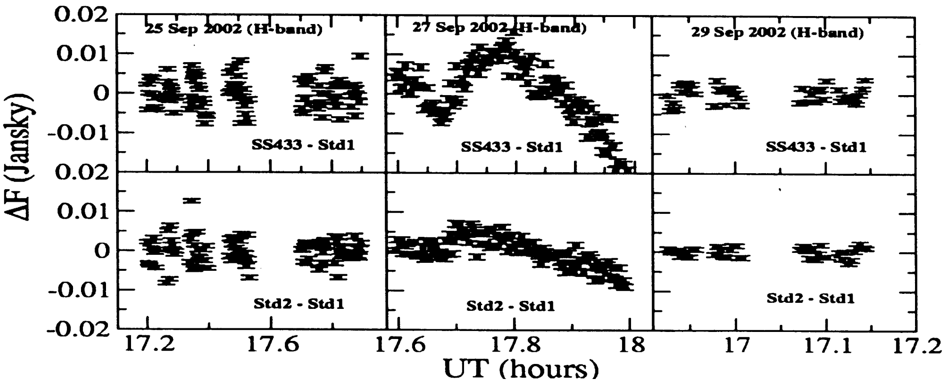

Figure 3. Results of differential photometry in H band using MT. Abu telescope is shown for some days as an example of intrinsic variability of SS433. The upper panel shows the difference of intensity with respect to a standard star in the field while the lower panel shows the difference between two standard stars located within the same field. The differential flux variation of SS433 is above 2σ level in comparison to that of the standard stars. The variation in SS433 is most pronounced on 27 September 2002.

be coming from the blue-shifted jet, i.e., the jet pointing towards us. We also find very small time-scale (few minutes) variations in all the wavelengths which could be suggestive of small bullets propagating from the base of the jet on the accretion disk to the radio regions. The differential photometry in IR gives very clear indications that these short time scale variations were intrinsic to the jet (Fig. 3). In optical spectra we observed that the blue- and red-shifted H_α lines to appear at the same location on the 27th of Sept. 2002 – on the 28th the intensities of these lines were very low possibly because the so-called optical bullet emission was on the decaying phase. Our optical and X-ray spectra indicated that the kinematic model generally gives the correct description even today.

To highlight the contribution by the Mt. Abu telescope, we note that the light-curve, imaging as well as the differential photometry reported by Chakrabarti et al., (2003) and Paper 1 have been major components of this multiwavelength campaign. The intrinsic variability of a few minutes time-scale was proven beyond doubt by this differential photometry.

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