Bull. Astr. Soc. India (2006) **34**, 1–9

Broadband radio spectrum of SS433

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Received 28 September 2005; accepted 8 December 2005

Abstract. We obtained a broadband radio spectrum of the galactic compact object SS433 through the multi-wavelength campaign using the Giant Meter Radio Telescope (GMRT) and the Effelsberg 100-m Radio Telescope. The observations took place from 2005 January 03 to 2005 February 08 using eight different frequencies. We observed a flare which appeared to have started prior to January 18 and lasted till February 08. The light curves show a progressively larger time-delay as the radio frequency goes down. The peak of the 6 cm lightcurve is delayed by ~ 3 days with respect to the peak of the 9 mm lightcurve. There is an indication of the flattening of the spectrum and possibly a turnover at ~ 1.5 GHz. If we interpret this to be due to synchrotron self-absorption, the required magnetic field would become too large, however, free-free absorption by hot thermal surrounding medium formed due to stellar winds is still a possibility. All sky monitor (ASM) aboard Rossi X-ray Timing Experiment (RXTE) showed very high X-ray count on 2005 January 25 when the flare was well underway. This may be due to slamming of the radio 'bullets' with previously ejected, relatively slowly moving material.

Keywords : Stars (individual): SS433 – Radio – Radio sources – Radio-frequency spectra

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1. Introduction

There have been quite a few multiwavelength campaigns in Radio frequencies in SS433 in the past (e.g., Seaquist et al. 1980, Seaquist et al. 1982, Vermeulen et al. 1993; Bursov and Trushkin, 1995) which studied SS433 when it was in quiet state as well as when it had flares. While some have claimed to obtain synchrotron turnover (Seaquist et al. 1980) at a low frequency when SS433 was in a quiet state and turnovers at very high frequencies (Seaquist et al. 1982), others have found clear evidences of increasing time-delay (on the order of a few days) as the observation frequencies go down (e.g., Bursov and Trushkin, 1995). It is generally found that at frequencies higher than the turnover frequency, the spectral slope is ~ -0.6, i.e., $I_\nu \propto \nu^{-0.6}$. In the current *Paper*, we present one of our recent observations independently verifying most of these assertions using two different radio telescopes. The observations were carried out during 2005 January 03 to 2005 February 08. For observations at 9 mm, 1.3 cm, 2.0 cm, 2.8 cm and 6 cm, we used the 100 m Effelsberg Radio telescope, located at Effelsberg, Germany and for observations at 21.4 cm, 23.4 cm and 29.4 cm we used the Giant Meter Radio Telescope (GMRT) located near Pune in India. We obtained the lightcurves at these frequencies and observed a flare. The spectrum of 2005 February 04 showed an indication of a turnover at ~ 1.5 GHz. This could be due to synchrotron self-absorption or due to free-free absorption. We combine our results with the All Sky Monitor (ASM) data of RXTE satellite to show that SS433 was perhaps active in X-rays also in this period.

In the next Section, we present the discussion on the observing techniques and the observational results. In Section 3, we present the discussion on the observations and finally, in Section 4, we present our results.

2. Instruments used and data reduction

The multi-frequency radio observations in the wavelength range of 9 mm to 6 cm (frequency range of 4.85 GHz to 32 GHz) were carried out using the 100m Effelsberg radio telescope. Since the source was point-like (compared to the telescope beam) and quite bright ($\gtrsim 0.3$ Jy) in the range of frequencies observed, we were able to determine the flux densities with "cross-scans": these consisted of 8 to 32 (depending on the observing frequency and the source strength) individual sub-scans through the source position. Half of these sub-scans (each with a length of about 4 to 5 telescope beams) were performed in azimuth and half in elevation. This enabled us to check the position offsets in both the coordinates and correct for those.

As the first step of the data analysis, a Gaussian profile was fitted to every sub-scan. The amplitude of these Gaussians (i.e., the result of the convolution of the point-like brightness distribution of the source with the antenna beam) was a measure of the flux density of the source. After applying a correction for small pointing offsets, the amplitudes of all individual sub-scans in one cross-scan were averaged. At $\lambda \leq 2$ cm, the sub-scans of one direction (azimuth or elevation) were averaged before fitting the Gaussian in order to increase the SNR. Additionally, for the short wavelengths, the opacity of the atmosphere was determined and each measured flux density for the atmospheric attenuation was corrected.

After correcting the measurements for the elevation-dependent sensitivity of the antenna, our observations were calibrated to the absolute flux density scale (Baars et al. 1977, Ott et al. 1994) by using the primary calibrators: 3C286, 3C48, and NGC7027. These observations could also be used to correct for a possible time-dependence of the telescope's sensitivity. The final measurement errors were derived from the formal statistical errors and a contribution from the residual fluctuations of the calibrators was obtained. The resulting measurement uncertainties usually lay in the range of $0.3 - 1\,\%$ at $\lambda = 6, 2.8\,$cm; for the shorter wavelengths they were somewhat higher (1-5 % depending e.g., on weather conditions).

The multi-frequency radio observations in the wavelength range of 21.4 cm to 29.4 cm (frequency range of $1020\,MHz$ to $1400\,MHz$) were carried out using the Giant Meter Radio Telescope (GMRT) (see, Pal and Chakrabarti, 2004 for details). We used 16 MHz bandwidth. Each data was binned for 16 seconds. Bad data was flagged. The data was background subtracted, calibrated, band-passed and channel averaged using appropriate tools of AIPS package. 3C48 and 3C286 were used as flux calibrator and 2011-067 was used as phase calibrator.

3. Observational results

In Fig. 1, we show the multiwavelength lightcurves of SS433 from 2005 January 03 to 2005 February 08. The actual data points with error-bars are shown both for the Effelsberg and GMRT telescopes. The long & short-dashed, dotted, dashed, dash-dotted, long-dash-dotted curves are respectively for 23.4 cm, 6 cm, 2.8 cm, 1.3 cm and 9 mm respectively. The observations at 21.4 cm (square) and 29.4 cm (cross) were made on JD 2453405+, i.e., on February 04 when observations were carried out simultaneously at Effelsberg. The light curves give indication of a flare. This becomes prominent when we extrapolate on each day's data and imagine the observed peak to be located at the intersection point (marked by solid squares which join nearby observed data points by solid lines). If we had taken continuous observations, we would expect the results at or near this point. If this linear decay of the source flux is assumed, then one could measure the delay as a function of frequency (see, Fig. 3). Another interesting property is that the low energy radiation decays faster than high energy emissions. For instance, at 6 cm, the source flux is reduced to half in just ~ 4.5 days, while at 9 mm, it takes ~ 9 days for the same fractional reduction. On the same plot, by a vertical arrow drawn at JD 2453395.12, we show the time-frame when a possible X-ray flare occurred as per ASM/RXTE data. Fig. 2 shows the ASM plot of photon counts per second. SS433 being a very weak source, even negative counts have been reported on many days. However, on JD 2453395.12 and the

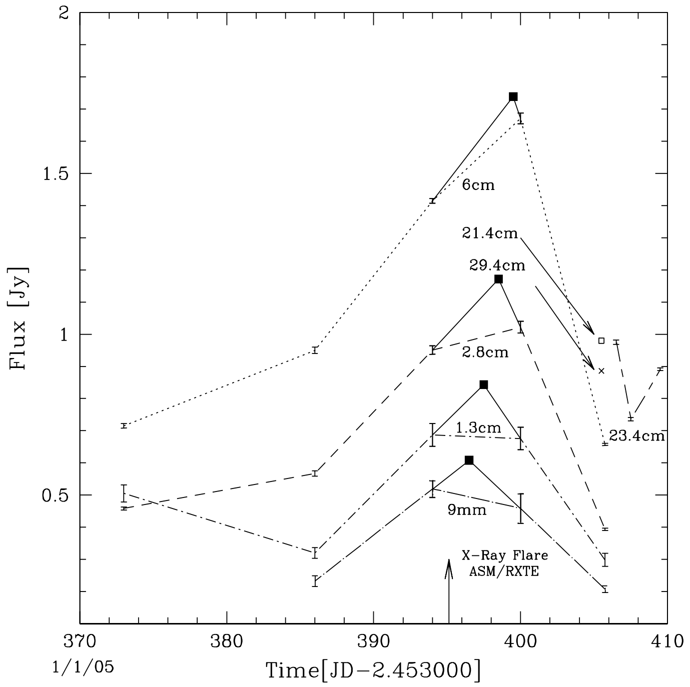

Figure 1. Lightcurves of SS433 during the campaign at various frequencies marked. The solid pieces of the curves near the peak have been obtained by linear interpolation of the observed data to 'guess' how the lightcurves would have looked like if the continuous observations were made. The solid squares are the interpolated peaks clearly showing several days of delay in between high and low frequency results.

day after, the count rates were very high. This could not have triggered the radio flare detected by us since the flare seemed to have started before hand. The other possibility is that the radio emitting ejecta or bullets (Chakrabarti et al. 2003) may have slammed into some previously ejected slowly moving component to produce this X-ray emission (e.g., Migliari 2003). On the other hand contamination from the sun cannot be ruled out as the ASM observes a wider section of the sky.

In Fig. 3, we show the plot of the time delay (days) as a function of the frequency. The solid circles are the actual delay measured with respect to the peak emission at 9 mm. The superposed curve corresponds to $t(days) \sim t_0 - (\frac{\nu}{\nu_0})^{1/2}$, where, $t_0 = 5.0$d, $\nu_0 = 1.3 \times 10^9$ Hz. The delays of 6.0 cm, 2.8 cm and 1.3 cm with respect to 9 mm are 3.08 d, 2.0 d and 0.9 d respectively. Such delays of the order of a few days have been reported before (Bursov and Trushkin, 1995) as well. If Δt is the delay with respect to 9 mm flare, it is easy to see that $\Delta t \propto \nu^\beta$, with $\beta \sim -0.8$. If we consider adiabatic expansion and employ the radio spectral index $\alpha = 0.66$ as observed in our data (see Fig. 4 below), then the particle spectrum ($N(E) \propto E^{-p}$) has the index $p = 2\alpha + 1 = 2.32$. This can

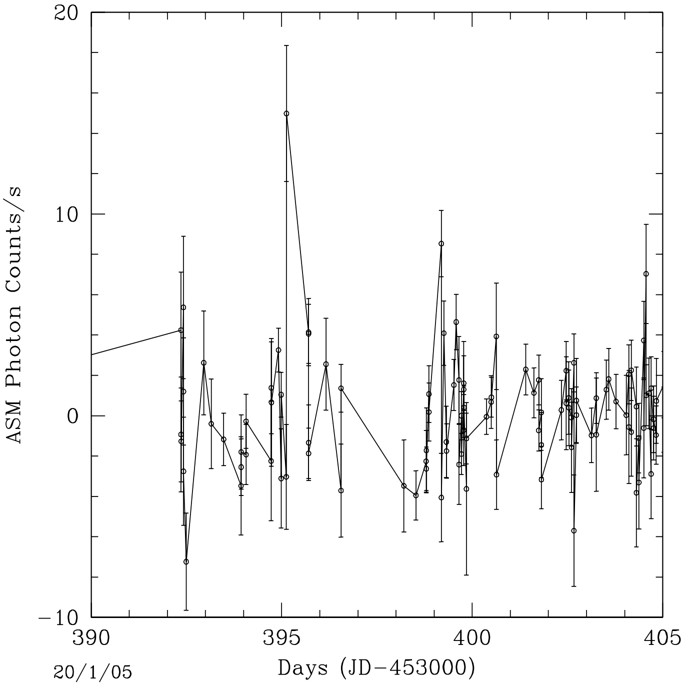

Figure 2. All sky monitor (ASM) results of the photon count rate during the campaign showing a significant rise of X-ray counts in the midst of the radio flare for a very short period definitely confined between JD2453395.1 and JD2453395.7.

be used to obtain the delay of the flare peak at different frequencies from $t_{m,\lambda} = t_0\lambda^{\frac{p+4}{4p+6}}$ (van der Laan 1966). The proportionality constant t_0 can be adjusted to get the peak at 9 mm in a way that the delays at other frequencies roughly match. We find that $t_0 = 3.0$ gives the delays at 6.0 cm, 2.8 cm and 1.3 cm with respect to 9 mm as 3.5 d, 1.8 d and 0.5 d respectively. Thus, according to van der Laan (1966) model, the flare at 9 mm started about $t_{m,0.9mm} = 2.87$ days prior to the estimated peak location at JD2453396.55, i.e., at JD2453393.7. This is not all that improbable as the beginning of the flare could indeed be anywhere between JD2453386 and JD2453394 as the data is absent in between.

In order to check if the time delay is due to adiabatic expansion, and the flare is an isolated event, we can use a consideration similar to Ishwar-Chandra et al. (2002) applied to GRS 1915+105 and compute p and α and the resulting time delays. These numbers seem to be off by a large margin. For instance, α comes out to be 0.74 at 9 mm, but 2.54 at 6 cm.

In Fig. 4, we present our multi-wavelength spectrum on three different days (i) on 2005 January 16 before the flare began (ii) on 2005 January 30 when the flare was on the way to decline and (iii) on 2005 February 04 when the flare was over. The flux at high

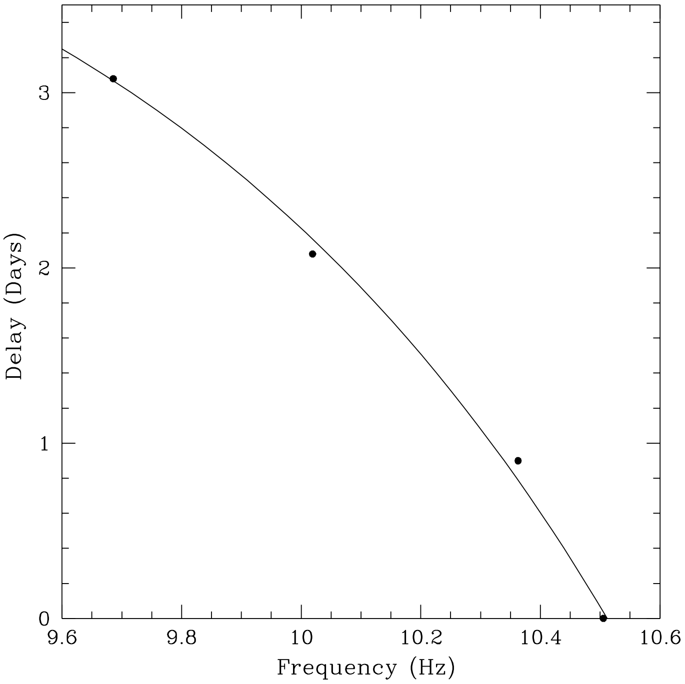

Figure 3. The delay in the peak intensities is plotted as a function of emitted frequency at solid circles. The solid curve is an analytical fit of the form $t(days) \sim 5.0 - (\frac{\nu[GHz]}{1.3})^{1/2}$.

frequencies on all the three days varies as $\nu^{-0.66}$. There is an indication of a turn-over at around 1.5 GHz on February 04 observation. Given that the decay-time of flux is strongly frequency dependent, it is possible that the turnover is not real and in fact an artifact. It is to be noted that Seaquist et al., 1982, also reported turn-overs at around 3 GHz. This observation we have fitted (solid line) with the following two-component model of synchrotron self-absorption of the form (e.g., Seaquist et al. 1982):

$$S_\nu = S_0 \nu^{-\alpha_0} + S_1 \nu^{-\alpha_1} \frac{1 - exp(-\tau_1 \nu^{-\alpha_1 - 2.5})}{\tau_1 \nu^{-\alpha_1 - 2.5}} \tag{1}$$

where, we find the fitted values to be $S_0 = 0.51$, $S_1 = 1.1$, $\alpha_0 = \alpha_1 = 0.6$ and $\tau_1 = 2.8$. Here τ_1 is the optical depth at $\nu = 1$GHz. The pair (S_0, α_0) corresponds to the optically thin quiescent state, and (S_1, α_1, τ_1) characterizes the optically thick component modeled as a uniform slab which could be variable. These parameters can be correlated to θ and $B_\perp$ (see, Seaquist et al. 1982) and we obtain $\theta/B_\perp^{1/4}) \sim 0.34 \times 10^{-2}$ (arcsecond Gauss$^{-1/4}$) which is comparable to what Seaquist et al. (1982) found.

Since the radio emission from the jets of SS433 is mainly due to synchrotron radiation by the non-thermal electrons, the spectrum shows a power-law nature of spectral index $\alpha = (p-1)/2$, where p is power-law index of non-thermal electron distribution. The

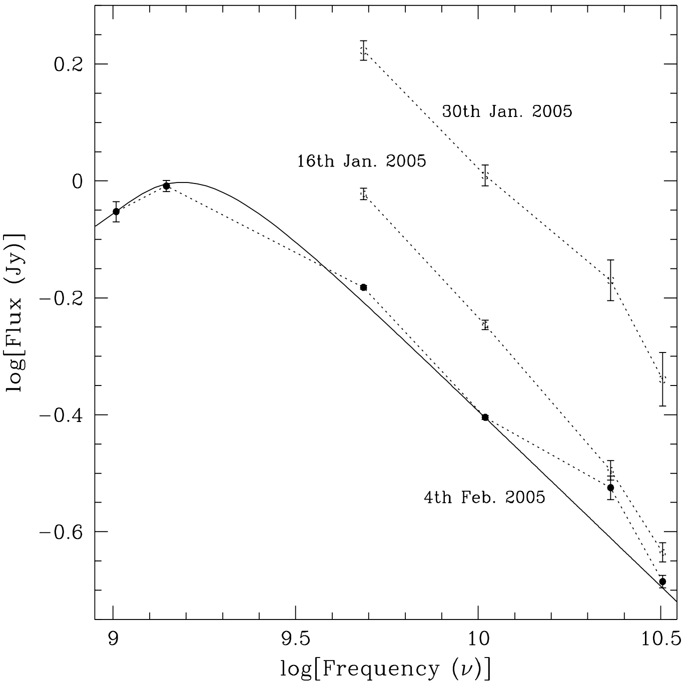

Figure 4. Spectra of SS433 in radio frequency before, during and after the flaring event. While the results of 16th Jan. (JD 2453386.04) and 30th Jan., 2005 (JD 2453400.03) follow power law emission, that on the 4th of Feb. 2005 (JD 2453405.83) shows an indication of a turnover at around 1.5GHz.

emitting medium is optically thick for low frequency $\nu < \nu_s$ and remains optically thin for high frequency $\nu > \nu_s$. The synchrotron self absorption frequency ν_s is calculated by equating the observed flux with the source function for non-thermal emission. It gives the relation (see, Pacholczyk, 1970),

$$S_\nu = 66.2 f(p) \left(\frac{\theta}{40}\right)^2 B^{-1/2} \nu_s^{5/2}, \text{ where, } f(p) = \left(\frac{1}{1-p}\right) \frac{\Gamma\left(\frac{3p+19}{12}\right)\Gamma\left(\frac{3p-1}{12}\right)\Gamma\left(\frac{3}{4}\right)}{\Gamma\left(\frac{3p+22}{12}\right)\Gamma\left(\frac{3p+2}{12}\right)\Gamma\left(\frac{5}{4}\right)}. \quad (2)$$

Here, S_ν is the observed flux in Jansky, θ is the angular size of the emitting region in milliarcseconds (mas), B is the magnetic field (averaged over the pitch angle) in Gauss and ν_s is in GHz. Putting, $\theta \sim 40$mas and $p = 1.65$ as seen from the slope of the spectrum. We get a measure of the magnetic field for $\nu_s \sim 1.5$GHz to be more than 20000 Gauss which is quite impossible.

On the other hand, if the turn-over is due to the two component free-free absorption, the data could be fitted with

$$S_\nu = S_0 \nu^{-\alpha_0} + S_1 \nu^{-\alpha_1} exp[-\tau_1 \nu^{-2.1}], \tag{3}$$

with $S_0 = 0.39$, $S_1 = 1.21$, $\alpha_0 = \alpha_1 = 0.6$ and $\tau_1 = 0.91$. In this case, the optical depth τ_1 at 1 GHz is related to the emission measure E and the electron temperature T_e by,

$$\tau = 2.74 \times 10^{-20} (\frac{T_e}{K})^{-1.35} (\frac{E}{cm^{-5}}). \tag{4}$$

For a standard stellar mass loss rate of $\dot{M} \sim 10^{-5} M_\odot\,\mathrm{yr}^{-1}$, the velocity of the wind of $\sim 1000\,\mathrm{km\ s}^{-1}$and the distance of the radio emission region of $\sim 10^{15}\,\mathrm{cm}$ (Margon, 1984; Chakrabarti et al. 2005), the emission measure E becomes (Seaquist et al. 1982) $E = 5 \times 10^{25}\,\mathrm{cm}$. When we use this in Eq. (4) we find the temperature of the emission region to be around $37,700$ K.

4. Discussion and concluding remarks

In this Paper, we obtained a broadband radio spectrum of SS433 using the Giant Meter Radio Telescope (GMRT) and the Effelsberg 100-m Radio Telescope. We observed a moderate flare. The light curves show a progressively increasing time-delay as the radio frequency goes down. The peak of the 6 cm lightcurve is delayed by ∼ 3 days with respect to the peak of the 9 mm lightcurve. If we fit the van der Laan (1966) model of the expansion of the jets, we find that the flare may have started around JD2453393.7 i.e., around 2005 January 23. There is an indication of the flattening of the spectrum and possibly a turnover at ∼ 1.5 GHz. If we interpret this to be due to synchrotron self-absorption, the required magnetic field would become unreasonably large. However, the free-free absorption due to hot thermal winds is still a possibility for the observed turnover. On the other hand, given that the flares at lower frequencies decay faster, this turnover could be an artifact. All sky monitor (ASM) aboard Rossi X-ray Timing Experiment (RXTE) showed a very high X-ray count on 2005 January 25, when the flare is well underway. From ASM data we deduce that the X-ray flare, if any, must take place between JD2453395.1 and JD2453395.7, whereas the radio flare started around or before JD2453393.7. We believe that this could be due to a glitch or some other inexplicable reason.

This work is partly supported by a CSIR SRF (SP) grant and from ISRO RESPOND (SM). The authors also thank the RXTE team for the ASM light curve.

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