Astron. Astrophys. 328, 283–289 (1997)

ASTRONOMY AND ASTROPHYSICS

Short term radio variability and polarization properties of LSI+61°303

M. Peracaula[1], **J. Martí**[2,1], **and J.M. Paredes**[1]

[1] Departament d'Astronomia i Meteorologia, Universitat de Barcelona, Av. Diagonal 647, E-08028 Barcelona, Spain
[2] CEA/DSM/DAPNIA/Service d'Astrophysique, Centre d'Études de Saclay, F-91191 Gif-Sur-Yvette, France

Received 9 May 1996 / Accepted 7 March 1997

Abstract. We report the results of more than 30 h of VLA monitoring at 6 cm of the radio emitting X-ray binary LSI+61°303. Small amplitude ($\sim$ 4 mJy) radio flares have been detected superposed onto the early decay of the expected periodic radio outburst of this source. Such kind of microflares seem to exhibit a recurrence period of 1.4 h. Among different possibilities, we interpret them tentatively as caused by secondary luminosity driven shocks. In addition, we report and discuss the detection of linear polarization in LSI+61°303 at the $\sim$ 2% level during one of the observing sessions.

Key words: stars: LSI+61°303 – radio continuum: stars – stars: variables – X-rays: stars – polarization

1. Introduction

LSI+61°303 is a well-known massive Be Radio Emitting X-ray Binary (REXRB) that coincides with the optical counterpart of the Galactic Plane variable radio source GT 0236+610, originally discovered by Gregory & Taylor (1978). The most remarkable property of LSI+61°303 is the occurrence of periodic radio outbursts every orbital period of 26.5 d (Taylor & Gregory 1982; Taylor & Gregory 1984, hereafter TG84). There is also some evidence that the radio outburst amplitude at centimetric wavelengths is modulated between $\sim$ 50 and $\sim$ 300 mJy with a long-term $\sim$ 4 yr period (Gregory et al. 1989; Paredes et al. 1990; Estalella et al. 1993). Ray et al. (1996), on the basis of their extensive radio monitoring during 1.5 years, suggest that this modulation could be quasi-periodic or an envelope to the outburst maxima.

In X-rays, LSI+61°303 was first detected by Bignami et al. (1981). Recently, Goldoni & Mereghetti (1995) and Taylor et al. (1995) also detected LSI+61°303 using ROSAT data, with luminosities of $\sim 10^{34}$ erg s^{-1} in the 0.1-2.4 keV range. The observations of Taylor et al. (1995) are particularly important since they show clearly that X-ray outbursts also occur in LSI+61°303. Probably, they recur with the same 26.5 d radio period, but there is not enough data yet to confirm this suspicion. In addition, LSI+61°303 has been suggested to be associated with the COS-B ($>$ 100 MeV) γ-ray source CG135+01 (Hermsen et al. 1977). EGRET observations (Fichtel et al. 1994) give further support to this association and imply γ-ray luminosities of 10^{36}-10^{37} erg s^{-1} and even higher.

The flaring radio emission of LSI+61°303 has a typical nonthermal spectrum, i.e., consistent with synchrotron radiation from relativistic electrons. This behaviour is very well illustrated by multi-frequency radio observations carried out throughout a full orbital cycle, such as those shown in Hjellming & Han (1995) and Paredes et al. (1996). Several models have been proposed in order to account for the origin and/or time evolution of the relativistic electron population: originated in a relativistic pulsar wind (Maraschi & Treves 1981; Lipunov & Nazin 1994); being accelerated after a supercritical accretion event during periastron passage (Taylor & Gregory 1982, 1984; Taylor et al. 1992; Martí & Paredes 1995); a change of the neutron star accretion regime along an eccentric orbit (Zamanov 1995). The relationship between X-ray and radio flares, and perhaps even γ-ray flares, still deserves further consideration. Outburst models based on supercritical accretion may have to explain the relatively low X-ray luminosity of LSI+61°303 possibly involving a photon shift towards higher energies due to inverse Compton emission.

Previous radio photometry with $\sim$ 10 minute resolution has been published by Gregory et al. (1979) and TG84. These authors reported significant flux density variations in time scales from a few hours to as short as 30 minutes. According to TG84, these details in the LSI+61°303 radio light curve can be accounted for by episodic events of relativistic particle production due to luminosity-driven shocks (LDSs). In the context of supercritical accretion models, the LDSs should occur around the periastron passage of a highly eccentric orbit, when the radiation pressure of the normal star increases up to the Eddington limit and a blast wave sweeps away the amount of matter in excess of the critical accretion rate. A similar model has been proposed

Send offprint requests to: M. Peracaula by Haynes et al. (1980) for the periodic radio outbursts of the REXRB Cir X-1.

In particular, TG84 point out that the outburst flux density rise reported by Gregory et al. (1979) was observed to consist of particle injection episodes. They attributed them to consecutive LDSs with a duration of a few 10^3 s and with a remarkably repeatable separation interval of $\sim 10^5$ s. Each LDS episode caused a 6 cm flux density increase of a few tens of mJy. The combined effect of several LDSs may lead to the formation of a large ionized plasma cloud or plasmon. This plasmon containing shock-accelerated relativistic electrons will later expand, accounting for the time and spectral evolution of the strong periodic LSI+61°303 radio outbursts, as modeled by Paredes et al. (1991). It is important to point out here that the separation interval between shocks is interpreted as the free fall time of the accreted matter from the periastron separation. TG84 also find that the shock clears the volume between the binary components in a time scale safely shorter than the shock interval, so that the next blast can take place, consistent with their picture.

In this paper, we present new radio variability and polarization observations of LSI+61°303. Our analysis is carried out over a total time span of more than 30 h split into three different, non-consecutive observing days. Since LSI+61°303 is usually a relatively bright radio source, the data can be analyzed with minute and hour time resolution for the I and QUV Stokes parameters, respectively. One of our main results here is the detection of small amplitude radio flares with an apparent period of 1.4 h that we try to understand in the framework of LDSs. A second interesting result is the detection of occasional $\sim 2\%$ linear polarization in the source radio emission.

2. Observations and data reduction

The observations were carried out with the VLA interferometer of NRAO[1] at a wavelength of 6 cm and with an effective bandwidth of 50 MHz. The log of observations is listed in Table 1. This table also contains the radio phase of LSI+61°303 according to the radio period and phase origin of TG84. During the observing sessions, the VLA was participating in several VLBI experiments on LSI+61°303 to be reported elsewhere. Nevertheless, in addition to the phased array mode for VLBI experiments, the VLA can also provide simultaneously the normal interferometer output that we have used in the present paper.

The VLA normal interferometer data were edited and calibrated using the AIPS package of NRAO. The amplitude calibrators adopted were 1331+305 and 0137+331, for which 6 cm flux density values of 7.43 Jy and 5.50 Jy were assumed. The phase calibrator used was 0228+673, which was observed just before and after each scan of LSI+61°303, usually three or four times per hour. The source 0228+673 was also used as the polarization calibrator. The average values of the bootstrapped flux densities and polarizations of 0228+673, for each observing day, are given in Table 1. The absolute position angle of polarized emission was determined from the primary calibrator 1331+305. During the observations, the weather conditions at the VLA site were usually fair. The only exception was a 80% cloud coverage during the first three hours of the third observing day, that cleared completely soon after.

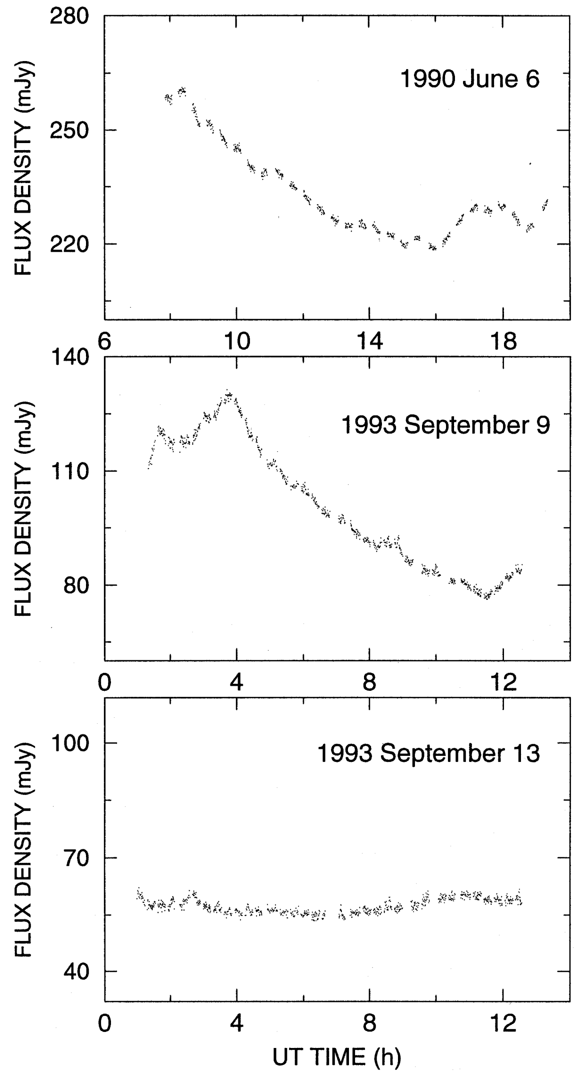

Fig. 1. Radio light curves of LSI+61°303 as observed with the VLA with time resolution of 30 seconds. From top to bottom, the plots correspond to the observing sessions of 1990 June 6, 1993 September 9 and 1993 September 13, respectively. The rms of each data point is usually 1 mJy or less.

Since LSI+61°303 always appeared as a variable but dominating strong source, we started by self-calibrating each observing session in phase only. A simple point source model for LSI+61°303 was found to be appropiate. The plots in Fig. 1 show the details of the radio light curve for all VLA observing sessions in an expanded time scale. These plots have been obtained using the AIPS task DFTPL and each point corresponds to an average of 30 seconds.

[1] The NRAO is operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation.

Table 1. Log of the VLA 6 cm observations

Date	VLA Configuration	Phase Calibrator	Bootstrapped Flux Density (Jy)	Degree of Linear Polarization (%)	P.A. of Linear Polarization (°)	Radio Phase
1990 June 6	A	0228+673	1.65 ± 0.01	1.9 ± 0.1	112 ± 1	0.72
1993 September 9	CnD	0228+673	2.74 ± 0.01	1.8 ± 0.1	108 ± 1	0.66
1993 September 13	CnD	0228+673	2.67 ± 0.01	2.2 ± 0.2	108 ± 3	0.81

3. Results on short term variability analysis

All panels in Fig. 1 show that the flux density of LSI+61°303 changes significantly during typical time scales of $\sim$ 1 h or even less. Using nonrelativistic causality arguments, this places an upper limit of $\sim 10^{14}$ cm to the size of the emitting region. This value is fully consistent with source sizes of a few 10^{13} cm derived from VLBI observations (Taylor et al. 1992; Massi et al. 1993) and supported by outburst modelling based on particle injection into expanding plasmons (Paredes et al. 1991).

The largest amplitude variation observed took place on 1993 September 9, when the LSI+61°303 flux density changed from 131 mJy to 76 mJy in $\sim$ 7 hours. In fact, the general trend of the data on that day does not rule out that we caught the peak of one of the strong radio outbursts, at radio phase 0.65. For the other two sessions, the total variation was much less dramatic and did not exceed 20% in a time scale of $\sim$ 10 h. It is noticeable that a simple eye inspection of the curves at the two top panels of Fig. 1 strongly suggests that some sort of microflares could be superimposed on the general trend of the radio light curve, and at more or less regularly spaced time intervals.

As such microflares appear to be clearly active on 1993 September 9, we will first concentrate our attention on this observing session. In order to confirm a possible periodicity of the microflares, we removed the long-term trend of the data by subtracting from each point the average flux density of the neighboring points within a window of 1 h length. The rectified radio light curve obtained is shown in Fig. 2. Here the presence of microflares is clearly enhanced. Their amplitude is $\sim$ 4 mJy, equivalent to about 4% of the total flux density. Averaging windows between 0.5 and 1.5 h were also applied to the data. Finally we chose it to be 1 h length as a compromise between a too high degree of smoothing and the preservation of data points in the tails of the curve.

We used the rectified radio light curve in Fig. 2 to search for periods in the range from one minute to a few hours. The methods used in this search were CLEAN, as adapted by Roberts et al. (1987) to time series analysis, phase dispersion minimization (PDM) method by Stellingwerf (1978) and the classical method of autocorrelating the data series. From the periodograms of Fig. 3, we see that the three methods indicate the presence of a possible period P = 1.4 h. The periodograms also show significant power at harmonics of $P/2$ and $2P$.

In Fig. 4 we show the mean radio light curve obtained by folding the 1993 September 9 data with the 1.4 h period. The amplitude of the mean microflare is $\sim$ 2 mJy. The mean curve

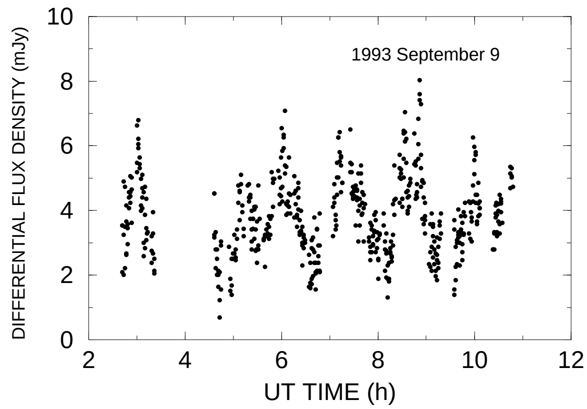

Fig. 2. The rectified 6 cm radio light curve of LSI+61°303 in 1993 September 9 resulting from the substraction of a baseline fit to the data. The occurence of microflares with mJy amplitude is clearly evident. To avoid possible confusion or overlap of the light curve peak with one of the microflares we do not use the data around 4 h UT.

of each individual flare does not show a specific repeatability in the structure of the profile of the microflares.

A similar period analysis has been also carried out for the radio light curves of 1990 June 6 (radio phase 0.72) and 1993 September 13 (radio phase 0.81). In the periodograms of the 1990 data, the same harmonics as those of the 1993 September 9 data are found although its significance in front of other peaks is not dominant. We think this is not surprising because, as is noticeable in Fig. 1, the data from the source during the 1990 June 6 run features regular significant gaps. This fact decreases both the confidence in the baseline fit to the data and in the results of period search. The period analysis of the 1993 September 13 light curve shows no evidence of recurrent microflares. In the next section we discuss a possible interpretation of both the presence of microflares around the phase of the radio outburst peak and their absence in later phases.

4. Discussion of microflares

We have already indicated that previous observations by Gregory et al. (1979) found neither evidence for any hourly periodic behaviour in their high time resolution radio data nor any significant variations on time scales shorter than half an hour. We note, however, that the rms noise in the data of Gregory et al. (1979) was higher than the amplitude of the detected microflares and that the radio phase interval covered by their observations (0.2-0.6) was different from ours. In contrast, from the observa-

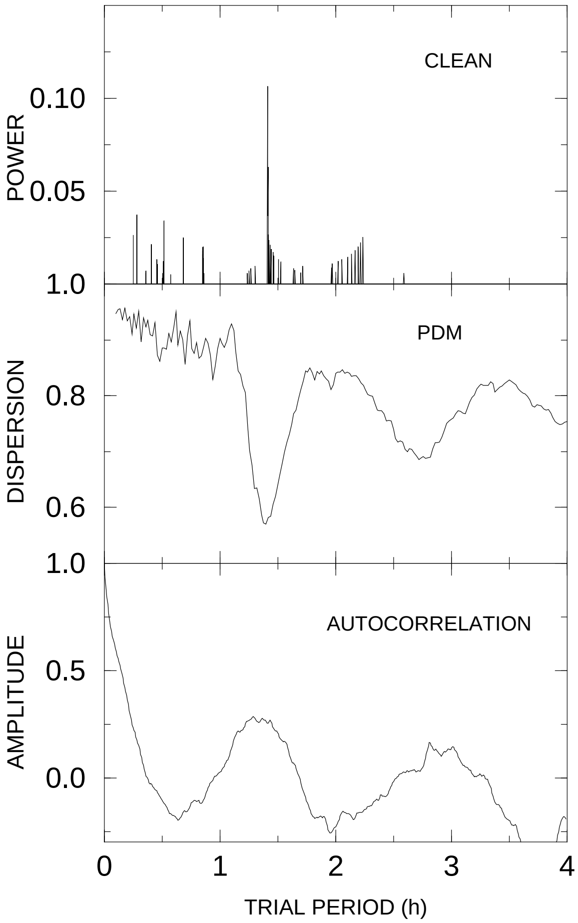

Fig. 3. Results of the periodicity searches using the CLEAN (top), PDM (center) and autocorrelation (bottom) methods applied to the observations of 1993 September 9. All three techniques show evidence for possible underlying period at 1.4 h.

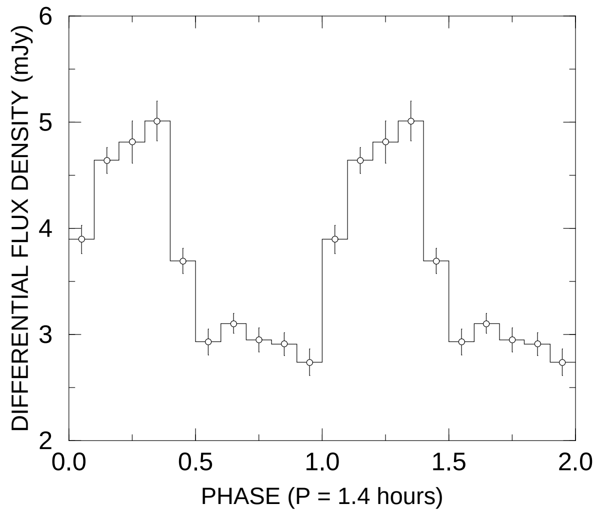

Fig. 4. Mean 6 cm radio ligth curve of LSI+61°303 in 1993 September 9 obtained by folding the data with the 1.4 h period. The data have been averaged every 0.1 phase and plotted twice. The error bars represent the formal estimate of the statistical uncertainty of the mean within each bin.

tions reported here, we think that evidences of hour scale radio periodicity may be present in general in the early decay of the LSI+61°303 radio outbursts. This is particularly clear in our 1993 September 9 data.

It is not unsual for REXRBs to exhibit radio variability on time scales of a few hours, even to a few minutes, as in the case of the possible black hole system GRS 1915+105 (Rodríguez & Mirabel 1996a). However, it is less often that this variability on time scales much shorter than the orbital period turns out to be periodic or quasi periodic. A few examples known so far include the X-ray transient source GS 2023+338, which has shown sinusoidal radio variations with periods in the range 22-120 minutes as it slowly decayed with an optically thick synchrotron spectrum (Han & Hjellming 1992). There has been also detection of flux density oscillations in the low level emission of GRS 1915+105, with periods of a few tens of minutes and amplitude changes by a factor of two (Pooley 1995; Rodríguez & Mirabel 1996b).

Based on analogy with extragalactic sources, Han & Hjellming (1992) interpreted the short term radio variability of GS 2023+338 in terms of surface brightness fluctuations caused by shock events at the ends of jets. The possibility that these hour range periods could reflect the rotation period of a neutron star does not seem very likely because they appreciably exceed that of the slowest X-ray pulsars known. Another possibility could be a hot spot in keplerian rotation around the compact object, as recently proposed by Rodríguez & Mirabel (1996b) to explain the remarkably smooth sinusoidal oscillations observed by them in GRS 1915+105. However, we believe that the lack of smoothness in the LSI+61°303 microflares is more consistent with a Han & Hjellming (1992) shock event interpretation than with a rotation mechanism.

In LSI+61°303, the outburst decay has an optically thin synchrotron spectrum. Therefore, in contrast with GS 2023+338, the LSI+61°303 short term radio variability should reflect actual variations in the radio source relativistic electron content rather than just surface brightness effects. Nevertheless, if models based on supercritical accretion are correct, we tentatively suggest that microflares during the decay of the strong LSI+61°303 radio outbursts could still be attributed as well to shock events accelerating fresh energetic particles. It is our assumption here that, shortly after the synchrotron emitting plasmon responsible for the main outburst has been generated, secondary LDSs may possibly continue to take place for as long as supercritical accretion conditions still persist.

To see if a LDS scenario would be consistent with the observations, we must first consider two points: (i) what is the typical rise time of the main radio outburst and (ii) what is the possible duration of the supercritical accretion phase beyond that rise. The radio outburst rise time in LSI+61°303 is usually observed to be $\sim$ 2 d (Paredes et al. 1991; Estalella et al. 1993). The supercritical accretion duration is more difficult to estimate, but according to Martí & Paredes (1995) it may well last for about 0.1 radio phase interval even for highly eccentric orbits, i.e., possibly larger than the rise time. So once the first and possibly more energetic shocks have travelled beyond the binary system volume in ~ 2 d and build up the radio emitting plasmon at scales of a few 10^{13} cm, supercritical accretion still may persist allowing secondary LDSs to occur. However, as the accretion rate tends now to decrease with time, these later shocks will produce less energetic radio flares, which we identify with the observed microflares during September 9 (phase ~ 0.66). This picture is furthermore in agreement with the fact that Fig. 1 shows that microflares were later absent on September 13 (phase ~ 0.81), when supercritical accretion was probably no longer occurring.

Although a detailed model is beyond the scope of this paper, we may use the simple formulation of Haynes et al. (1980) and TG84 for LDSs in order to gather some further physical insight. These authors assumed spherically symmetric supercritical accretion at a rate $\dot{M}_{\rm acc}$ onto a neutron star of mass $M_{\rm c}$ with a free-fall density law $\rho(r) = \Lambda r^{-3/2}$, where $\Lambda = \dot{M}_{\rm acc}/4\pi\sqrt{2GM_{\rm c}}$. For a blast wave of the form described by Sedov (1959), the shock radius will travel radially as a function of time according to $R = (E/\Lambda)^{2/7}t^{4/7}$, where E is the energy injected into the blast. In our case, the time separation between microflares is $\Delta t \simeq 1.4$ h. If we roughly interpret this as a free-fall time, the corresponding distance of the accreting matter reservoir from a 1 $M_{\odot}$ neutron star is $r_{\rm ff} \simeq 1.4 \times 10^{11}$ cm, considerably smaller than the periastron separation. Then, for an accretion rate higher but close to its Eddington limit ($\sim 2 \times 10^{-8}$ $M_{\odot}$ yr^{-1}) and plausible blast energies of 10^{39}-10^{41} erg, the shock front is able to clear the volume limited by $r_{\rm ff}$ in 10^1-10^2 s, i.e., consistently shorter than Δt.

It may be expected from this LDS interpretation that microflares in the radio should likely be preceded by nearly coincident microflares in X-rays, with the same 1.4 h period. Unfortunately, the best X-ray observations published so far by Taylor et al. (1996) do not have integration times long enough to search for this period. Additional longer integration time observations would be required to test this idea. Finally, if supercritical accretion does not occur in LSI+61°303, we should try to interpret the microflares in the context of the alternative models where the LSI+61°303 radio outbursts are the result of the interaction between the normal wind from the primary and the relativistic wind from the neutron star (Maraschi & Treves 1981; Lipunov & Nazin 1994; Zamanov 1995). It is possible that some sort of oscillation in the wind boundaries could cause the microflares but this is possibly a much more complicated problem.

5. Polarization

5.1. Polarization results

We searched for polarized emission in LSI+61°303 for each of the three observing days separately. After correcting for the antenna instrumental polarization response using the AIPS task PCAL, maps of the source were obtained in all Stokes parameters. For every day, these maps were computed using the corresponding full self calibrated uv data set, nearly ~ 10 h long each. Self calibration was always easily successful because LSI+61°303 behaved as a very strong point source, in contrast with the weakness of other common stellar radio sources.

We were succesful to detect a significant amount of linear polarization only on 1993 September 13. On that day, the measured degree of linear polarization ($\Pi_{\rm l} = \sqrt{U^2+Q^2}/I$) was found to be as high as $\Pi_{\rm l} = 2.0 \pm 0.1\%$. The Signal to Noise Ratio (SNR) of the linearly polarized emission, as it appears in the self calibrated $\sqrt{Q^2+U^2}$ map of that day, is higher than ~ 30. Nevertheless, the detection of polarization is already present before self calibrating the data to improve the rms noise. Since the detection of linear polarization at a 2% level in LSI+61°303 is a new interesting result, we have performed some tests to rule out a spurious origin. In particular, we decided to split the VLA array into two subarrays without common baselines. This clearly reduces sensitivity but, in spite of that, we have been able to obtain in each independent subarray nearly the same result for 1993 September 13 as with all the antennas. On the other hand, on 1990 June 6 and 1993 September 9 LSI+61°303 was found to be almost unpolarized with $\Pi_{\rm l} \sim 0.2\%$ or less.

For 1993 September 13, when significant linearly polarized emission was detected at the star position, the uv data were further divided into intervals of one hour to study possible time variations. An averaging time of one hour was selected as a compromise between both detecting the LSI+61°303 polarized emission and monitoring its variability. Monitoring of the Stokes parameters was carried out both by using the AIPS task DFTPL and by generating a series of polarization maps of the uv data split as a function of time. This second option has been finally prefered here since we realized that a weak but noticeable radio source $\sim 15'$ NE from LSI+61°303 is cleaned better. The resulting time history of the linearly polarized flux density and polarization degree is shown in Fig. 5, where the $\sqrt{Q^2+U^2}$ flux density evolves within 0.8 and 1.7 mJy and $\Pi_{\rm l}$ varies between 1.5-3%. During the observation, the position angle (not shown here) also varied a few tens of degree around an average value of $\Psi \simeq 120°$.

5.2. Linear polarization discussion

Given the synchrotron mechanism of the LSI+61°303 radio outbursts, we expected that some degree of linear polarization should be detectable. Furthermore, as the linear polarization of an optically thick synchrotron source is usually much less than for an optically thin source (Pacholczyk 1970), we also may expect a tendency in $\Pi_{\rm l}$ to increase as the radio emitting plasmon expands and its optical depth decreases.

While it is beyond the scope of this paper to model the polarization evolution during the radio outbursts, this expectation is certainly confirmed by the results quoted above. For the sessions of 1990 June 6 and 1993 September 9, when LSI+61°303 was in a bright state ($S_{\rm 6cm}$ $\sim$100-200 mJy), the linear degree polarization was always very low ($\Pi_{\rm l} \sim 0.2\%$). These two sessions belong to different orbital cycles, but both correspond to

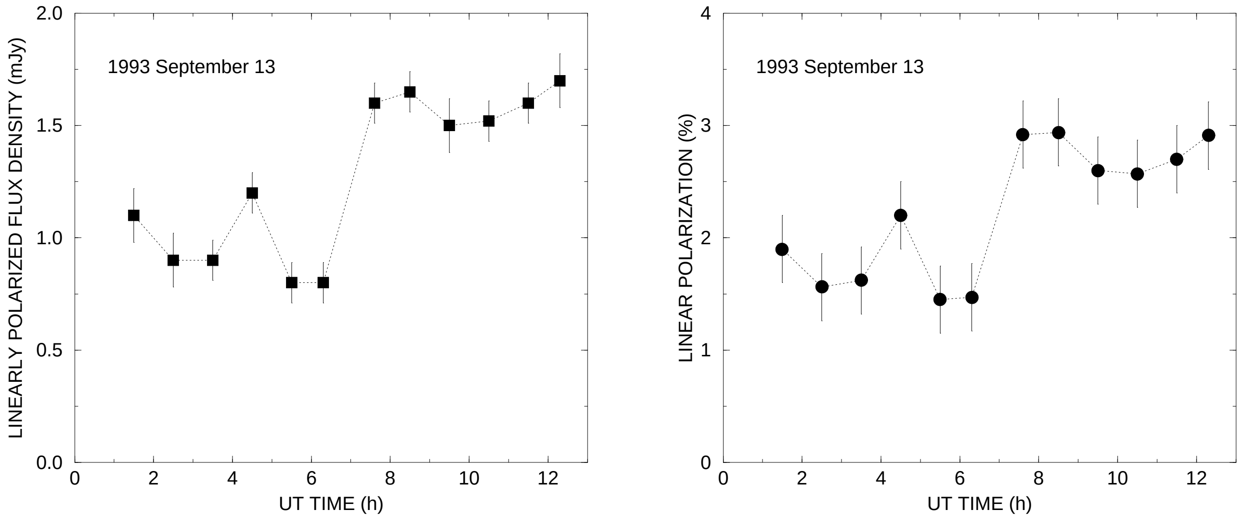

Fig. 5. (Left) Time evolution of the linearly polarized flux density of LSI+61°303 during 1993 September 13, when the source was in the highest state of polariation observed. The values plotted here have been derived from a series of Stokes maps. (Right) Time evolution of the LSI+61°303 degree of linear polarization during 1993 September 13. For both the left and right panels, each data point corresponds to an average of 1 hour and 3σ error bars are shown.

similar radio phases (0.66 and 0.71) that are likely to be near the time of the radio outburst peak. Although we do not have spectral index information here, the multi-frequency monitoring of other cycles does not rule out that the source is at least partially optically thick at 6 cm in the vicinity of the radio outburst peak. On the contrary, the situation was quite different for the session of 1993 September 13. Here LSI+61°303 had decayed in brightness by a factor of two from the previous observing session 4 days before. At this later radio phase (0.81), the source was likely to be fully optically thin and with a higher degree of linear polarization. In agreement with that, on 1993 September 13, LSI+61°303 displayed a clearly increased 2% value of $\Pi_{\rm l}$.

5.3. Circular polarization

The circular polarization of synchrotron radiation is normally a second order effect. However, if $\Pi_{\rm c}$ is indeed measurable, it may provide a direct estimate of the magnetic field. For a system of relativistic electrons in a uniform magnetic field and with an isotropic pitch angle distribution, the degree of circular polarization can be estimated as $\Pi_{\rm c} \sim (3B/\nu)^{1/2}$, where B is the magnetic field in gauss and ν the radio frequency in MHz (Sciama & Rees 1967).

Circular polarization in LSI+61°303 was not detected in these observations; our estimation of the upper limit is $\sim 0.4\%$. Using the approximate expression given above, upper limits for the magnetic fields of the order of ~ 0.01 G are derived. These values are two orders of magnitude lower than the magnetic field strenghs of ~ 1 G derived from equipartition arguments by Massi et al. (1993) and from adiabatic expansion models by Paredes et al. (1991). Nevertheless, this discrepancy must not be a reason for strong concern. As Sciama & Rees (1967) also point out, there may be several effects that reduce the observed net circular polarization, with some of them being non-uniform magnetic fields, self-absorption or contribution from volumes of weaker magnetic field. Thus, it should not be surprising that the circular polarization in a synchrotron source such as LSI+61°303 is quite low; and reliable detection of circular polarization will require dedicated observations with specialized, accurate calibration.

6. Conclusions

Microflares with an amplitude of ~ 4 mJy and a possible recurrence period of ~ 1.4 h have been detected in the radio light curve of LSI+61°303 as a result of more than 30 h of VLA monitoring. The microflares were observed to be continuously active during ~ 8 h but only when the source was decaying from a bright level, possibly the peak of the radio outburst. A tentative interpretation is proposed based on secondary LDSs while a supercritical accretion rate still persists.

A 2% amount of linear polarization has been also detected in LSI+61°303 during one of our observing sessions. The detection of linear polarization confirms the synchrotron nature of the radio emitting mechanism of this source. There is not yet enough polarization data to reveal if a relationship exists between the periodic radio outbursts and the state of polarization of the source. However, a tendence is suggested towards higher linear polarization values as the source decays and becomes optically thin.

Acknowledgements. We acknowledge partial support by DGICYT (PB94-0904). J.M. also acknowledges support from a postdoctoral fellowship of the spanish Ministerio de Educación y Ciencia. The authors thank the referee A.G. de Bruyn for helping to improve this paper and D. Gabuzda for careful reading and discussion.

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Note added in proof: After the submission of this paper, new observational facts have arisen concerning LSI+61°303. The possible X-ray period of 26.5 days, suggested in the introduction, has been detected by the authors using public data from the All Sky Monitor on board of the RXTE satellite.

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