Simultaneous multifrequency single-pulse properties of AXP XTE J1810–197

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ABSTRACT
We have used the 76-m Lovell, 94-m equivalent Westerbork Synthesis Radio Telescope (WSRT) and 100-m Effelsberg radio telescopes to investigate the simultaneous single-pulse properties of the radio emitting magnetar Anomalous X-ray Pulsar (AXP) XTE J1810–197 at frequencies of 1.4, 4.8 and 8.35 GHz during 2006 May and July. We study the magnetar’s pulse-energy distributions which are found to be very peculiar as they are changing on timescales of days and cannot be fit by a single statistical model. The magnetar exhibits strong spiky single giant-pulse-like subpulses, but they do not fit the definition of the giant pulse or giant micropulse phenomena. Measurements of the longitude-resolved modulation index reveal a high degree of intensity fluctuations on day-to-day time-scales and dramatic changes across pulse phase. We find the frequency evolution of the modulation index values differs significantly from what is observed in normal radio pulsars. We find that no regular drifting subpulse phenomenon is present at any of the observed frequencies at any observing epoch. However, we find a quasi-periodicity of the subpulses present in the majority of the observing sessions. A correlation analysis indicates a relationship between components from different frequencies. We discuss the results of our analysis in light of the emission properties of normal radio pulsars and a recently proposed model which takes radio emission from magnetars into consideration.

Key words: stars: neutron – pulsars: general – pulsars: individual: AXP J1810–197.

1 INTRODUCTION
Anomalous X-ray Pulsars (AXPs) and Soft Gamma-ray Repeaters (SGRs) form a class of slowly rotating neutron stars with rotational periods ranging from 2 to 12 s, called magnetars. Magnetars are characterized by properties such as: emission over a wide spectrum of wavelengths (γ-ray, X-ray, optical, near infrared and radio), rapid spin-down and a very high magnetic field (higher than $10^{14}$ G, which is two orders of magnitude higher than for a radio pulsar of the same age and three orders of magnitude greater than for an average radio pulsar). These properties are very peculiar compared to the normal rotating neutron star behaviour and are best understood in the context of the magnetar model first discussed by Duncan & Thompson (1992).

The AXP XTE J1810–197 was serendipitously discovered in 2003 as an X-ray pulsar by Ibrahim et al. (2004) in the data taken with the Rossi X-Ray Timing Explorer (RXTE) while observing the known SGR 1806–20. A search in the archival XTE data showed that it produced an outburst around 2002 November with a persistent decline of its X-ray flux since then. The reported X-ray pulsar spin period was 5.54 s with a spin-down rate $\sim 10^{-11}$ ss$^{-1}$ which, using standard methods, implied a magnetic field strength of $\sim 3 \times 10^{14}$ G (Ibrahim et al. 2004). Due to this unusual long-term flux variability (outburst and exponential decline), it was classified as the first transient magnetar.

In 2004, a radio source with a strong flux density of 4.5 ± 0.5 mJy was found at the exact position of XTE J1810–197 by Halpern et al. (2005) in the data from the Very Large Array Multi-Array Galactic Plane Imaging Survey (VLA MAGPIS) survey at 1.4 GHz. Archival data were searched for any earlier detections but only upper limits could be estimated. Observations made by Camilo et al. (2006) at the Parkes radio-telescope and the Green Bank Telescope discovered

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3 ANALYSIS AND RESULTS

Observations of individual pulses from XTE J1810−197 allowed us to perform a variety of analysis techniques which we describe below. Before performing the analysis, all data sets have been corrected for any Radio Frequency Interference (RFI) present. In the case of the Lovell and WSRT observations rebinning was applied to increase the signal-to-noise (S/N) ratio and to match the 5.4 ms time resolution of the Effelsberg data set. If more than one data set was present per telescope per session, they were aligned in longitude and appended together to improve the statistics. This was done only for pulse-energy distributions because any interruption (i.e. missing pulses) between consecutive data sets affects fluctuation and correlation analysis results. For the correlation analysis, we aligned the data in phase and pulse number. Starting from session 2, we identify two emission regions in the average pulse profile, labelled as MP, and interpulse (IP) according to the classification of Kramer et al. (2007). The MP region can be divided into at least three separate longitude regions containing separate components as marked in the panels in Fig. 1. The average profile from the 1.4 GHz

Figure 1. An example of an average pulse profile of XTE J1810−197 from the observation made with the Effelsberg radio telescope during session 3. This plot shows the component naming convention used in this paper.
Lovell data in sessions 1 and 2 lacks the third component visible in the 4.9 GHz WSRT and 8.35 GHz Effelsberg data sets. The IP is not present in the first session and is only visible in the Effelsberg data in the second session. It is, however, visible in all three data sets in the third session. For the full list when the components are present see Table 1.

3.1 The shape and stability of the pulse profile

Fig. 2 presents an example of a sequence of pulses from XTE J1810–197 observed at a frequency of 8.35 GHz during session 1. The plotted pulse-longitude range corresponds to the whole range of MP as can be seen in Fig. 1. One can easily see that the subpulses are much narrower than the width of the average profile and appear at the longitude ranges corresponding to different components (see for instance the subpulses around pulse number 50). Also, it is worth noticing, that the subpulses associated with M1 are stronger than the subpulses from the remaining MP components, at any observed frequency and epochs, except the 8.35 GHz Effelsberg data set in session 3 where M2 becomes the strongest component in the MP longitude range (see Fig. 1). The strong and spiky subpulses tend to be separated by $\sim 4\degr$ ($\sim 61$ ms) throughout the data.

3.2 Fluctuation analysis

It was first shown by Drake & Craft (1968) that for some pulsars, subpulses exhibit ‘drifting’ across the pulse window in an orderly fashion. This phenomenon forms ‘drift bands’ as can be seen in the ‘pulse stack’ formed when one takes successive pulses and plots them on the top of one other. The techniques used in this paper to investigate this phenomenon involve the Fourier transform and are known as the longitude-resolved fluctuation spectrum (LRFS; Backer 1970) and two-dimensional fluctuation spectrum (2DFS; Edwards & Stappers 2002). The procedure for the fluctuation analysis of our data sets is identical to those presented by Weltevrede, Stappers & Edwards (2007), so we will present only a basic summary here.

The first step in the fluctuation analysis is to form an average profile from a pulse stack by vertically integrating each phase bin within the same longitude along consecutive pulses. Fig. 3 shows the results from analysis at frequencies of 1.4, 4.9 and 8.35 GHz from session 1, where the average profile is drawn with the solid line in the top panel. The abscissa denotes the pulse phase in degrees. The top panel also presents the longitude-resolved modulation index (LRMI; solid line with error bars). The LRMI is a basic method to estimate the presence of subpulse modulation. We only show LRMI values when the error in the LRMI is less than 0.5.

To investigate whether this modulation is systematic or lacks organization, the 2DFS has to be calculated. This is done by dividing the pulse stack into blocks of 512 pulses$^1$ and applying the discrete Fourier Transformation along lines with different slopes in the pulse stack. After averaging the spectra from each transformed block, the final spectrum is produced (Fig. 3, panels below average profiles). If the pulsar exhibits subpulse drifting this will be visible in its spectra as a region, so-called feature, of enhanced power in the grey scale. The vertical separation of possible drift bands is denoted by $P_1$ which is expressed in pulsar periods, $P_0$. The information about the horizontal separation of the possible drift bands, and thus whether the subpulses are drifting over a certain longitude range, is denoted by $P_2$ and is expressed in longitude units. A positive or negative $P_2$ value of a feature in the 2DFS denotes the separation of the subpulses, indicates that the subpulses appear later or earlier in successive pulses, respectively.

We present the average profiles, LRMI and 2DFS from all telescopes from session 1 in Fig. 3. The results from our fluctuation analysis show no visible spectral features indicating that there is no regular drift patterns in any of our observations. However, one can see that there are spectral features in the 2DFS plots indicating subpulse modulation is not associated with drifting subpulses, which will be discussed below. The LRMI in the 8.35 GHz Effelsberg data set shows a significant drop in the middle of M1, while towards its trailing edge the LRMI values increase. Inspecting the pulse stack indicates that this drop is caused by the frequent occurrence of many strong and narrow subpulses with similar intensities at that pulse phase. Similar behaviour appears in all the data sets in this session, but it is less visible in the 1.4 GHz Lovell and the 4.9 GHz WSRT data sets. In both the WSRT and the Effelsberg data sets, the LRMI values are larger than the Lovell data set by a factor of 2. The vertically integrated 2DFS (lower panels in Fig. 3) shows similarity in shape across all the frequencies but changes in intensity. There are two bumps and a strong peak in the middle of the vertically integrated 2DFS. We interpret the bumps as apparent subpulse separation, i.e. subpulses tend to be equally separated in the pulse profile throughout the observation. The peak is not related to the magnetar behaviour but indicates a baseline variation due to effects extrinsic to the source and instrumental effects due to the weather. This peak is also visible in the vertically integrated profiles.

$^1$ Wherever the number of pulses was sufficient, otherwise shorter transforms was used.
Figure 3. Fluctuation analysis results shown for frequencies of 1.4 GHz (left-hand panel), 4.9 GHz (middle panel) and 8.35 GHz (right-hand panel) from session 1 (MJD 53886). The upper panels show the integrated pulse profile (solid line) with the peak amplitude normalized to 1, and the LRMI, LRMI (solid line with error bars). The lower panels show the 2DFS where the ordinate of the resulting spectra is given in cycles per period (cpp) which corresponds to $P_0/P_3$ ($P_0$ is the pulsar period, and $P_3$ denotes the vertical separation of possible drift bands) and the abscissa is also in cpp but now it corresponds to $P_0/P_2$ ($P_2$ denotes the horizontal separation of possible drift bands in longitude units). The grey-scale intensity of 2DFS corresponds to the spectral power. The presence of a significant spectral feature with a value of $P_3$ and a positive or negative value of $P_2$ indicate that the subpulses appear with a preferred periodicity of $P_3$ pulsar periods and horizontal separation given in longitude units. The side panels correspond to horizontally (left-hand panel) and vertically (bottom panel) integrated spectrum.

In session 2, the 2DFS plots show no visible spectral features indicating there is no preferred periodicity. The average profiles indicate small changes from session 1 to session 2 indicating that the subpulse separation is now less regular. The 2DFS plots from the WSRT data set, but it is weaker. In the Effelsberg data set, the peak is no longer visible, while the bumps increase in intensity.

In session 3, the 1.4 GHz Lovell data set (not shown) demonstrates a significantly large value of the LRMI at the trailing edge of the MP first component. This indicates infrequent emission of very strong subpulses. The LRMI for the IP (not shown) was not calculated because of the large error in the measurement in modulation indices due to a small number of bright pulses. Because of the low S/N ratio in the 4.9 GHz WSRT observations, there are only a few values of the LRMI calculated for the MP and none for the IP. The 8.35 GHz Effelsberg data set LRMI for the MP is two times lower than for the session 2 data set, hence is similar to the data set from session 1 (Fig. 4, right-hand panel). The M2 LRMI values become lower than those in M1 and M3. This indicates smaller intensity fluctuations of subpulses appearing in the middle component and larger variations on the side components throughout the observation. The LRMI for the IP rises until it peaks in the middle of the average IP profile, which means that there are large intensity variations at this longitude.

3.3 Pulse-energy distributions

The results of the fluctuation analysis described in the previous section clearly give evidence of intensity fluctuations over short periods of time, even within the same observing session. To study the pulse-amplitude characteristics of XTE J1810−197, we have made pulse-energy distributions for all frequencies and epochs for both the MP and IP. Then, for each of the component of the MP and for the IP, we fit their pulse-energy distributions with two well-known models. Because the emission of XTE J1810−197 shows strong and spiky giant-pulse-like subpulses, we used power-law statistics to model this behaviour as shown by Lundgren et al. (1995), while...
for the ‘normal’ pulses the lognormal statistic was used as discussed by Cairns, Johnston & Das (2001):

\[ P_{\text{powerlaw}}(E) \propto E^p, \quad (1) \]

\[ P_{\text{lognormal}} = \frac{\langle E \rangle}{\sqrt{2\pi\sigma E}} \exp \left[ -\left( \ln \left( \frac{E}{\langle E \rangle} \right) - \mu \right)^2 / (2\sigma^2) \right], \quad (2) \]

Since the power-law distribution integral is infinite, we introduced the parameter \( E_{\text{min}} \), a minimum energy of the pulses, which together with \( p \) is used for fitting the power-law. The lognormal model is fit with \( \mu \) and \( \sigma \). The average energy of the model distribution, \( \langle E \rangle \) was set to match that of the observed distribution. In our analysis, we also took into account the effect of the noise. Since the noise in some of our observations was not pure Gaussian,
due to the RFI present (e.g. 8.35 GHz Effelsberg data sets) we convolved the observed noise with the model distributions. The derived parameters were optimized for the best fit by minimising the $\chi^2$ using the amoeba algorithm (Press et al. 1986) and are compared in Table 2. The detailed description of the procedure of the fitting is well described by Cairns (2004) and Weltevrede et al. (2006). We discuss specific cases below, but we note here that in general it was not possible to fit the distributions well with a single model.

Fig. 5 presents the MP energy distributions for all the telescopes from session 1. The lowest row shows pulse-energy distributions from 1.4 GHz with ascending frequency towards the top row. The components of the MP region are compared starting from M1 (left-hand column) through M2 (middle column) ending with M3 (right-hand column). For this session, only the M1 from the Lovell and WSRT data sets is best fit by lognormal pulse-energy distributions. The remaining components and the whole 8.35 GHz Effelsberg data set follow power-law-like statistics. The Effelsberg M1 is very strong and separates itself from the noise in the pulse-energy distribution (Fig. 5; top left-most plot). We emphasize that the Effelsberg M1 pulse-energy distribution is clearly a power-law without weaker underlying emission. This is different from the case of normal radio pulsar emission, where the giant pulses result in power-law tail extending from the pulse-energy distribution.

In session 2, the 1.4 GHz Lovell pulse-energy distribution is best fit by lognormal behaviour. However, it also shows a long tail in the M1 pulse-energy distribution. M1 and M3 in the 8.35 GHz Effelsberg data set show similar behaviour (Fig. 6). This introduces some complexity to the pulse-energy distribution fitting. Those pulse-energy components with long tails cannot be fit with a single fit of either power-law or lognormal distribution. To try to get better fits, the distributions were split into two halves, the weak and strong pulses in terms of intensity, and then both halves of the distribution were fit with either lognormal or power-law distributions, like the giant pulse tails of normal radio pulsar distributions are usually fit (Lundgren et al. 1995). The Effelsberg IP (Fig. 7; left plot) shows a peak and a flat tail in its pulse-energy distribution, but it is possible to fit its pulse-energy distribution with a lognormal pulse-energy distribution.

Session 3 is the only one, where the IP becomes present in all the data sets. Unfortunately, the IP subpulses from the 1.4 GHz Lovell data set are not seen above the noise level in the pulse-energy distribution, despite their appearance in the pulse stack. This is due to the weak S/N ratio and interference present in that data set. The M1 from the Lovell is best fit by a lognormal distribution, while M2 is best fit by a power-law distribution. The 4.9 GHz WSRT pulse-energy distributions show a power-law-like behaviour in all the components. A very strong IP is visible in the 8.35 GHz Effelsberg data set, its pulse-energy distribution is similar to the data set from session 2. The MP and the IP pulse-energy distributions show lognormal-like behaviour. Similarly to the previous session both the M2 and M3 pulses show a complex pulse-energy distribution and the IP shows a peak, indicating many pulses with flux close to the average energy of the IP, and a long tail in the pulse-energy distribution.

| Observation (d) | Telescope & component | $p$ | $\mu$ | $\sigma$ | $\chi^2$ | $N_{\text{d.o.f.}}$ | $P(\chi^2)$ |
|----------------|-----------------------|-----|-------|--------|---------|----------------|----------------|
| 53886/06-05-31 | Lovell M1             | 2.28| 0.26  | 346    | 125     | $3 \times 10^{-4}$ |
|                | Lovell M2             | -2.81|       | 463    | 176     | $7 \times 10^{-5}$ |
|                | WSRT M1               |    | 11.10 | 0.63   | 304     | 95 $3 \times 10^{-5}$ |
|                | WSRT M2               | -2.35|       | 130    | 62      | $2 \times 10^{-5}$ |
|                | WSRT M3               | -2.15|       | 191    | 86      | $9 \times 10^{-2}$ |
|                | Effelsberg M1         | -1.85|       | 390    | 149     | $3 \times 10^{-8}$ |
|                | Effelsberg M2         | -1.89|       | 438    | 125     | $2 \times 10^{-5}$ |
|                | Effelsberg M3         | -1.41|       | 448    | 147     | $4 \times 10^{-10}$ |
| 53926/06-07-10 | Lovell M1             | 1.91| 2.99  | 382    | 107     | $9 \times 10^{-3}$ |
|                | Lovell M2             | -7.68|       | 285    | 103     | $8 \times 10^{-10}$ |
|                | Eff M1 Strong         | 5.38| 2.88  | 120    | 123     | $3 \times 10^{-3}$ |
|                | Eff M1 Weak           | -0.49| 3.27  | 1704   | 121     | $8 \times 10^{-9}$ |
|                | Effelsberg M2         | -0.54| 0.53  | 357    | 90      | $7 \times 10^{-2}$ |
|                | Eff M3 Strong         | -0.89|       | 41     | 123     | $3 \times 10^{-1}$ |
|                | Eff M3 Weak           | -7.29| 1.25  | 402    | 103     | $7 \times 10^{-3}$ |
|                | Effelsberg IP         | -1.97| 2.36  | 1446   | 93      | 0.0 |
| 53933/06-07-17 | Lovell M1             | 1.46| 0.97  | 423    | 116     | $3 \times 10^{-11}$ |
|                | Lovell M2             | -2.10|       | 558    | 92      | $1 \times 10^{-10}$ |
|                | WSRT M1               | -2.86|       | 279    | 74      | $2 \times 10^{-7}$ |
|                | WSRT M2               | -2.86|       | 281    | 84      | $5 \times 10^{-12}$ |
|                | WSRT IP               | -1.78|       | 440    | 261     | $6 \times 10^{-6}$ |
|                | Eff M1 Strong*        |    |       |        |         |                |
|                | Eff M1 Weak           | -1.98| 0.99  | 463    | 103     | $1 \times 10^{-12}$ |
|                | Effelsberg M2         | -0.59| 0.48  | 276    | 98      | $1 \times 10^{-3}$ |
|                | Eff M3 Strong*        |    |       |        |         |                |
|                | Eff M3 Weak           | -0.11| 4.12  | 557    | 83      | 0.0 |
|                | Effelsberg IP         | -1.86| 2.41  | 1241   | 118     | 0.0 |

*Insufficient number of pulses to do the fitting.
distribution. Especially the Effelsberg data set shows long tails. Considering only the Effelsberg strong pulses above 5 times the average energy of the component, their pulse-energy distribution is statistically insignificant because of the low number of pulses. The fit to the IP data from Effelsberg is also not significant.

To better illustrate the strong intensity fluctuations of XTE J1810–197 and to investigate any longitude-dependence of its strong subpulses, we have produced contour plots of the longitude-resolved cumulative pulse-energy distributions. Fig. 8 (left-hand column) presents the distributions calculated for all the telescopes from session 1. The average profile is drawn with the thick line, while different line styles denote the contours of the cumulative pulse-energy distribution at the energy levels of 1, 10 and 50 per cent, normalized by the average peak energy $\langle E_p \rangle$ of the average pulse profile. The 10 per cent contour, for example, shows the energy level of the pulse-energy distribution above which 10 per cent of pulses can be found. The second type of plot (right-hand column; Fig. 8) indicates the brightest time samples of each pulse-longitude bin (dashed line) scaled to the average intensity at that pulse-longitude bin, plotted on top of the average pulse profile (solid line).

In the 1.4 GHz Lovell observation of session 1, subpulses appearing in the first component do not vary much, which indicates stable emission, this behaviour changes in M2 (Fig. 8; left-hand column, top row) and this behaviour is repeated in session 2 where it becomes very weak, although there are still some spiky subpulses present. The 4.9-GHz WSRT observation shows strong subpulses in M1 only, and the emission is stable throughout the rest of the profile during all sessions.

To illustrate the session-to-session changes, we used observations from the Effelsberg telescope. The strong signal and the presence of the IP, as can be seen in Fig. 9, show how the emission from different components changes in time. M1 in the MP is always strong and the contour plots show a strong stable emission (shown by 50 per cent energy level contours). It is also worth noting that there are two peaks emerging in time. M2 grows stronger from session to session, and it always shows stable and strong emission. M3 is weak and is dominated by the presence of a few strong spiky subpulses.
3.4 Single pulse correlation

The last stage of our analysis was to perform a single pulse correlation. Before the analysis, we needed to align the data. The reason for this is the interstellar dispersion which causes the pulses received at higher frequencies to arrive earlier than the lower frequencies and the different path-lengths to the telescopes. Therefore, all pulse arrival times have been corrected to a common reference frame. We transferred the times of the pulses to the Solar system barycentre, using the DE200 ephemeris (Standish 1982). Then, the overlapping data sets at the different frequency pairs were taken for alignment, which was done by comparing the times of arrival of the pulses. Each data set was aligned in time with a one-phase bin accuracy for each frequency pair. With the time resolution of 5.4 ms, the data sets were sufficiently aligned and all the telescope-specific delays were negligible. We applied two techniques of single pulse correlation, the longitude-resolved linear correlation (LRLC) and the longitude-resolved cross-correlation (LRCC). Both methods are complementary and give interesting results as we will show below.

The longitude-resolved linear correlation is based on a method first introduced by Popov (1986). In order to produce the so-called ‘linear correlation map’ of the pulse-to-pulse variations, the linear correlation array $C_{i,j}$ as presented in the work of Karastergiou et al. (2001) needs to be calculated according to the following formula:

$$C_{i,j} = \frac{1}{n \times \sigma_{f,i} \times \sigma_{g,j}} \sum_{k=1}^{n} \left[ f_i(k) \times g_j(k) - \langle f_i \rangle \langle g_j \rangle \right],$$

where $f_i(k)$ and $g_j(k)$ are time series of a bin $i$ from two distinctive frequencies with $k$ being the pulse number, while $\sigma_{f,i}, \sigma_{g,j}$ being their standard deviations, respectively.

The region of the highest linear correlation is expected to fall on the region around a diagonal which represents the time and spatial scale along which the subpulse intensities are linearly correlated. The LRLC method provides a good insight into linear dependent intensity variations of individual pulses at different observed frequencies. However, it does not take into account phase, shape information and non-linear dependencies between the components of the pulse from the different frequencies. The presence of low-intensity but persistent RFI in one of the data sets causes the appearance of a wave-like pattern in the linear correlation map as can be seen in the lower panel of Fig. 10.
An example of the total intensity linear correlation between the 1.4 GHz Lovell and 4.9 GHz WSRT (upper plot) and the 1.4 GHz Lovell and 8.35 GHz Effelsberg (lower plot) data sets can be seen in Fig. 10. The linear correlation of M1 is always strong between all frequency pairs. Most of the correlation regions in our results are very narrow. This confirms the results from previous analysis steps, of strong and moderately stable emission from M1 at all frequencies and at all epochs. Surprisingly, the linear correlation of M2 is not as high despite the results showing it as the region with lowest intensity fluctuations which is characterized by low modulation indices in all our analysis. It is also interesting to note that the correlation seems to increase again towards the trailing edge of the pulse profile. The IP is visible only in the last two sessions, however in the case of session 2, the IP appears only in the 8.35 GHz Effelsberg data set. This constrains the IP correlation analysis to the last session only. Unfortunately, the IP in the 1.4 GHz Lovell data set is very weak and the correlation results comprising this data set are unreliable. The linear correlation of the remaining data sets is equally strong across the whole IP range and higher than that of MP.

Information on the shape and non-linear dependencies can be obtained by applying the LRCC method. This method of analysis is also more resistant to the presence of the periodic RFI in the 8.35 GHz Effelsberg data. The principle of producing the cross-correlation map is somewhat similar to the LRLC but instead of equation (3) we first apply the Fast Fourier Transform to both data sets. The next step is to multiply the first transformed data set by the complex conjugate of the second one. This produces a complex result of which the imaginary part is zero. Taking only the real part of the resulting cross-correlation coefficients matrix, the cross-correlation map is made as in the LRLC method. Examples of the results from the LRCC are presented in Fig. 11. The results of the cross-correlation analysis are similar to that of linear correlation. In session 3, we noted the presence of a weak cross-correlation between the different components. Further analysis revealed that the occurrence of regions of higher correlation outside diagonal is caused by the RFI present in the 8.35 GHz Effelsberg data set. The region of correlation along the diagonal is very narrow in all of the correlated data sets. Similarly to the LRLC, the cross-correlation is strong in M1 in all of the LRCC results, and can be explained by the similarities in shape and of the components at different frequencies. The next two components M2 and M3 are well correlated only between 4.9 and 8.35 GHz data sets (Fig. 11, right-hand panel). The correlation results of 1.4 GHz with 4.9 or 8.35 GHz data sets do not show any correlation in M2 and M3 components.

4 SUMMARY AND CONCLUSIONS

We have analysed the data from the simultaneous multifrequency single-pulse observations of XTE J1810–197 conducted at the frequencies of 1.4, 4.9 and 8.35 GHz, during observing sessions in 2006 May and July. The phenomena revealed by our analysis indicate that the radio emission is clearly different to the known radio pulsar properties. Previous work by Camilo et al. (2007b,c), Kramer et al. (2007) and Lazaridis et al. (2008) has shown an interesting overview of peculiarities of the pulsed radio emission from the magnetar, for example flat spectral index, $\alpha = 0.0 \pm 0.5$, high degree of polarization or long-term evolution of the polarization angle swing with time. The results presented in our work confirm that the mechanism responsible for the magnetar radio emission appears to have a different origin or perhaps even multiple origins, compared to the normal radio pulsars.

XTE J1810–197 has a broad, multicomponent profile with the IP only becoming present after session 1. The results from Kramer et al. (2007) show that the separation between the MP and the IP is less than 180° which may be caused by an extremely wide MP beam ($\rho \sim 44'$) or by a non-dipolar magnetic field structure. The evolution of the average pulse profile takes place on day-to-day time-scales. This is clearly visible in the highest frequency data where the first component decreases in intensity, while the second and third become more prominent. Kramer et al. (2007) postulate, after examining the average pulse profiles of XTE J1810–197 from a greater number of observing sessions, that the magnetar requires an unusually long observing time to obtain a stable profile or even lacks one, perhaps like PSR B0656+14 known for its bursting behaviour (Weltevrede et al. 2006).

The modulation index values change dramatically from one component to another even within a single observing frequency. Weltevrede et al. (2007) define the modulation index to be the
Figure 8. The contour plot of the longitude-resolved cumulative pulse-energy distributions from the 1.4 GHz Lovell (top row), 4.9 GHz WSRT (middle row) and 8.35 GHz Effelsberg (bottom row) radio telescope observations from the session 1. Left-hand panel: the thick solid line is the average pulse profile. The dashed line shows the brightest time sample for each pulse-longitude bin. The other lines are the contours of the longitude-resolved cumulative pulse-energy distributions at the energy level of the 1, 10 and 50 per cent compared to the average peak energy $\langle E_p \rangle$ of the average pulse profile. Right-hand panel: the thick solid line is pulse profile. The dashed line shows the brightest time sample for each pulse-longitude bin compared with the average intensity $\langle E_{\text{bin}} \rangle$ at that pulse longitude.
LRMI $m_i$ at the pulse longitude bin $i$ where $m_i$ has its minimum value. In most of the sources used in their analysis the LRMI shows a minimum in the middle of the pulse profile with a typical value of $m \sim 0.5$, where the total intensity is relatively high. We also find that tendency in our results, but the magnitude of the values is somewhat closer to the values reported for the Crab Pulsar ($m = 5$). This agrees with the conclusion that due to the infrequent occurrence of the strong subpulses with narrow widths and broad distribution...
of the subpulse intensities, the modulation index is on average significantly larger in XTE J1810−197. We must note, however, that in few cases, frequent occurrence of many strong and narrow subpulses with similar intensities at certain pulse phases of MP results in lower LRMI values. The lowest values of the modulation indices occur during session 1, but even in this session they increase with increasing frequency as can be seen in Fig. 3 (upper panels). Such behaviour is in contrast to the normal radio pulsars where the LRMI values from lower frequencies are on average higher than that at higher frequencies (Weltevrede et al. 2007). As we move in to session 2, the intensity fluctuations grow stronger with minimum modulation indices at values of around 4 for the 1.4 GHz Lovell data sets. For the 8.35 GHz Effelsberg data, we calculate the minimum modulation indices to be one in the MP and two in the IP region. It is remarkable, that for both data sets in this session the modulation indices in the MP peak at values of 7.5 and 10 for the Lovell and Effelsberg data, respectively. These values are extremely high and except for the Crab Pulsar, unprecedented in the results.
from modulation analysis from normal radio pulsars (Weltevrede et al. 2007). In session 3, for the 4.9 GHz WSRT data sets due to the low S/N ratio, the LRMI values are not sampled densely throughout the whole pulse profile range, but available values are comparable with session 1. The Lovell and Effelsberg LRMI values are similar to that of session 1. The longitude-resolved modulation analysis results presented above show the variation of the LRMI values on day-to-day time-scales and dramatic changes with pulse phase. In all session, we find the frequency evolution of the LRMI values in contradiction with proprieties of normal radio pulsars.

The following steps of our analysis, the 2DFS, do not show any regular drifting behaviour in any sessions or any frequencies. However, we find phenomenon manifesting itself as characteristic bumps in the XTE J1810−197 vertically collapsed 2DFS. We interpret this phenomenon as the tendency of the subpulses to be equally separated in the consecutive pulses’ profiles throughout observation. We also note the presence of a peak visible in the vertically collapsed 2DFS at 1.4 GHz Lovell, 4.9 GHz WSRT from session 1 (Fig. 3, left and middle panels) and 8.35 GHz Effelsberg from session 3 (Fig. 4, right-hand panel in the upper row) data sets. We interpret the peak as a signature of the baseline variations in those data sets. The lack of regular drift from the magnetar might be associated with its rapidly changing emission properties and young age (τ < 10 kyr). In their work, Weltevrede et al. (2007) have shown that the fraction of young pulsars showing regular drifting is very low. Although, one could also argue that the strong radio variability might mask any regular structures or the physics of the magnetar’s radio emission is different from radio pulsars.

The high variability of the magnetar emission is also reflected in its pulse-energy distributions. For all sessions at all observed frequencies, we have made pulse-energy distributions for each of the MP component as well as for the IP (whenever present). We fit each of the pulse-energy distribution with models based on a power-law or lognormal statistics for comparison between our observations and existing pulsar emission models. As justified later in this section, propagation effects in the interstellar medium are negligible for our data analysis and are therefore ignored. Table 2 presents the results of the best fits. The significance of the best fits is low due to the oversimplified models, but changes in the best-fit models of the components in different sessions are nevertheless, very peculiar. We interpret that as indicating the possible presence of multiple emission mechanisms with different statistical behaviour embedded in the same pulse phases.

In a series of papers, Cairns and collaborators (Cairns et al. 2001; Cairns, Johnston & Das 2003a, 2004; Cairns et al. 2003b) investigate different possible models of the emission physics using observations of PSRs B0833−45 (Vela Pulsar), B1641−45 and B0950+08. They show that the models of emission vary with changing pulse phase in the analysed sources. They find in these pulsars, that longitude-resolved pulse-energy distributions which appear to be lognormal and are representative of the normal pulsar radio emission, can be fit with a single emission model or convolution of Gaussian-lognormal or double lognormal models. This multimodel manifestation is explained as two non-related waves coupling together in the inhomogeneous plasma in the pulsar magnetosphere. While Cairns et al. successfully fit the longitude-resolved pulse-energy distributions with lognormal statistics, in many cases it is also valid to use it to fit the integrated pulse-energy distributions (Johnston & Romani 2002). The presence of approximately power-law distributions is caused by these different phenomena. The origin of these phenomena can be identified based on the values of power-law indices and can be associated with (i) giant pulses i.e. pulses which have integrated flux density greater than 10 times the integrated flux density of the average profile, (ii) giant micropulses, which have a peak flux density that is 10 times the peak flux density of the average profile at the same phase, but less than 10 times integrated flux density of the average profile, (iii) so-called precursor emissions occurring just before the MP as for Crab Pulsar (Moffett & Hankins 1996; Cordes et al. 2004), which have power-law distributions that are non-intrinsic and caused by Gaussian distributions from the background normal pulsar emission convolved with higher energy lognormal components. We argue that in the case of the magnetar, M1 consists of strong and narrow giant-like subpulses followed by a component of weak precursor-like subpulses.

The giant pulse and giant micropulse phenomena are known in a few radio pulsars like PSRs B0531+21 (Crab Pulsar; Staelin & Reifenstein 1968), B0833−45 (Vela Pulsar; Johnston et al. 2001), B1937+21 (Soglasnov et al. 2004) or B1133+16 (Kramer et al. 2003). The emission of these pulses can be characterized by the power-law energy distributions, broad-band emission or occurrence within narrow pulse phases. These phenomena are believed to be associated with the high-energy emission in the outer magnetosphere (Johnston & Romani 2002; Cairns 2004). In the case of XTE J1810−197, we also see strong spiky subpulses which could be associated with the giant pulse phenomenon, but their widths are larger than that of giant pulses of normal radio pulsars. Also, their occurrence, which covers the whole longitude range of that component, stands in contradiction to this definition. The most prominent example illustrating the above phenomenon in our observations is the first component, especially in the Effelsberg data sets from sessions 2 and 3 as can be seen in Fig. 6. This component has many strong and spiky subpulses appearing within its whole longitude range, which dominates the high-energy tail in its pulse-energy distributions. This makes fitting the pulse-energy distributions with only one law impossible. However, the attempt to decouple the component distribution into low- and high-energy parts also did not result in good fits. A similar case occurs for PSR B0656+14 (Weltevrede et al. 2007), where weak emission is coupled with a component responsible for high energy bursts. In the case of XTE J1810−197, there may be more than two models contributing at one phase in the observed distributions. As shown later the magnetars’ very dynamic magnetosphere may be an explanation for such multicomponent pulse-energy distributions. This argues that the emission is in general broad-band, but the degree of variability is very different. Those components average together in pulse-energy distributions, which makes them difficult to fit properly using known statistical models.

Despite the changes in the pulse profile and pulse-amplitude characteristics on short time-scales, the correlation analysis gave results which contradict the overall picture of unstable emission from XTE J1810−197. The LRLC analysis shows significant correlation results in the majority of the frequency pairs used. The narrow and high correlation regions denote significant dependence between the intensities of the subpulses on small time- and spatial scales. The correlation always occurs between the first components in all of the analysed frequency pairs, with sporadic correlation between the third components. In contrast, the second component, is found to be a stable emission region with lower modulation indices, was very weakly correlated. To examine the non-linear dependency between frequencies we used the LRCC method. The correlation is weaker when compared to the LRLC method, but correlated regions are also very narrow, showing that there are similarities in the phase and shape of the subpulses at different observed frequencies.
While the larger time-scale flux variations might be normally attributed to interstellar scintillation, they have been rejected in the work of Camilo et al. (2007c) and Lazaridis et al. (2008) as being responsible for the variability over short time-scales. This points to the intrinsic behaviour of the magnetar as a cause. The lack of a regular drift, broad pulses, the presence of subpulses with quasi-periodic modulation, difficulties with fitting the data with single logarithmic or power-law models allow us to draw a conclusion of non-stable emission due to the possible turbulent magnetar magnetosphere. A model explaining that emission has been proposed very recently. In his work, Thompson (Thompson 2008a,b) gives an extensive explanation of the pair creation processes in ultrastrong magnetic field and particle heating in a dynamic magnetosphere. He considers the details of the QED processes that create electron-positron pairs in high magnetic fields of the order of $10^{14}$ G. He discusses the possibility of a strong enhancement of the pair creation rate in the open-field circuit and outer magnetosphere by instabilities near the light cylinder. Thompson also refers to the flat radio spectra as a possible result of the high plasma density in the open magnetic field lines. One of the model explanations of the magnetar’s broad pulse profile, is its beam geometry. In normal radio pulsars, wide pulse profiles are usually caused by the alignment between rotation and magnetic pole axis. The line of sight of the observer stays within the emission beam for a large fraction of the pulse period resulting in the long duty cycle. In the case of XTE J1810–197, the solution of fitting the position angle swing with the Rotating Vector Model (Radhakrishnan & Cooke 1969) results in non-aligned geometry ($\alpha = 44^\circ$, $\beta = 39^\circ$), but the beam radius inferred from the MP pulse has a width of about $\rho \sim 44^\circ$ as shown by Kramer et al. (2007). This result excludes viewing geometry as a reason for a wide pulse profile in XTE J1810–197. The model of the dynamic outer magnetosphere has a promising application in explaining the radio emission from the magnetars and is consistent with the magnetars’ emission features such as flat radio spectra, broad pulses and rapid variability.

Since the detection of radio emission from XTE J1810–197, its relation to the new class of objects called Rotating Radio Transients (RRATs; McLaughlin et al. 2006) was suggested. The lack of X-ray counterpart in any of known RRAT sources argued against this hypothesis until Reynolds et al. (2006) reported the first X-ray detection from RRAT J1819–1458. This RRAT was known to emit radio bursts with 4.26 s spin period based on its timing analysis and the inferred dipole surface magnetic field of about $5 \times 10^{13}$ G. The detection of the periodic X-ray pulsations aligned with the radio bursts by McLaughlin et al. (2007) allowed the comparison of its X-ray emission properties with XTE J1810–197 and excluded a close relationship with this RRAT. However, it would be very interesting as proposed by Rea et al. (2008) to search for the RRAT-like radio bursts from XTE J1810–197 at its quiescence level. This could investigate the hypothesis of a link between the magnetars, RRATs and young radio pulsars.

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