PERIODIC OR RANDOM ACCELERATION IN SOLAR FLARES?

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Abstract. The issue whether acceleration and injection of electron beams is coherently modulated by a single quasi-periodic source, or whether the injection is driven by a stochastic process in time or (eventually fragmented) in space, is investigated by means of a periodicity analysis of metric type III bursts.

We analyze 260 continuous type III groups observed by Ikarus (ETH Zurich) in the frequency range of 100-500 MHz during 359 solar flares with simultaneous $\geq 25$ keV hard X-ray emission, in the years 1980-1983. Pulse periods have been measured between 0.5 and 10 s, and can be described by an exponential distribution, i.e. $N(P) \propto e^{-P/\sigma_P}$. We measure the mean period $P$ and its standard deviation $\sigma_P$ in each type III group, and quantify the degree of periodicity by the dimensionless parameter $\sigma_P/P$. The representative sample of 260 type III burst groups shows a mean periodicity of $\sigma_P/P = 0.37 \pm 0.12$, while Monte-Carlo simulations of an equivalent set of truly random time series show a distinctly different value of $\sigma_P/P = 0.93 \pm 0.26$. This result suggests that the injection of electron beams is periodically modulated by a particle acceleration source which is either compact or has a global organization on a time scale of seconds.

Key words: Solar Flares – Particle Acceleration – Radio Emission

1. Introduction

The issue whether the energy release in a solar flare is triggered at a critical place and spreads randomly like a chain reaction to many independent local dissipation processes (also referred to as "statistical flare"), or whether the energy dissipation is controlled by a global condition during the event, can be investigated by means of a time series analysis of radio type III bursts, which are unambiguous tracers of individually injected electron beams.

The quasi-periodicity of type III bursts has been first investigated by Fourier methods, with the finding of quasi-periodic features in 74-80% of the analyzed flares, with periods in the range of 1-6 s (Mangeney & Pick 1989; Zhao, Mageney & Pick 1991). These earlier studies were mainly confined to the frequency of 164 MHz, and a minimal duration of 30 s was required. Here we report on results from a larger study (Aschwanden, Benz & Montello 1993) with 359 flares, where we included type III groups with any duration ($\approx 2$-430 s), and scanned a large number of ($\approx 100$) frequencies.
2. Observations

The radio observations have been acquired with the broadband frequency-agile spectrograph Ikarus (100-1000 MHz) of the Bleien radio observatory of ETH Zurich (Switzerland). Instrumental descriptions are given in Perrenoud (1982). In the 100-500 MHz frequency range, the dynamic spectra were recorded with a frequency resolution of 3 MHz in the (interference-free) frequency bands of 100-145 MHz, 160-172 MHz, 229-394 MHz, and 425-464 MHz. The time resolution is 100 ms, and the sensitivity corresponds to an r.m.s. noise level of \( \lesssim 1 \) solar flux unit (1 SFU = \( 10^{-22} \) W m\(^{-2}\) Hz\(^{-1}\)).

We analyzed broadband radio type III bursts in the 100-500 MHz frequency range from all flares which have been simultaneously recorded with the digital radio spectrograph Ikarus and the Hard X-Ray Burst Spectrometer (HXRBS) onboard the Solar Maximum Mission (SMM) spacecraft in the years of 1980-1983. This dataset contains 359 jointly observed flares, whereof 270 flares have sufficient data quality and frequency coverage in radio for our analysis. This dataset was found to be representative with regard to flare size and flare duration (if the frequency distributions are compared with those of the entire HXRBS dataset), but a possible bias may be introduced with regard to “radio-richness”, because of the burst trigger criterion of Ikarus. The dynamic spectra were digitally recorded after the initiation of a solar burst trigger, specified by several criteria including a flux threshold and a minimal flux increase in a selected frequency range.

3. Data Analysis

We analyzed the periodicity of metric type III bursts in continuous groups (free of intermittency). These groups of type III bursts contain either normal-drifting type III bursts, type J bursts, type U bursts, or reverse-slope (RS) bursts (see examples in Fig.1). Since radio type III bursts tend to occur in groups clustered in time and frequency, we selected from each flare those time segments and frequency bands where the type III burst rate appears to be steady and stationary. For each time segment with a continuous group of type III bursts we selected the optimal frequency band where the rate of type III bursts was highest. To obtain the best signal-to-noise ratio of the radio flux and to optimize complete sampling of weak type III bursts we integrated over the maximum possible frequency range covered by observation and free of terrestrial disturbances. However, we restricted the bandwidth by the requirement that the frequency-drift of the type III bursts must not affect the separation of subsequent bursts.

We identified 260 time segments with continuous type III burst activity, occurring during 155 flares. After we integrated the radio flux over an appropriate frequency range, we employed an interactive structure recog-
Fig. 1. Quasi-periodic groups of type III bursts (1980 June 6 flare), type J and occasional type U bursts (1980 Aug 25, 1981 Jan 29). In each flare the dynamic spectrum recorded by Ikarus is shown with a grayscale plot, the selected time segment and frequency band is indicated with a white box, and the extracted time profile with the detected peak times (vertical lines) is shown below. The mean frequency drift rate is labeled with \((\text{d}v/\text{d}t)\), the pulse period with \((P \pm \sigma_P)\), the degree of periodicity with \((\sigma_P/P)\), and the number of pulses with \(N_P\).
nition code to detect individual type III bursts and to measure their peak times \( t_i \) and time intervals \( P_i = t_i - t_{i-1} \), to evaluate the mean period \( P \) and the standard deviation \( \sigma_P \) for each group. To quantify the degree of periodicity in a time series we found it most useful to use the dimensionless parameter \( \sigma_P/P \), which is also a measure of the mean phase deviation. For a strictly periodic time series we expect no scatter of the mean phase, i.e. \( \sigma_P/P = 0 \), while it can be shown that the scatter for a random or stochastic time series is expected to be \( \sigma_P/P \approx 1 \).

4. Results

While our method was designed to measure periods in the range of 0.5-10 s, we effectively detected periods in the range of 0.46-8.6 s. The arithmetic mean of all 260 periods was found to be \( P = 1.96 \pm 1.16 \) s. The measured distribution of periods has a peak around 1-2 s, and drops off exponentially with longer periods, i.e. \( N(P) \propto e^{-P/1.0s} \).

The degree of periodicity, \( \sigma_P/P \) of all 260 type III groups was found to be close to a normal distribution, with a mean of \( \sigma_P/P_{III} = 0.37 \pm 0.12 \) (Fig.2). This high degree of periodicity is distinctly different from the statistics expected from time series governed by stochastic behavior.

In order to illustrate the difference in the degree of periodicity between observed and stochastic time series, we performed a Monte-Carlo simulation.
of random time structures, using the same number of 260 events with exactly
the same number of pulses per event (varying between 3 and 56) as it was
measured for the type III groups. Each of the 260 time series was given
a total duration of unity and the times \( t_i \) of the pulses were simulated by
random numbers in the interval \([0,1]\). The times \( t_i \) of the pulses were sorted
in time, and the mean intervals (period \( P \)), the standard deviation (\( \sigma_P \)),
and the degree of periodicity (\( \sigma_P/P \)) was calculated for each time series.
The distribution of periodicities \( \sigma_P/P \) found in this set of 260 truly random
time series was found to be close to a normal distribution, with a mean of
\( \sigma_P/P_{random} = 0.93 \pm 0.26 \) (Fig. 2). Besides the fact that the two distributions
have a significantly different mean, there is virtually no overlap between the
two distributions, because the periodicity of type III groups was found to be
confined to \( \sigma_P/P \leq 0.6 \), while the degree of periodicity is \( \sigma_P/P_{random} \geq 0.6 \)
for \( \approx 90\% \) of the random time series.

5. Conclusions

In this study we investigated a large, representative set of flares and moni-
tored a broad frequency range in radio in an attempt to retrieve the intrinsic
injection rate of electron beams. The major finding here is that all flares
with multiple type III bursts were found to be modulated with a high degree
of periodicity, that is distinctly not compatible with random characteristics.
The acceleration or injection of electron beams seems to be modulated by
a periodic source, opposed to a source with independent spatial fragmenta-
tion, which would produce stochastic, temporally uncorrelated signatures in
radio.

There are a number of flare scenarios which propose a fragmentation of
the primary energy release, based on theoretical or observational arguments.
Some observational evidence for a fragmented production of type III bursts
was found when type III fine structures (analyzed in the temporal as well as
spectral domain) were correlated with the \( \geq 25 \) keV HXR flux (Aschwanden
et al. 1990). Our finding of a coherent modulation of electron beam injection
on time scales of \( \lesssim 1 \) s does not exclude a spatial fragmentation on small
spatial scales, but the coherence over the time interval of a pulse width puts
an upper limit on the spatial extent of a potentially fragmented accelerator.

The coherent modulation of plasma parameters inside the acceleration
source is likely to be communicated on a magnetohydrodynamic time scale,
i.e. with Alfvénic speed \( v_A \). Thus the size \( L_A \) of a coherent source is probably
limited by the Alfvénic propagation time over roughly a half pulse period,
i.e.

\[
L_A \leq v_A \cdot \frac{P}{2} = 1.1 \cdot 10^{11} \frac{BP}{\sqrt{n_i}} \quad [cm].
\] (1)
The electron density is \( n_e = 10^9 \text{ cm}^{-3} \) for the fundamental plasma frequency at 300 MHz, the typical frequency where we observed the highest injection rate. Assuming a typical magnetic field of \( B \lesssim 100 \text{ G} \) and \( n_i = n_e \) at the injection site, we obtain an estimate of \( L_A \lesssim 3500 \text{ km} \) for the radius of the coherent injection source. This upper limit \( L_A \) applies to the extent of the injection or acceleration region, and is always smaller than the observed size of type III sources, which increases rapidly with height due to scattering and the divergence of the magnetic field (Mercier 1975; Roelof & Pick 1979).

Flare scenarios which propose a spatial fragmentation on large scales of \( \gtrsim 10^4 \text{ km} \) are not consistent with upper source limits of coherent sources inferred here, and would conflict with Alfvénic synchronization inside the coherently modulated source volume (Eq.1). Flare scenarios with coherent-phase acceleration [when the acceleration time is shorter than the (periodic) change of the accelerating electric field], e.g. electric fields generated by oscillatory current sheets (Tajima et al. 1987), are good candidates to explain the phase-coherence of injected electron beams observed here.

Acknowledgements

The work was supported at GSFC and UMd by NASA grants NAS5-30442, NAGW-3080, NAGW-3456, NAG5-2001, and NAG5-2352. The operation of Ikarus was supported through Swiss NSF grant 20-34045. We gratefully acknowledge the assistance of Maria L. Montello (CUA) in data analysis.

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