Probing Pulsar Microstructure using the GMRT

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Abstract : Radio emission from pulsars exhibits various time scales, ranging from seconds, milliseconds, and down to microseconds. The last kind, referred to as ``microstructure'' is the most difficult to study as it requires the highest sensitivity at the shortest time scales, and requires precise correction of interstellar dispersion effects. The GMRT, with its large collecting area at metre and centimetre wavelengths, combined with the availability of modes that allow the more accurate coherent dedispersion technique to be applied to the beamformer data, provides an excellent instrument for the study of pulsar microstructure. Furthermore, by using a combination of modes with the legacy and upgraded GMRT receivers, we are also able to study the microstructure emission simultaneously at fairly widely separated frequencies such at 325 and 650 MHz. We report here some of the new results from our ongoing study of pulsar microstructure for a sample of bright pulsars, including some for which microstructure has been seen for the first time. We probe in detail properties such as the broadband nature, the temporal and spectral behaviour, the variation across the emission window, as well as the polarisation properties of microstructure emission, and bring out some interesting new results.

Introduction to Pulsar microstructure

- For normal pulsar, averaging of few thousand single pulses produces a stable average profile
- However, individual pulses are highly variable in shape and strength -- structure ranges from sub-pulse (~ 10 msec for normal period pulsars) to micro-pulse (~ 100 microsec for normal period pulsars)
- The milli-period timescale intensity fluctuations (often quasi-periodic) in sub-pulse emission (e.g. figure 1) is referred to as pulsar MicroStructure (MS) e.g. Craft et al, 1968; Hankins 1972
- Evidence for MS is seen clearly in autocorrelation function of single pulses : typical timescale and periodicity of MS can be estimated (e.g. figure 1); timescale of MS found to increase with pulsar period; e.g. Cordes et al 1990; Kramer et al 2002; Mitra et al 2015
- Generally found to be broad-band in nature, over ~ octave frequency range
- Seen in many of the brighter, normal period pulsars; recently detected in millisecond pulsars for the first time (De et al, 2017) – scaling of time scale with pulsar period found to hold true.
- Q : is MS emission the fundamental building block of pulsar emission? Possible models for MS : geometric sweeping of micro-beams or temporal modulation of emission ? e.g. Gil 1982

Pulsar Microstructure with the GMRT : Experiment and data

- MS studies limited to the brightest pulsars due to sensitivity limits
- Few studies of detailed frequency evolution of MS and its polarisation properties
- The GMRT, with it's high sensitivity, wide frequency coverage and capability for simultaneous multi-frequency observations (with coherent dedispersion) well suited to probe new parameter space in this area of MS studies (Gupta et al, 2017; Reddy et al, 2017, De & Gupta, 2016)
- Here we report on results from
  - Single frequency full polar mode observations at 325 & 610 MHz (32 MHz bandwidth)
  - Simultaneous dual frequency total intensity data at 325 MHz (32 MHz) & 650 MHz (200 MHz)
  - Wideband observations over 300 to 500 MHz with coherent dedispersion

On the broadband nature of microstructure emission :

- For most pulsars, we do find that MS is largely seen simultaneously at 325 and 650 MHz, and is hence broadband over this octave range; e.g. for one data set of B0329+54 :

Total number of Pulses	*Pulses with MS at both freq*	*Pulses with MS at low freq*	*Pulses with MS at high freq*	*Pulses with MS ONLY at high freq*	*Pulses with MS ONLY at low freq*
1239	353	577	475	122	224

- But majority of the cases in the last 2 columns above are found to be due to low SNR, as seen in figure 2.
- However, can identify ~ 12 pulses where MS is truly seen ONLY at higher frequency (figure 3)
- Similar results are found for other pulsars.
- => Except for a handful of few pulses, the MS emission is by and large broadband in nature
- However, MS does evolve with frequency significantly for some cases (figures 4 & 5) :
  - MS under two different sub-pulse emission components appears to show different frequency behaviour e.g. PSR B2016+28 (figure 4)
  - In the case of continuous coverage with relatively narrow bands (e.g. PSR B1642-03 across 200 MHz with 25 MHz sub-bands, in figure 5) coming and going of narrow MS emission features, alongwith slow evolution of the MS structure can be seen.
  - Detailed follow-up of these features could provide insight into mechanism of MS emission

Polarisation of microstructure emission :

- High quality single pulse data in full polar mode at 325 & 610 MHz are quite revealing
- Though micropulses are seen to be significantly polarised, the fraction of linear and circular appear to fluctuate a lot (figure 6)
- Angle of linear polarisation shows significant changes at the location of the MS emission (figure 6) – evidence that orthogonal polarisation modes are important for MS emission.
- Detailed modeling of such polarisation behaviour of MS emission can provide useful insight on the emission mechanism

Conclusions and future plans :

- The GMRT provides a strong platform for detailed investigation of microstructure emission from radio pulsars
- New data from the GMRT, simultaneous at two widely separated frequencies, shows that though the MS emission is generally broadband (at least upto an octave) there are a small but significant number of pulses where significant evolution of the MS is seen – needs a detailed investigation.
- Initial studies of polarisation behaviour shows interesting variations of amplitude of linear and circular polariation, as well as of angle of linear polarisation – needs detailed modeling

Acknowledgements: We would like to acknowledge support of the GMRT staff for carrying out the observations. The GMRT has been built and is run by the National Centre for Radio Astrophysics of the Tata Institute of Fundamental Research

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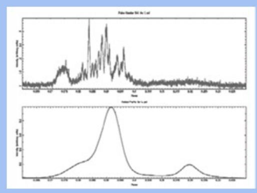

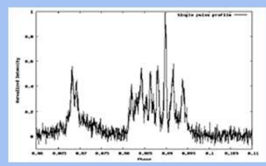

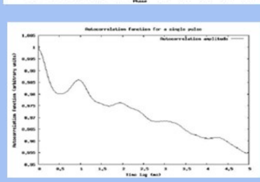

Figure 1 : (a) Top left : Average profile (bottom panel) alongwith a single pulse (top panel) showing MS emission, for PSR B0329+54 610 MHz with the GMRT. (b) Top right : single pulse from PSR B2016+28 with GMRT, showing clear MS (c) Bottomr right : ACF function for the signal in (b) above, showing time scale and periodicity of the MS signal.

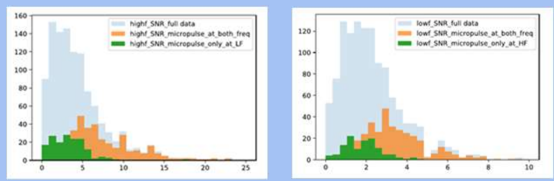

Figure 2 : Histograms of signal-to-noise ratio (SNR) for single pulses at high frequency (610 MHz; left panel) and low frequency (325 MHz; right panel) for (a) all pulses that show MS at that frequency (light blue) (b) all pulses detected to show MS at BOTH frequencies (orange) and (c) pulses showing MS ONLY at the OTHER frequency (green). As can be seen, category (c) pulses are those with the poorest SNR, which is a likely explanation why MS is NOT seen at the OTHER frequency for these cases.

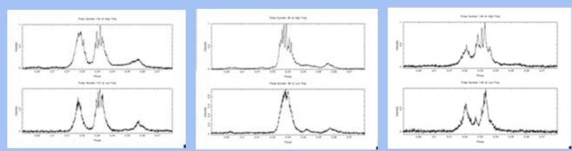

Figure 3 : Examples of selected single pulses from PSR B0329+54, with simultaneous data at 325 and 610 MHz : left panel is a case where matching MS is seen at both frequencies, whereas other 2 panels show cases where MS is seen ONLY at the higher frequency (610 MHz).

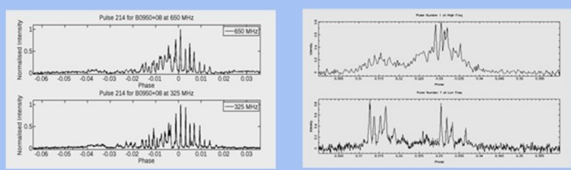

Figure 4 : Examples of selected single pulses from PSRs B0950+08 (left panel) and B2016+28, with simultaneous data at 325 and 610 MHz. Whereas the MS for B0950+08 is quite prominent and very similar at both the frequencies, that for B2016+28 is less prominent and shows significant evolution with frequency.

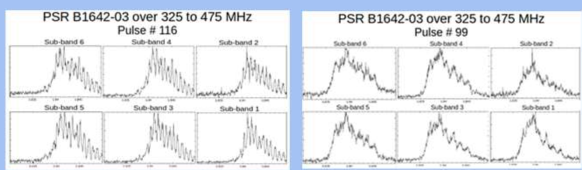

Figure 5 : Two selected single pulses from PSR B1642-03, from wideband 300-500 MHz coherently dedispersed data, split into 8 sub-bands of 25 MHz (of which 6 sub-bands are shown). Left panel shows a pulse with strong MS; right panel shows one with weaker MS. In both cases, finer changes in shape and strength of the MS over the sub-bands can be seen, including occurrence of sharp pulses in some sub-bands.

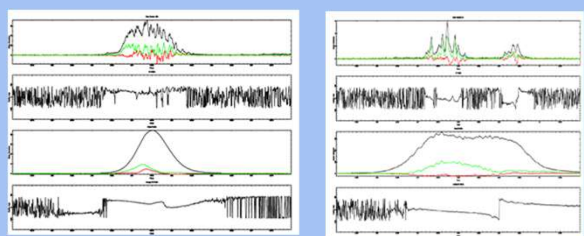

Figure 6 : Sample results from full polar mode data (green : linear polarisation; red : circular polarisation; linear polarisation angle in black in separate panels) showing MS emission from single pulses (alongwith average profile properties in bottom panel) for (a) single pulse from PSR B1642-03 (left panel) and (b) PSR B2016+28 (right panel).