The extreme radio emission of PSR B0656+14 — Is B0656+14 a very nearby Rotating Radio Transient?

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Abstract. We present a detailed study of the single radio pulses of PSR B0656+14. The emission can be characterized by two separate populations of pulses: bright pulses have a narrow “spiky” appearance in contrast to the underlying weaker broad pulses. The shape of the pulse profile requires an unusually long timescale to achieve stability (over 25,000 pulses at 327 MHz) caused by spiky emission. The extreme peak-fluxes of the brightest of these pulses indicates that PSR B0656+14, were it not so near, could only have been discovered as an RRAT source. The strongest bursts represent pulses from the bright end of an extended smooth pulse-energy distribution, which is unlike giant pulses, giant micropulses or the pulses of normal pulsars. Longer observations of the RRATs may reveal that they, like PSR B0656+14, emit weaker emission in addition to the bursts.

1. Introduction

PSR B0656+14 is one of three nearby pulsars in the middle-age range in which pulsed high-energy emission has been detected (the “The Three Musketeers”). It was included in a recent extensive survey of subpulse modulation in pulsars in the northern sky at the Westerbork Synthesis Radio Telescope by Weltevrede et al. 2006a. In the single pulses analysed for this purpose exceptionally powerful and longitudinally narrow subpulses reminiscent of “giant” pulses were found. We therefore set out to explore the full nature of PSR B0656+14’s pulse behaviour in the radio band (Weltevrede et al. 2006c). This pulsar’s extreme bursts are far from typical of older better-known pulsars, but are similar to those detected in the recently discovered population of bursting neutron stars. These Rotating RAdio Transients (RRATs; McLaughlin et al. 2006) typically emit detectable radio emission for less than one second per day, causing standard periodicity searches to fail in detecting the rotation period. The intermittent extreme bursts we have detected in PSR B0656+14 led us to argue that this pulsar, were it not so near, could itself have appeared as an RRAT (Weltevrede et al. 2006b).

2. Observations

The results presented in this paper are based on two observations made using the 305-meter Arecibo telescope. Both observations had a centre-frequency of 327 MHz and a bandwidth of 25 MHz. Almost 25,000 and 17,000 pulses with a sampling time of 0.5125 and 0.650 ms were recorded using the Wideband Arecibo Pulsar Processor (WAPP) for the observation made in 2003 and 2005 respectively. The Stokes parameters have been corrected off-line for dispersion, Faraday rotation and various instrumental polarization effects. For more details we refer to Weltevrede et al. 2006b and 2006c.

3. Stability of the pulse profile

For most pulsars one can obtain a stable pulse profile by averaging a few to a few hundred pulses, so our observations of up to 25,000 pulses could have been expected to be long enough. However PSR B0656+14 proved to be far from typical, as the pulse profile is highly unstable. To illustrate this time dependence, the profiles of successive blocks of one thousand pulses were calculated (left panel of Fig. 1). The scintillation bandwidth is much smaller than the observing bandwidth, so the intensity of the profiles are unaffected by interstellar scintillation. This is not because of systematic errors due to polarization calibration uncertainties (Weltevrede et al. 2006c). A much longer observation would be required to find out if there exists a time scale for the pulse profile to stabilize.

4. The spiky emission

A typical pulse sequence of this pulsar is shown in the left panel of Fig. 2. One can see that the frequent outbursts of radio emission are much narrower than the width of the pulse profile. The emission also has burst-like behaviour in the sense that the radio outbursts tend to cluster in groups of a few pulse periods. Furthermore, this clustering sometimes seems to be weakly modulated with a quasi-periodicity of about 20 pulse periods (see for instance the bursts around pulse numbers 55, 75, 95, 115 and 135).
Fig. 1. The pulse profiles obtained by averaging successive blocks of one thousand pulses each of the 2005 Arecibo observation. The left panel shows all the emission and the middle and right panel show the spiky and weak emission separately. The 1-sigma error bars are plotted in the top left corner.

The brightest bursts are also shown to have quasi-periodic structures with a $\sim 11$ ms and a $\sim 1$-ms timescale (Weltevrede et al. 2006c). Besides these bursts there are many pulses (and large fractions of the pulse window) that contain no signal above the noise level. We will use the term *spiky* to refer to these bursts of radio emission.

Although the pulse sequence of the left panel of Fig. 2 is dominated by the very apparent spiky emission, this is accompanied by an almost indiscernible background of weak emission. To separate these two components of the emission, we have applied an intensity threshold to the data. The intensities of the time samples in the pulse stack of the weak emission are truncated if they exceed this threshold. The time samples in the pulse stack of the spiky emission contains only samples with intensity in excess of this threshold. When the pulse stack of the weak emission is added to the pulse stack of the spiky emission, one retrieves exactly the original pulse stack.

We have set the threshold intensity such that 99% of the noise samples are below this threshold value. Not only do the noise fluctuations make it impossible to completely separate the weak and spiky emission, it is also very well possible that the energy distributions of the two components overlap. In Fig. 2 one can see the pulse stacks obtained after separation of the spiky and weak emission. The integrated power of this sequence of weak pulses is about 3 times greater than that of the sequence of the spiky emission. This shows that a significant fraction of the pulsar’s emission lies at or below the noise level.

The brightest measured pulse is $116 \langle E \rangle$ (where $\langle E \rangle$ is the average integrated pulse energy). This is exceptional for regular radio pulsars and based on the energy of these pulses alone, PSR B0656+14 would fit into the class of pulsars that emit so-called giant pulses. Nevertheless, there are important differences between giant pulses and the bright bursts of PSR B0656+14. The bursts of PSR B0656+14 have timescales that are much longer than the nano-second timescale observed for giant pulses, do not show a power-law energy-distribution, are not confined to a narrow pulse window and are not associated with an X-ray component. This suggests differing emission mechanisms for the classical giant pulses and the bursts of PSR B0656+14. Also the possible correlation between emission of giant pulses and high magnetic field strengths at the light cylinder clearly fails for PSR B0656+14. However, giant pulses have been claimed in other (slow) pulsars that also easily fail this test and for millisecond pulsars a high magnetic field strengths at the light cylinder seems to be
a poor indicator of the rate of emission of giant pulses (Knight et al. 2006).

The bursts of PSR B0656+14 are even more extreme when we consider their peak-fluxes. The highest measured peak-flux of a burst is 420 times the average peak-flux of the pulsed emission, which is an order of magnitude brighter than the giant micropulses observed for the Vela pulsar (Johnston et al. 2001) and PSR B1706–44 (Johnston & Romani 2002). Giant micropulses are not necessarily extreme in the sense of having a large integrated energy (as required for giant pulses), but their peak-flux densities are very large. Not only are the bursts of PSR B0656+14 much brighter (both in peak-flux and integrated energy) than those found for giant micropulses, they are also not confined in pulse longitude and they do not show a power-law energy-distribution as the giant pulses and micropulses do.

At the leading edge of the profile we detected a burst with an integrated pulse-energy of $12.5 \langle E \rangle$. What makes this pulse so special is that it has a peak-flux that is 2000 times that of the average emission at that pulse longitude (left panel of Fig. 3). Its dispersion track exactly matches what is expected for this pulsar (middle panel of Fig. 3), proving that this radio burst is produced by the pulsar. Notice that the effect of interstellar scintillation is also clearly visible (different frequency channels have different intensities) and that the dispersion track is the same for the two pulses in the centre of the profile. This burst demonstrates that the emission mechanism operating in this pulsar is capable of producing intense sporadic bursts of radio emission even at early phases of the profile. There are only two bursts with a peak-flux above the noise level detected at the longitude of the peak of this pulse out of the total of almost 25,000 pulses (see right panel of Fig. 3). This implies either that these two bursts belong to an extremely long tail of the distribution, or that there is no emission at this longitude other than such sporadic bursts.

6. The RRAT connection

The observational facts are that PSR B0656+14 occasionally emits extremely bright bursts of radio emission which are short in duration. Although these bursts appears to be different than that of the giant (micro)pulses, it seems to be similar to those found for the RRATs. Weltevrede et al. 2006b show that the luminosities of the bursts of the relatively nearby PSR B0656+14 (288 pc; Brisken et al. 2003) is very typical for the known RRAT sources. Although the slope of the top end of the peak-flux distribution of PSR B0656+14 is in the range of the giant pulses (between $-2$ and $-3$), it is better described by a lognormal than by a power-law distribution. This again suggests that the bright bursts of PSR B0656+14 are different from the classical giant pulses. The top end of the RRAT distribution with the highest number of detections seems to be harder (with a slope $-1$), but for the other RRATs this is as yet unclear. For instance, the tail of the distribution of PSR
B0656+14 seems to be consistent with the distribution of the RRAT with the second highest number of detections. Normal periodicity searches failed to detect the RRATs, which places an upper limit on the average peak-flux density of weak pulses among the detected bursts of about 1:200 (McLaughlin et al. 2006). Because the brightest burst of PSR B0656+14 exceeds the underlying peak-flux by a much greater factor, PSR B0656+14 could have been identified as an RRAT, were it not so nearby. Were it located twelve times farther away (thus farther than five of the RRATs), we estimate that only one burst per hour would be detectable (the RRATs have burst rates ranging from one burst every 4 minutes to one every 3 hours). The typical burst duration (about 5 ms) of PSR B0656+14 also matches that of the RRATs (between 2 and 30 ms).

Were PSR B0656+14 twelve times more distant, the RMS of the noise would increase by a factor 144 relative to the strength of the pulsar signal. When we artificially add gaussian-distributed noise at this level to the observation, we find no sign of the pulsar’s (2.6-Hz) rotation frequency in 35-minute segments of the data yet the brightest pulse is easily detected with 18σ (Weltevrede et al. 2006b). For telescopes with a lower sensitivity than Arecibo (e.g. Parkes) then even if PSR B0656+14 were quite a bit closer it would not reveal it’s periodicity in a similarly long observation. Only in the spectrum of the whole 1.8-hour observation the periodicity of a twelve times more distant PSR B0656+14 would be marginally detectable for Arecibo. This means that a distant PSR B0656+14 could only be found as a RRAT in a survey using Arecibo, unless the pointings were unusually long.

7. Implications and discussion

The emission of PSR B0656+14 can be characterized by spiky (with low occurrence rate within each pulse) and weak emission (with a high occurrence rate over the full width of the pulse). PSR B0656+14 intermittently emits pulses that are extremely bright compared to normal pulsars and with pulse energies well above ten times the average pulse-energy these pulses formally qualify as giant pulses. Nevertheless these pulses differ from giant pulses and giant micropulses in important ways. Many of the exceptional properties of PSR B0656+14 have led us to point out that this pulsar, were it not so near, could have been discovered as an RRAT.

Our identification of PSR B0656+14 with RRATs implies that at least some RRATs could be sources which emit pulses continuously, but over an extremely wide range of energies. This is in contrast to a picture of infrequent powerful pulses with otherwise no emission. Therefore, if it indeed turns out that PSR B0656+14 (despite its relatively short period) is a true prototype for an RRAT, we can expect future studies to demonstrate that RRATs emit much weaker pulses among their occasional bright bursts. We would also predict that their integrated profiles will be found to be far broader than the widths of the individual bursts, and will need many thousands of bursts to stabilize.

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