Is pulsar B0656+14 a very nearby RRAT source?

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ABSTRACT

The recently discovered RRAT sources are characterized by very bright radio bursts which, while being periodically related, occur infrequently. We find bursts with the same characteristics for the known pulsar B0656+14. These bursts represent pulses from the bright end of an extended smooth pulse-energy distribution and are shown to be unlike giant pulses, giant micropulses or the pulses of normal pulsars. 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. Longer observations of the RRATs may reveal that they, like PSR B0656+14, emit weaker emission in addition to the bursts.

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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. These are commonly known as "The Three Musketeers" (Becker & Trümper 1997), the other two being Geminga and PSR B1055–52. PSR B0656+14 was included in a recent extensive survey of subpulse modulation in pulsars in the northern sky at the Westerbork Synthesis Radio Telescope (WSRT) by Weltevrede et al. (2006). In the single pulses analysed for this purpose, the unusual nature of this pulsar's emission was very evident, especially the brief, yet exceptionally powerful bursts of radio emission.

These extreme bursts of radio emission of PSR B0656+14 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. From the greatest common divisor of the time between bursts, a period has been found for ten out of the eleven sources. The periods (between 0.4 and 7 s) suggest these sources may be related to the radio-quiet X-ray populations of neutron stars, such as magnetars (Woods & Thompson 2006) and isolated neutron stars (Haberl 2004). However, Popov et al. (2006) have shown that the estimated formation rate of magnetars is too low. Furthermore the spectrum of the only RRAT for which an X-ray counterpart has so far been detected (Reynolds et al. 2006) seems to be too cool, too thermal and too dim for a magnetar, but is consistent with a cooling middle-aged neutron star like PSR B0656+14 (Shibanov et al. 2006). Also the pulse period and the slowdown-rate of PSR B0656+14, as well as the derived surface magnetic field strength and characteristic age, are within the range of measured values for RRATs.

2. Observations

The results in this paper are based on an archival and a new observation made using the 305-meter Arecibo telescope on 20 July 2003 and 30 April 2005 respectively. 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[1]) for the 2003 and 2005 observation respectively. The Stokes parameters have been corrected off-line for dispersion, Faraday rotation and various instrumental polarization effects.

The data were in some instances affected by Radio Frequency Interference, but this could relatively easily be removed by excluding the pulses with the highest root-mean-square of the off-pulse noise (about 1% of the data in both observations) from further analysis. The results derived from both observations (of which the one from 2005 is relatively clean) are very similar, making us confident in the results.

The observations are not flux calibrated, but are sufficiently long to get a pulse profile with high precision. From its shape it follows that the peak-flux of the profile is about 17 times that of the integrated flux-density over the entire pulse phase. The average flux at our observing frequency is estimated to be 7.2 mJy, based on the measurement of the spectral index (-0.5) and flux-density by Lorimer et al. (1995) at 408 MHz. Therefore the peak-flux of the profile is approximately 0.12 Jy. The scintillation bandwidth of PSR B0656+14 is much smaller than the observing bandwidth, so no intensity fluctuations appear in the data as a function of time due to interstellar scintillation.

3. The radio bursts of PSR B0656+14

To characterize the bright pulses of PSR B0656+14, the pulse-energy distribution is calculated (see Fig. 1). In this plot the energies are normalized to the average pulse-energy $\langle E\rangle$. The brightest measured pulse is 116 $\langle E\rangle$, which is exceptional for regular radio pulsars. Based on the energy of these pulses alone, PSR B0656+14 would fit into the class of pulsars that emit so-called giant pulses (e.g. Cairns 2004). About 0.3% of the pulses of PSR B0656+14 are brighter than 10 $\langle E\rangle$, which is the working definition of 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 (e.g. Soglasnov et al. 2004; Hankins et al. 2003), 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 (around 10^5 Gauss; Cognard et al. 1996) clearly fails for PSR B0656+14 (766 Gauss). However, giant pulses have been claimed in other (slow) pulsars that also easily

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[1] `http://www.naic.edu/~wapp`

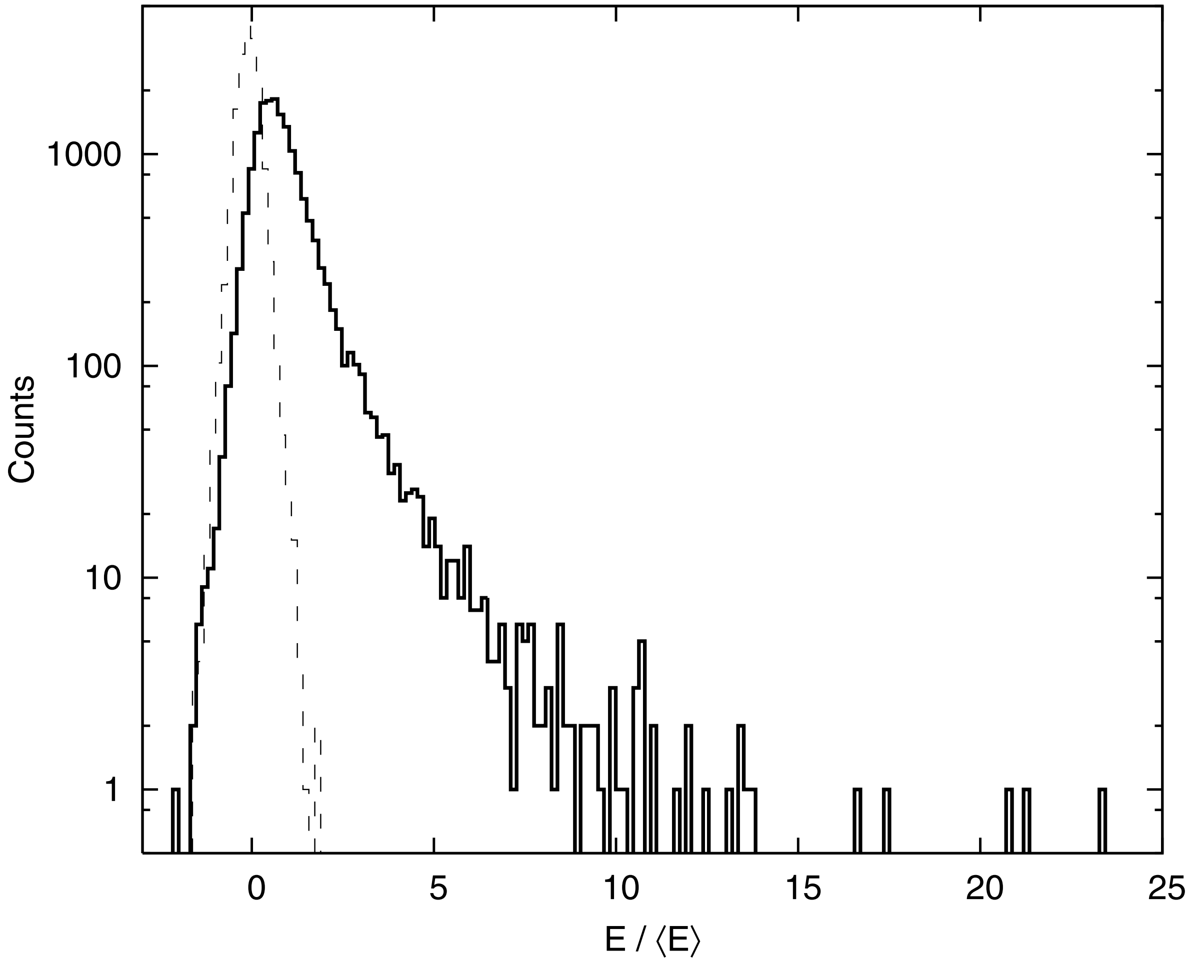

Fig. 1.— The pulse-energy distribution of the 2005 observation of PSR B0656+14 (solid line) and the off-pulse distribution (dashed line). The brightest pulse is about 116 times stronger than the average, which is outside the plotted energy-range.

fail this test (e.g. Kuzmin & Ershov 2004; Kramer et al. 2003) 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 (see Fig. 2). 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.

4. The RRAT connection

It is unclear how the extreme pulses of PSR B0656+14 fit into the zoo of apparently different emission types of radio pulsars. They are brighter than the giant micropulses, and not constrained to a particular pulse longitude and, despite being energetic enough, they are too broad to be characterized as classical giant pulses. However, the observational facts are that PSR B0656+14 occasionally emits extremely bright bursts of radio emission which are short in duration. One cannot help but see the similarities with the RRATs.

One important question is whether the luminosities of the bursts of the relatively nearby

Table 1: Comparison of the peak-flux of the brightest bursts of PSR B0656+14 and those of the RRATs. Here $S_{\rm peak}$ is the peak-flux of the brightest detected burst for each source, D the distance and $L_{\rm peak} = S_{\rm peak}d^2$ the peak-luminosity of the brightest detected burst.

Name	$S_{\rm peak}$ mJy	D kpc	$L_{\rm peak}$ Jy kpc^2
B0656+14	59000	0.288	4.1
J0848–43	100	5.5	3.0
J1317–5759	1100	3.2	11
J1443–60	280	5.5	8.5
J1754–30	160	2.2	0.77
J1819–1458	3600	3.6	47
J1826–14	600	3.3	6.5
J1839–01	100	6.5	4.2
J1846–02	250	5.2	6.8
J1848–12	450	2.4	2.6
J1911+00	250	3.3	2.7
J1913+1333	650	5.7	21

PSR B0656+14 (288 pc; Brisken et al. 2003) and those of the RRATs are comparable (there is no indication that the spatial distributions of RRATs and PSRs are different; McLaughlin et al. 2006). The brightest burst we found in the centre of the profile has a peak-flux that is 420 times the average peak-flux. With an average peak-flux of 0.12 Jy (see Sect. 2), this corresponds to a peak flux of 50 Jy. If one compares luminosities (Table 1), one can see that the brightest burst of PSR B0656+14 is as luminous as those of four of the eleven RRATs, and therefore very typical for these sources.

It is not only interesting to compare the luminosities of the bursts, but also their peak-flux distributions. Although the slope of the top end of the 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 (see Fig. 4).

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 ten times farther away, 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).

5. Implications and discussion

We have shown that PSR B0656+14 could have been identified as an RRAT, had it been at the typical distance of the known RRATs. We have no way of telling whether its capacity to produce intense bursts of emission right across its profile is related to its age, period, inclination, or even its immediate galactic environment, since this behavior has been found in no other pulsar. The pulse-energy distribution is not a power-law, but is better fit by a lognormal distrubition and such distributions are thought to be common for pulsars (e.g. Cairns et al. 2004).

In a study of 32 pulsars, Ritchings (1976) found that PSR B0950+08 shows the highest degree of pulse-to-pulse intensity variation. Nevertheless, the brightest pulse found in an extensive study of its field statistics by Cairns et al. (2004) is approximately 5 $\langle E \rangle$. Vela does not show pulses brighter than 10 $\langle E \rangle$ and only 0.5% of the pulses are brighter than 3 $\langle E \rangle$ (Johnston et al. 2001). For PSR B0656+14 4% of the pulses are brighter than 3 $\langle E \rangle$. Therefore the emission of PSR B0656+14 appears to be extremely erratic compared with both normal pulsars and pulsars with giant micropulses.

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 (predicted by Zhang et al. 2006) 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 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.

Hopefully, radio observations of RRATs will soon be able to test these predictions. These, together with the detection of more RRATs and potentially their high-energy counterparts, will shed light on their true nature. The transient nature of these sources makes them difficult to detect. However it is likely that the Galactic population exceeds that of the "normal" radio pulsars (McLaughlin et al. 2006). Thus surveys with long pointings, such as those planned with LOFAR for example, or many observations of the same region of sky are required. Surveys at low frequencies will also be more sensitive to nearer RRATs as the greater degree of dispersion will allow them to be more easily distinguished from radio frequency interference.

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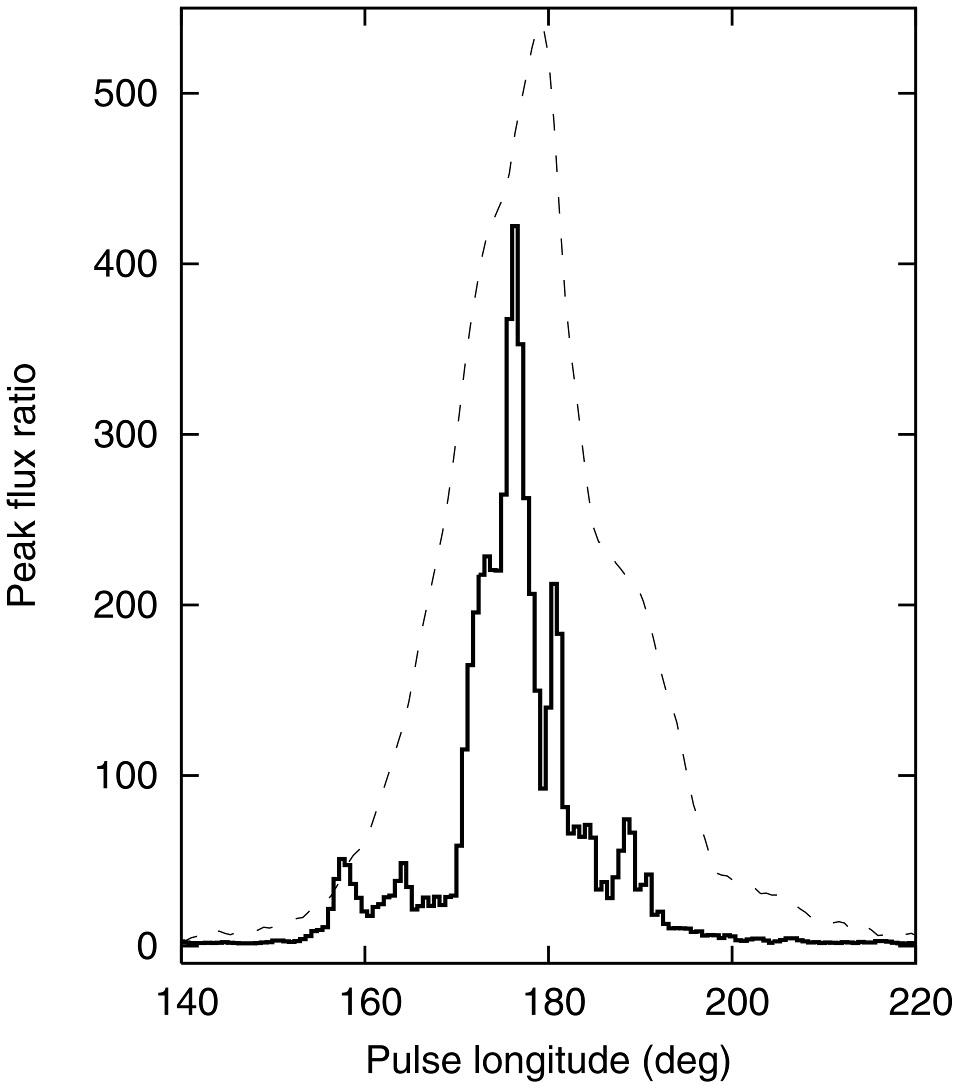

Fig. 2.— The dashed line is the average profile of our 2005 observation. The solid line shows the ratio between the peak-flux of the brightest burst at each longitude and the average peak-flux of the profile.

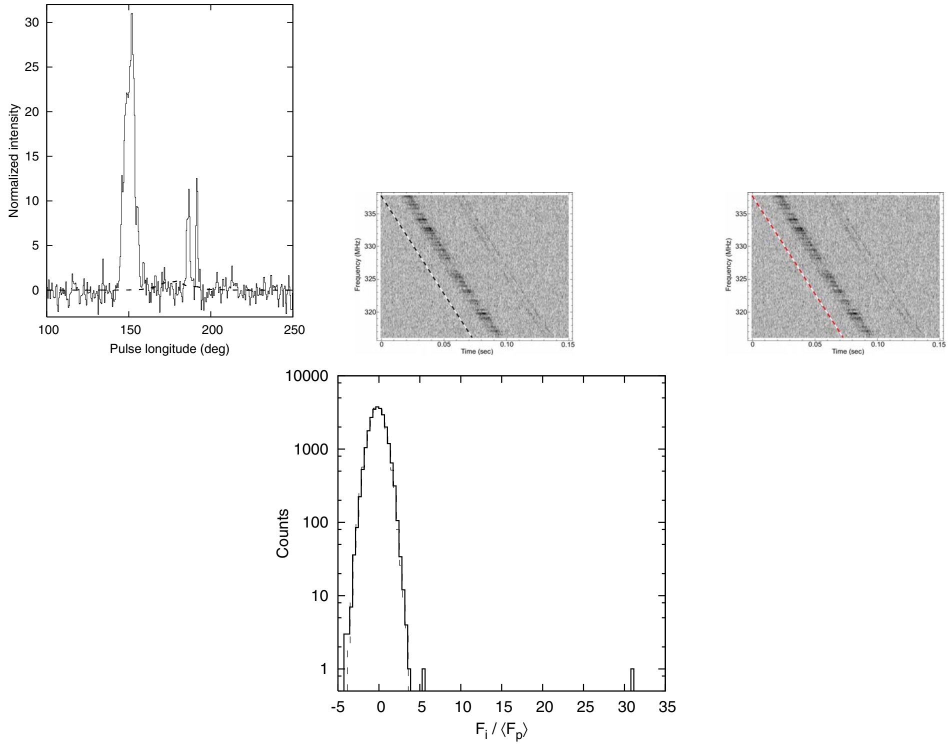

Fig. 3.— The bright radio burst detected at the leading edge of the pulse profile in the 2003 observation. **Left:** The burst (solid line) compared with the average pulse profile (dashed line). **Middle:** The same burst, but now with frequency resolution. The data in this plot is not de-dispersed and its dispersion track matches exactly what is expected for the known dispersion measure (DM) of this pulsar (dashed line). **Right:** The longitude-resolved energy-distribution at the longitude of the peak of the strong pulse (solid line) and the off-pulse distribution (dashed line). The peak-fluxes (F_i) are normalized to the average peak-flux of the profile ($\langle F_p \rangle$).

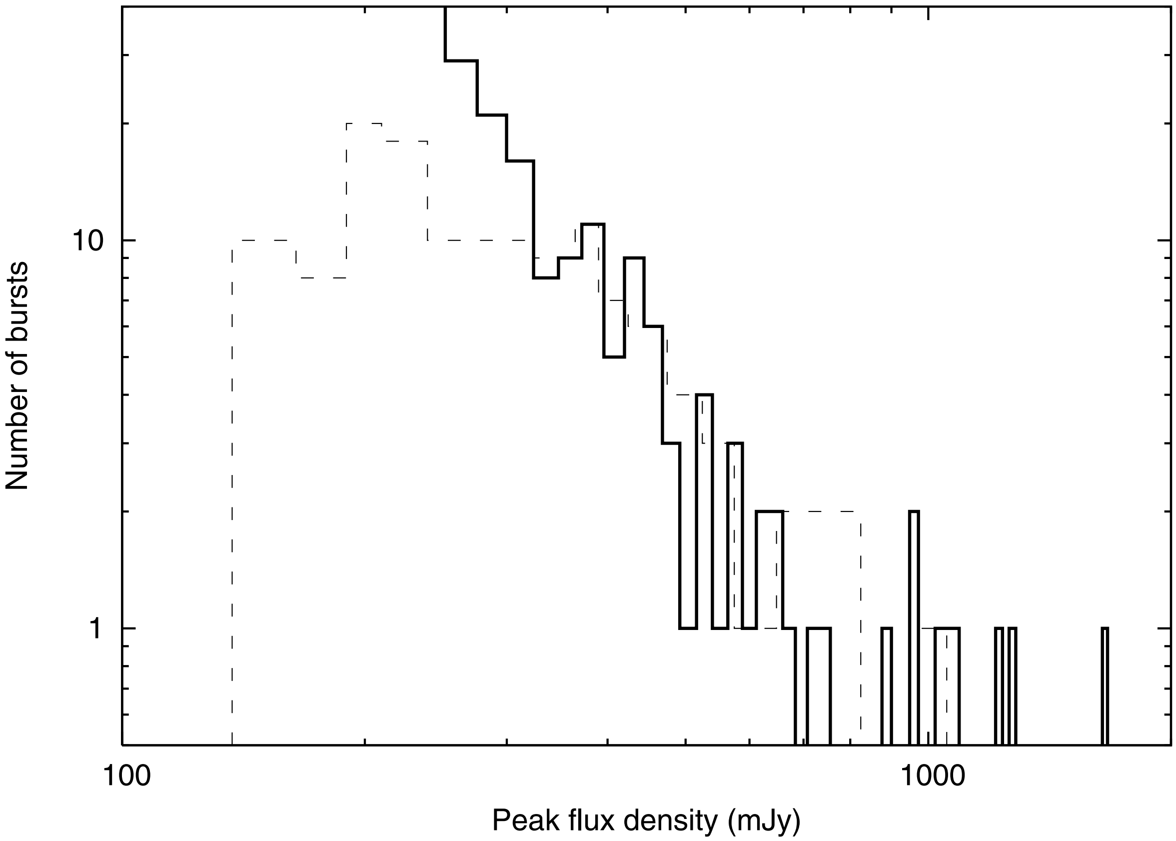

Fig. 4.— The peak-flux distribution of the 2003 observation of PSR B0656+14 (solid line), compared with RRAT J1317–5759 (dashed line) as observed by McLaughlin et al. (2006). The fluxes of PSR B0656+14 are scaled to let the two distributions overlap.