Radio Profile Instability in the Millisecond Pulsar PSR J0437–4715 due to Spiky Emission

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ABSTRACT
The instability in one of the components of the radio integrated profile (IP) of the millisecond pulsar PSR J0437–4715 is correlated with the occurrence of the spiky emission in that component. It is speculated that the instability in other components is also due to the spiky emission. This might have important implications for interpreting the individual components of the IP as independent beams or regions of emission.

Key words: pulsars – PSR J0437–4715 – PSR B1821-24 – single pulses – radio – profile instability.

1 INTRODUCTION
The coherent radio emission mechanism of rotation powered pulsars is as yet an unsolved problem. The broad similarity in the coherent radio emissions from normal and millisecond pulsars (McConnell et al. (1996), Gil & Krawczyk (1997), Jenet et al. (1998), Vivekanad et al. (1998), Kramer et al. (1999), Vivekanand (2000)) is intriguing; that a similar mechanism operates over three to four orders of magnitude difference in their periods and period derivatives is probably an important clue to the coherent radio emission mechanism of rotation powered pulsars.

Of equal importance are the differences in the radio emission from these two classes of pulsars. One of them is the slow variation in the IP of millisecond pulsars (Camilo (1995), Backer & Sallmen (1997), Vivekanand et al. (1998), Kramer et al. (1999)), over time scales ranging from several hundred periods to hours and even days, which is quite unlike the fast mode changing phenomenon observed in some normal pulsars (Backer (1970), Helfand et al. (1975), Manchester & Taylor (1977), Rathnasree & Rankin (1995)). Neither phenomenon has a satisfactory explanation so far.

Here it is shown that the slow IP variations seen in one of the components of PSR J0437–4715 (Vivekanand et al. (1998)) are correlated with variations of the spiky emission in that component (Vivekanand (2000)).

2 PROFILE INSTABILITY IN PSR J0437–4715
Figure 1 shows IP of PSR J0437–4715 at five different epochs, observed at 326.5 MHz using Ooty Radio Telescope (ORT); only a single linear polarization was available. From top to bottom the five panels correspond to (1) 9 files observed from UT 15:27:59 to UT 15:42:08 on 7 Mar 1995, (2) 2 files observed at UT 15:43:57 and UT 15:45:49 on 7 Mar 1995, (3) 12 files observed from UT 16:04:17 to UT 16:23:22 on 7 Mar 1995, (4) 13 files observed from UT 15:39:25 to UT 16:04:21 on 9 Mar 1995, and (5) 3 files observed at UT 15:51:21, UT 15:53:02 and UT 15:54:40 on 14 Mar 1995. Each file consists of 12 125 useful periods of data. The instrument, the method of observation and data analysis are described in Ables et al. (1997), Vivekanand et al. (1998), Vivekanand (2000), and Vivekanand (2001).

In fig. 1 the first panel from top corresponds to the profile labelled type B in fig. 8 of section 5 of Vivekanand et al. (1998). The second panel contains the two files that show a transition from type B to type A, and the third and fourth panels together correspond to the profile labelled type A. The main difference between the profiles of fig. 1 here and fig. 8 of Vivekanand et al. (1998) is the more accurate period, differing by a few microseconds, that is used for folding the data (Vivekanand (2001)).

On 7 Mar 1995, the peak flux of the third component of the IP of PSR J0437–4715 decreased from 3.3 to 2.6 over a period of ≈ 36 minutes (panels 1 to 3 of fig. 1). During this time the peak flux of its central component increased from 5.2 to 5.6, and that of its first component increased marginally from 2.1 to 2.3. These correspond to fractional flux variations of 21.2%, 7.7% and 9.5% respectively, which are much larger than the ≈ 1% to 2% maximum allowed by purely random noise. Two days later PSR J0437–4715 had an IP similar to that observed earlier (panel 4). Five days later its first component became stronger than its third component (panel 5), exactly contrary to its behavior a week earlier (panel 1). Vivekanand et al. (1998) argued that these profile variations are intrinsic to PSR J0437–4715, and are not an ar-

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tifact due to the single polarization observations of ORT coupled with Faraday rotation in the variable ionosphere. In the next section it will be shown that the IP variations of component 3 are highly correlated with the occurrence of the spiky emission in that component.

3 PROBABILITY OF OCCURRENCE OF SPIKES

On account of limited signal-to-noise ratio of the data (Vivekanand 2001), only the 500 strongest spikes in each data file were analyzed; ideally one would have liked to completely separate the spiky from the non-spiky emission for this exercise.

First, the 500 strongest spikes in each data file were identified and their positions (phases) were obtained as described in Vivekanand 2001. Next, these positions were plotted against the numbers of the periods in which they occurred, for those spikes which satisfied following two selection criterion: (1) their peak signal to noise ratio should be greater than 12.5, and (2) the error on their position should be less than 20 micro seconds ($\mu$s). However the final result is not very sensitive to these two selection criterion.

Figure 2 plots the positions of 375 of the 500 strongest spikes in the data file labelled 50661527, as a function of the period number. This belongs to the profile category labelled B by Vivekanand et al. 1998; the rms errors on the positions are less than the width of the dots. There are 52, 314 and 9 spikes in the three main components of the IP, respectively. If the two selection criterion are dropped, one obtains 66, 421 and 13 spikes in the corresponding components of the IP, which are entirely consistent with earlier numbers. In file labelled 50661538 belonging to the same category, that was observed at UT 15:38:41 on 7 Mar 1995, PSR J0437−4715 was at one of its lowest average fluxes. The number of spikes in the three main components of the IP, with and without the selection criterion, are 39, 301 and 1, and 56, 442 and 2, respectively, which are again fractionally similar. The two selection criterion do not significantly alter the results of this article.

Figure 3 plots the positions of the 500 strongest spikes in the data file labelled 50661612, which belongs to the category labelled A by Vivekanand et al. 1998. Here the number of spikes in the three main components of the IP are 46, 453 and 1, respectively; no spikes have been selected out due to the high average pulsar flux in this data file. Clearly the fraction of spikes in the third component of the IP has decreased significantly compared to category B. This is verified in a visual check of as many periods as is reasonably possible. Even in file labelled 50661538, several periods had spikes in the third component of the IP, that were not part of the 500 strongest spikes.

Table 1. Statistics of occurrence of strong spikes in fig. 1, for panel 1 (top row), panels 3 and 4 (middle row) and panel 5 (bottom row). The second column contains the number of data files in each row. $N_0$ is the total number of spikes in those files; $N_1$, $N_2$ and $N_3$ are the number of spikes in the three main components of the IP of that row, respectively; the boundaries of the components are shown by the dashed lines in fig. 2 and fig. 3. The last column contains the average flux (in arbitrary units) of PSR J0437−4715 in those panels, along with its rms error.

| PANEL | FILES | $N_0$ | $N_1$ | $N_2$ | $N_3$ | ⟨FLUX⟩ |
|-------|-------|-------|-------|-------|-------|---------|
| 1     | 9     | 3598  | 408   | 3155  | 35    | 3.10 ± 0.09 |
| 3 & 4 | 25    | 12405 | 1255  | 11144 | 6     | 3.54 ± 0.06 |
| 5     | 3     | 344   | 33    | 311   | 0     | 2.00 ± 0.12 |

To test this more rigorously, the above numbers were totalled for all files in each category of the IP; the results are shown in Table 1. The 9 files of panel 1 in fig. 2 yielded totally $N_0 = 3598$ spikes; the rest of the 4500 spikes were ignored due to the two criterion mentioned above. Out of these, $N_1 = 408$ spikes occurred in the first component of the IP, $N_2 = 3155$ spikes occurred in the second component, and the $N_3 = 35$ spikes occurred in the third component. This was for the type B profile. $N_0$ is 12405 for the 25 files of type A profile (panels 3 and 4 in fig. 2). From this one would have expected $N_1 = 408 / 3598 \times 12405 \approx 1407 \pm 38$, whereas one obtained the smaller number 1255. Similarly one expected $N_2 = 3155 / 3598 \times 12405 \approx 10878 \pm 104$ in the second component, but obtained the larger number 11144. But the most interesting number is the expected $N_3 = 35 / 3598 \times 12405 \approx 121 \pm 11$, which is significantly larger than the observed value of 6; and this occurs in spite of the average pulsar flux increasing by about 14% (Table 1). Clearly the decrease in rate of occurrence of spikes in the third component of the IP of PSR J0437−4715 is correlated with the decrease in average flux of that component.

This trend continues in the last row of table 1 (panel 5 of fig. 2); but caution is required here. Since one selects the 500 strongest spikes in each data file, the results should not depend upon the average flux of PSR J0437−4715 to the zeroth order. But for very low average flux of PSR J0437−4715 one expects to see no spike in the third component of the IP, since the probability of occurrence there is very low anyway (Vivekanand 2000). This is probably what is happening in the last row of table 1; the average number of spikes per file is significantly lower here.

The expected values of $N_1$, $N_2$ and $N_3$ in the last panel of fig. 2, based on the type B profile, are $39 \pm 6$, $302 \pm 17$ and $3 \pm 2$; these are consistent with the observed values. One would have liked to see a larger value for $N_1$ here, to be consistent with the increased flux of the first component of the IP; but one is probably dealing with small numbers due to limited data, as well as a significantly weaker pulsar flux in those files.

Table 1 has also been derived after removing the two selection criterion, and the results remain similar.

The N3 values in the 9 files of row 1 of table 1 range from 9 to 1. The first three files observed chronologically, labelled 50661527, 50661529 and 50661531, have $N_3 = 9$, 5 and 7, respectively. Now PSR J0437−4715 was strong in these files and weakened systematically with time. Not surprisingly, N3 values in the next six files are 3, 2, 4, 1, 2 and 2; these files are labelled 50661533 through 50661538. It is clear that there was no hope of seeing any spikes in the third component of the IP in the next two files, viz. 50661543 and 50661545 in panel 2 of fig. 2, even if they existed, due to the low average flux of $2.54 \pm 0.04$ in these two data files; which is why the single pulse mode of observation was discontinued after that time. However, after about 18 minutes, the average flux of PSR J0437−4715 became high again; which is why the single
pulse mode of observation was re-started once again. But $N_3$ for the next 12 data files, belonging to panel 3 of fig. 4, was a mere 5; only five data files had $N_3 = 1$, and the rest had $N_3 = 0$. More convincingly, $N_3$ was a mere 1 for the 13 data files belonging to panel 4 of fig. 4, and these contain some of the highest average flux data on PSR J0437–4715.

It is therefore concluded that the decrease in $N_3$ between the first two rows of table 1 is a feature intrinsic to PSR J0437–4715. That this decrease correlates with the decrease in the flux of the third component of the IP proves the basic hypothesis of this article. The clinching evidence would have been if one had actually seen the decrease in the number of spikes as time progresses (in figures similar to fig. 4 and fig. 5, in the two data files labelled 50661543 and 50661545 of panel 2 of fig. 4, which are believed to be in transition between categories B and A. Unfortunately, this is not possible due to the low average flux of PSR J0437–4715 in these two data files.

4 SUMMARY AND DISCUSSION

Vivekanand et al. (1998) showed that the IP of the millisecond pulsar PSR J0437–4715 changes significantly in shape over time scales of minutes and hours and even days. This is unlike the much faster mode changing known in normal pulsars. They argued that this behavior was intrinsic to PSR J0437–4715, and not an instrumental effect. Here it is shown that profile variations in the third component of the IP of PSR J0437–4715 are correlated with the rate of occurrence of the spiky emission in that component. Each period that contained any of the $35 + 6 = 41$ spikes, in the third component of the IP in Table 1, was visually checked for confirmation.

Before proceeding further, two comments are in order:

(i) The first concerns the availability of only a single polarization at ORT. Navarro et al. (1997) show that the percentage of linear polarization of PSR J0437–4715 at 438 MHz is highest at the peaks of components 2 and 3 in fig. 4 (also their fig. 1); component 1 has very low linear polarization. From their fig. 1 the position angle of linear polarization differs by less than $\approx 40^\circ$ at these two peaks. Therefore, it is possible that, in principle, differential Faraday rotation in a variable ionosphere at ORT can reduce the effective flux density of spikes in component 3 by $\approx 1 - \cos^2(40^\circ) \approx 41\%$ or less, in spite of the arguments of Vivekanand et al. (1998). This issue can be resolved satisfactorily only when full polarization observations of PSR J0437–4715 are available at 326.5 MHz. However, one would have expected an as frequent reduction of number of spikes in component 2 also, with respect to the number of spikes in component 3; this is not observed, although the statistical basis of such a conclusion is not strong. Furthermore, it is quite possible that the mean position of spikes, in components 2 and 3 of fig. 4, is not coincident exactly with the corresponding position of the peak of linear polarization. In such an eventuality, the effect discussed above would be less serious, since the linear polarization profiles in components 2 and 3 are fairly sharply peaked. Finally, similar profile variations have been noted by Bell et al. (1997) in PSR J0437–4715 at 430 MHz in full polarization observations. This author feels they might have wrongly attributed the observed profile variations to “relative gain variation in the two polarization channels and the high degree of polarization of the emission observed across the profile”.

(ii) Vivekanand (2000) has shown that the position of occurrence of spikes is uncorrelated with their height; no simple relation exists between these positions and the integrated profile (figures 5 and 6 of that paper). Therefore this author can not think of any obvious selection effect involving these parameters that can produce the result of this paper.

One would have liked to find a quantitative correlation between the rate of occurrence of spikes (Table 1) and the average flux in the other two components of the IP (fig. 4) also. Unfortunately this is complicated by two factors. Firstly, the average pulsar flux in a data file could be so low that the observed rate of occurrence of spikes in any component may be biased to a lower value. Secondly, the average flux of the spiky emission can also change in principle, from file to file and from component to component. To illustrate the problem, the fraction of $N_3$ spikes in Table 1 decreases down the rows, consistent with decrease in flux of the third component of the IP in fig. 5. However, the fraction of $N_1$ spikes in Table 1 also decreases, although marginally; this is inconsistent with the increase in flux of the first component of the IP; this can easily arise due to the reasons mentioned above, as also due to a small change in the occurrence rate of spikes in the second component of the IP, which has about 90% of the spikes.

PSR J0437–4715 has also been studied at $\approx 1400$ MHz by several workers, but this kind of behavior has not been reported so far. One possible reason is the low signal to noise ratio of their data. The other possible reason could be that PSR J0437–4715 does not show such behavior at other frequencies. There is a precedence for this – PSR B1821–24 shows radio profile instability at 1400 MHz but not at 800 MHz (Backer & Salimbeni 1997).

It is likely that the IP variations of the first component of PSR J0437–4715, as well as any other component, are also due to the rate of spiky emission in that component, although that has not been proved rigorously here.

It is further speculated here that the exact shape of the three principal components of the IP of PSR J0437–4715 is a consequence of the spiky emission, and not its cause. This is supported by fig. 5, where about 16% of the periods containing the 2000 strongest spikes in the entire data have an IP that has intense peaks in the three components; small variations in the spiky emission in any one of these three components is quite likely to change the shape of the overall IP of PSR J0437–4715.

This further enhances the doubt, expressed in the last section of Vivekanand (2000), about the interpretation of the individual components of the IP of PSR J0437–4715 as individual beams or regions of emission. It is worth exploring the suggestion in that paper regarding the independent method of resolving the IP into independent beams or regions of emission on the pulsar.

REFERENCES

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Figure 1. Integrated profiles of PSR J0437–4715 observed at 326.5 MHz using ORT, at five different epochs during 7 to 14 Mar 1995. The abscissa is in units of the pulsar period (also known as phase within the period), which is changing due to its binary nature but is ≈ 5.757 ms; the 56 time bins along the abscissa have a width each of ≈ 102.8 µs. The ordinates are in arbitrary units. The area under each IP is normalized to a constant value. The peak values in the three principal components of the IP are listed for comparison.
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Figure 2. Top panel: Integrated profile of 12 125 periods in data file labelled 50661527, observed at UT 15:27:59 on 7 Mar 1995. This is one of the nine files in the first panel of fig. 1; abscissa and ordinate are as in that figure. Bottom panel: Ordinate is the period number. The dots represent the 375 largest spikes in the data file. The dashed vertical lines are drawn at abscissa 0.417 and 0.578, which are taken to be the practical boundaries between the three main components of the IP of PSR J0437−4715.

Figure 3. Same as fig. 2 above, but for the data file labelled 5066162, observed at UT 16:12:47 on 7 Mar 1995. This is one of the twelve files in the third panel of fig. 1.

Figure 4. Integrated profiles of PSR J0437−4715 from data in file labelled 50681546, which contains the highest average pulsar flux in our collection. Top panel: 1961 periods containing 2000 highest peaks in the file. Bottom panel: The remaining 10 164 in that file.