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Single Pulses and the Plasma-physical Processes of Pulsar Radio Emission

Joanna M. Rankin

Physics Department, University of Vermont, Burlington, VT 05405 USA:
Joanna.Rankin@uvm.edu

Abstract. Pulsars were discovered on the basis of their individual pulses, first by Jocelyn Bell and then by many others. This was chart-recorder science as computers were not yet in routine use. Single pulses carry direct information about the emission process as revealed in the detailed properties of their polarization characteristics. Early analyses of single pulses proved so dizzyingly complex that attention shifted to study of average profiles. This is turn led to models of pulsar emission beams—in particular the core/double-cone model—which now provides a foundation for understanding single-pulse sequences. We mention some of the 21stC single-pulse surveys and conclude with a brief discussion of our own recent analyses leading to the identification of the pulsar radio-emission mechanism of both slow and millsecond pulsars.

Keywords. (stars:) pulsars: general, radiation mechanisms: nonthermal, polarization

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With the greatest pleasure and profound appreciation, I salute Dame Jocelyn Bell on the half-century of pulsar science which she initiated and on consequently her uniquely central place in this symposium of celebration and reflection.

The Individual Pulses from Pulsars

Single pulses are what pulsars do for us. Most radio pulsars emit continuously along their magnetic axes, but their rotation causes their emission to cross our sightline for only a brief time producing a pulse. It was such single pulses that Jocelyn Bell detected as in her first recording of CP 1919 on 1967 November 28, depicted in Figure 1.

Indeed, all the early radio observatories first studied the individual pulses from pulsars because the basic technique of computing average profiles required computers which were not then in general use. The recording instrument that was then a standard was the chart recorder, and some observatories had very sophisticated models that literally "breathed fire" as their red-hot pens marked the waxed charts flying by at high speed. Jocelyn Bell reports having had several hundred meters of charts to analyze for her dissertation.

At Arecibo where I arrived as a predoc student in February 1969, a computer was in use, but most of the pulsar searching was done on the chart recorders where such pulsars as AP 0823 and AP 1541 were discovered. This continued for some years because the charts could run while other programs were being conducted.

My favorite story of charts concerns Academician Prof. V. V. Vitkevich, founder of the Pushchino Observatory, who came to Arecibo in 1969 accompanied by his KGB shadow. He worked with the engineering staff to assure that the two recorders could run at their full breakneck speed of something like half a meter per second, and during his several runs on the telescope observing the pulsar then known as PP 0943, he produced what seemed like more rolls of paper than he could carry. We all wondered what would come of this material, but when he returned to Pushchino Observatory in the then Soviet Union

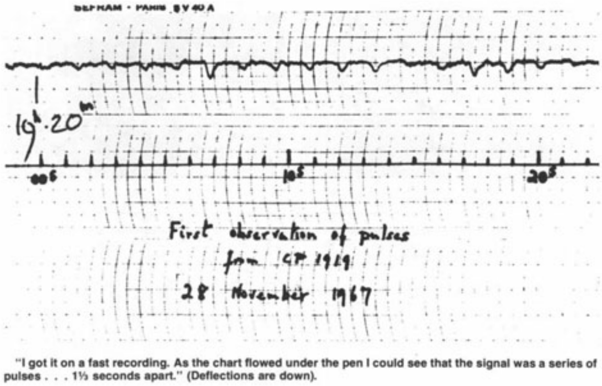

Figure 1. Single bright highly polarized pulses are what pulsars send us on each rotation. These are what Jocelyn Bell discovered, and as for most at the time, this was chart recorder science.

he clearly studied the charts carefully, and a paper reporting part of his discoveries can still be read in *Nature* (Vitkevich *et al.* 1969).

Single Pulses Provided All the First Lessons About Pulsar Behaviour

Most radio observatories excitedly turned to pulsars, and everyone studied their single pulses: Cambridge, Jodrell Bank, Parkes, Molonglo, Arecibo, NRAO, Pushchino, Bologna, Ooty and the NRAO 300-foot. Each instrument had its own particularly prominent pulsars for study and its own capabilities and issues which affected interpretation of its observations. These early single pulse trains were exciting and perplexing because each pulsar seemed to have its own distinct properties and personality.

Pulsar signals were investigated in every possible manner, and the "Big Three" pulse-sequence phenomena of subpulse drifting, nulling and mode-changing were all discovered early, Arecibo's larger sensitivity playing an important role: Drake & Craft (1968) first identified drifting, Backer (1970a,b) both nulling and moding. And typically during this time, these results were followed up before the ink was even dry, for instance by the identification of moding in MP 003107 (Huguenin *et al.*1970) and CP 0329 (Lyne 1971). Perhaps by the authors not getting much sleep major compendia of pulsar characteristics were published shortly (Lyne, Smith & Graham 1971; Taylor & Huguenin 1971). Microstructure in the radiation was also noted early at Arecibo by Craft *et al.* (1968), which led then to pioneering work by Hankins (1971).

Single Pulse Polarimetry Most Closely Reveals the Emission Physics

Most early instruments were arrays with a single linear or circular polarization, but where not people noticed early that the signals from two receiver feeds were different, raising interest in systematic polarimetry. Pulsar emission was highly polarized suggesting coherent emission! Parkes was the pioneer and shortly pointed out the key importance of polarimetry in its Vela pulsar observations (Radhakrishnan & Cooke 1969; Komesaroff 1970). Other telescopes rushed to follow suit as possible, and Dick Manchester's (1971) polarimetry survey was the first available. However, my nomination for sheer polarimetric creativity and early insight is Taylor, Huguenin, Hirsch & Manchester's (1971) depiction of the polarization of B0809+74's drifting subpulses.

Viewing Pulsar Signals Directly in Real Time

A radio telescope is a radio, and the signals being received can be viewed on an oscilloscope or even connected to a loudspeaker. Observers delighted in watching the pulses

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come in and learned much in so doing, even when we were recording the pulses on a computer. Many a colleague "got hooked" on pulsars in just this way. Sadly, this is now unusual. Wider bandwidths and more highly dispersed pulsars defeat the simplicity of this practice, even when the pulsars are quite strong. Perhaps some younger colleagues have never had this experience of "seeing" a pulsar in real time.

Retreat From Single-Pulse Studies; the Challenge of Classification

Single pulses presented observers with such withering complexity that most of us asked ourselves whether pulsar "weather" could ever be understood. Study of average profiles provided a tempting retreat in that broader band observations of a larger available pulsar population seemed to show some regularities. A first attempt at classification (Huguenin *et al.* 1971) prompted Backer's (1976) system showing that some pulsars had a central "pencil" beam surrounded by one or two emission cones.

My early work (Rankin 1983) distinguished two types of single profiles, core and cone and proposed classes based on frequency evolution, not only profile shape. Later work was able to quantify the angular dimensions of the beams in terms of the angular size of a pulsar's polar cap (Rankin 1990, 1993a,b), which scale with the inverse square root of the rotation period. This core/couble-cone model is now well known and provides a consistent quantitative basis for assessing the emission geometry of most slow pulsars. The model demonstrates that most slow pulsars have a similar overall beaming geometry, but its precision is limited by the illumination and polarization particularities of specific pulsars. Nonetheless, it provides a foundation for returning to the study of single pulses by distinguishing the core and conal emission and knowing how our sightline traverses the pulsar's emission-beam configuration.

An Inadequate Few Words About Recent Single-Pulse Investigations

Any attempt to review the efforts to interpret single pulses since the millenium goes from the impossible to the ridiculous; however, let me at least mention a few of the published studies. The massive dual frequency Westerbork surveys by Weltevrede *et al.* (2007, 2008) demonstrated that a majority of slow pulsars exhibit a secondary modulation. The GMRT's sensitive single-pulse, multi-band polarimetry facility has opened the possibility of studying populations of pulsars over nearly the entire sky (e.g., Mitra & Rankin 2011). LOFAR has pushed single-pulse observations to 100 MHz and below and are developing a polarimetry facility (e.g. Bilous *et al.* 2016). Finally, the recent GMT dual band survey connects polarimetry to drifting and other phenomena (Mitra *et al.* 2016).

Single-pulse Polarimetry Reveals the Plasma Radio Emission Physics

The 21st Century began with a long overdue shock for those concerned with the physics of pulsar radio emission: The beautiful Vela X-ray arcs in the *Chandra* images showed how the pulsar's rotation axis was oriented, that its proper motion was $\|$ to its rotation, and then that the radio emission was polarized $\perp$ to its emitting magnetic field. This in turn showed that pulsar RF must be a plasma process, putting to rest the lingering presumption that single-particle synchrotron (by "bunches") radiation might be involved. That many pulsars show proper motion alignments was then shown by Johnston *et al.* (2005). We pursued the consequences of these results in three ways, as outlined below.

Polarized Microstructure Shows No Sign of Single-Particle Synchrotron Radiation

As has long been known, bright single pulses of many radio pulsars show rapid intensity fluctuations, or microstructure, when observed with time resolutions of tens of microsec-

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onds or less. We conducted an Arecibo polarimetric survey of pulsars at both 327 and 1400 MHz with rotation periods ranging from 150 ms to 3.7 s using a uniform 60-μs sampling resolution. The 32 higher-frequency observations provide a broad and reliable basis for a detailed microstructure analysis. Close inspection of individual pulses reveals that most pulses exhibit quasi-periodicities with a well-defined periodicity timescale. While we find some pulses with a deeply modulated microstructure, most pulses show low-amplitude modulations on top of broad smooth subpulse features, thereby making it difficult to infer periodicities. We developed a method for such low-amplitude fluctuations wherein a smooth subpulse envelope is subtracted from each de-noised subpulse; the fluctuating portion of each subpulse was then used to estimate the periodicity via autocorrelation analysis. We find that the microstructure timescale is uniform across the total power and polarized fractions of the pulsar signals. In particular, no recognizable signature whatsoever of curvature radiation in vacuum in these highly resolved microstructures was found. Our analysis further shows a strong correlation between the fluctuation period and the pulsar rotation period. These results point to a coherent radiation mechanism wherein radio emission arises due to formation and acceleration of electron-positron pairs in an inner vacuum gap just above the magnetic polar cap, with subpulses corresponding to a series of non-stationary sparking discharges. We argue that in this model, microstructure periodicities reflect the temporal modulation of non-stationary plasma flow. See Mitra *et al.* (2012) for more details.

The Lowest Altitude Core Radiation is Polarized $\perp$ the Emitting Magnetic Field

Two entwined problems have remained unresolved since pulsars were discovered nearly 50 years ago: the orientation of their polarized emission relative to the emitting magnetic field and the orientation of their large space velocities (due to supernova "kicks"??) relative to their rotation-axs direction. The rotational orientation of most pulsars can be inferred only from the ("fiducial") polarization angle of their radiation, when their beam points directly at the Earth and the emitting polar flux tube field is $\parallel$ to the rotation axis. Earlier studies have been unrevealing owing to the admixture of different types of radiation (core and conal, two polarization modes), producing both $\parallel$ or $\perp$ alignments. However, Johnston *et al.* (2005) first showed clearly that many pulsars do show alignments of one type or the other, and we extended the evidence to this effect (Rankin 2007). In a more recent study, we analyzed the alignments of nearly 50 pulsars having three characteristics: core radiation beams, reliable absolute polarimetry, and accurate proper motions. The "fiducial" polarization angle of the latest, deepest core emission, we then find, is usually oriented $\perp$ to the proper-motion direction on the sky. As the primary core emission is polarized $\perp$ to the projected magnetic field in Vela and other pulsars where X-ray imaging reveals the orientation, this shows that proper motions usually lie $\parallel$ to the rotation axes on the sky. Two key consequences then follow: first, to the extent that supernova "kicks" are responsible for pulsar proper motions, they are mostly $\parallel$ to the rotation axis; and second most pulsar radiation is heavily processed by the magnetospheric plasma such that the lowest altitude "parent" core emission is polarized $\perp$ to the local emitting magnetic field, propagating—and escaping—as the extraordinary (X) mode. See Rankin (2015) and Poster #68 for more details.

Pulsar Radio Emission From Regions of Higher Plasma Frequency

A comprehensive high resolution, polarimetric study of B1933+16, the brightest core-radiation dominated pulsar in the Arecibo sky, has permitted us to measure its physical emission heights using aberration/retardation. At 1.5 GHz, the pulsar's polarization position-angle traverse is largely compatible with the rotating-vector model with α and

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β values of 125 and –1.2°. Using its accurate proper-motion alignment, the core and conal regions can be identified with the primary and secondary polarization modes and plausibly with the extraordinary and ordinary propagation modes. Polarization modal segregation shows that the core is comprised of two parts which we associate with later X-mode and earlier O-mode emission. Analysis of the broad microstructures under the core shows that they have similar timescales to those of the largely conal radiation of other pulsars studied earlier.

Aberration/retardation analysis was here possible for both the conal and core radiation and showed average physical emission heights of about 200 km for each. Comparison with other core-cone pulsars indicates that the core and conal emission arises from similar heights. Assuming the inner vacuum gap model, we estimate that at these emission altitudes the frequency of the observed radiation ν_{obs} is less than the plasma frequency ν_p for pulsar B1933+16 and several other well studied objects. We can then conclude that the radio emission properties are consistent with coherent curvature radiation by charged solitons (Melikidze *et al.* 2014; Mitra *et al.* 2015) where the condition $\nu_{obs} < \nu_p$ is satisfied. Mitra *et al.* (2016) for more details.

The five-component profile of the 2.7-ms pulsar J0337+1715 appears to exhibit a rare example of core/double-cone emission-beam structure in a millisecond pulsar (MSP). Moreover, three other MSPs, the Binary Pulsar B1913+16, B1953+29 and J1022+1001, seem to exhibit core/single-cone profiles. These configurations are remarkable and important because it has not been clear whether MSPs and slow pulsars ever exhibit similar emission-beam configurations, given that they have considerably smaller magnetospheres and magnetic field strengths. MSPs thus provide an extreme context for studying pulsar radio emission. Particle currents along the magnetic polar flux tube connect processes just above the polar cap through the radio-emission region to the light-cylinder and the external environment. In slow pulsars, radio-emission altitudes are typically about 3-500 km around where the magnetic field is nearly dipolar. For these MSPs with regular core/cone beam structure, we are able to use aberration/retardation to estimate the physical emission heights. Estimates of the physical conditions there point to radiation below the plasma frequency and emission from charged solitons by the curvature process. This parallels our work above on slow pulsars and is strong evidence that MSPs also radiate by curvature emission from charged solitons. See Rankin *et al.* (2017) and Poster #67 for more details.

How Does Pulsar Radio Frequency Emission Occur?

Most magnetospheric theories and recent simulations concur that electron-positron pairs should be formed and accelerated in an inner vacuum gap above a pulsar's magnetic polar cap. This is the source of the e+/e– secondary plasma within the polar flux tube. As long as this pair plasma is supplied copiously, the further processes below occur to generate pulsar RF radiation.

- Radio radiation emitted in a region at an altitude of about 3-500 km in slow pulsars, correspondingly lower in millisecond pulsars.
- This is a dense plasma region where the plasma and cyclotron frequencies are higher or much higher than the emitted RF frequency.
- Curvature radiation is the only allowed mechanism, excited by the two-stream instability in the e+/e– secondary plasma.
- Coupling occurs most easily to the extraordinary (X) propagation mode, which is $\perp$ to the local emitting magnetic field—as seen for the "parent" core emission. The ordinary (O) mode is strongly absorbed, and it is unclear how it escapes at all.

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• The emitting entities are highly non-linear solitons—*charged* plasma solitons—for which no adequate current theory exists.

This understanding, supported by a variety of observational evidence, identifies a single mechanism—curvature-accelerated charged solitons—as responsible for pulsar radio emission. However, no detailed physical theory exists for charged solitons, and even if it did, a number of large questions remain. For instance, how does the observed ordinary-mode emission escape? What is the origin of the observed circular polarization?

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