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A Plasma-Physical Understanding of Pulsar Radio Emission Physics

Thematic Areas: Formation and Evolution of Compact Objects
Stars and Stellar Evolution
Multi-Messenger Astronomy and Astrophysics

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Abstract: Pulsars generate a secondary electron-positron pair plasma. If the supply is sufficient, pulsars produce radio emission at altitudes of 300-500 km above the neutron star surface and thermal X-rays from backflow-heated polar caps. The last decade has solidified understanding of the physics of this radio and thermal X-ray emission through observational investigations dependent on the most sensitive radio and X-ray telescopes available. The field is poised to extend this understanding through studying pulsar radiation in terms of its basic plasma-physical properties. The physics of the pair-plasma generation is also becoming better understood through theoretical research and particle-in-cell (PiC) simulations. We focus here on the radio-emission physics when adequate pair plasma is available. Pulsar emission-physics research is likely to find applications in other high energy areas, improve pulsar timing efforts, and provide models which are highly relevant in our quest to understand fast radio bursts.

A Decade of Progress:

Core/cone emission: Pulsar radio emission is primarily of two types, core and conal. Radio beams have a core/double-cone topology that exhibits the geometry of a pulsar's polar cap and polar fluxtube. Most pulsars have average profiles that stem from sightline traverses through this core/double-cone beam system, and quantitative analyses of profiles in these terms provide accurate and consistent estimates of the basic geometry (Rankin 1993a,b; and *e.g.*, Weisberg *et al.* 1999, 2004; Skrzypczak 2018)—that is, the magnetic colatitude α and the sightline impact parameter β. Of most interest recently has been studies of pulsars that seem not to conform to the core/double-cone model (*e.g.*, Mitra & Rankin 2010; Teixeira *et al.* 2016; Rankin 2017; Olszanski *et al.* 2019) on the basis of their average profiles. These and other studies show that many pulsars obscure their fundamental core/double-cone geometry by a variety of effects—*i.e.*, mode changing, component conflation or episodic illumination. Core and conal emission show distinct effects; for instance, drifting subpulses are exclusively conal, whereas height dependent aberration/retardation is seen only in cores. Core/double-cone structure has even been identified in a few millisecond pulsars for the first time (Rankin *et al.* 2017) as will be discussed below.

Extension to MSPs: Paradoxically, it had seemed for some time that most slow pulsars are well described in terms of the core/double-cone model, whereas virtually no MSP profiles were seemingly compatible with it. MSPs do have larger polar caps, shallower magnetospheres and weaker magnetic fields, so it had seemed possible that different effects were operative in their emission. However, we were recently able to show that four prominent MSPs do seem to have core/cone or core/double-cone profiles (Rankin *et al.* 2017) showing that emission processes in MSPs cannot be far different than those of normal pulsars.

Physical Emission-height Determinations Using Aberration/Retardation: The height of the radio emission region is fundamental to understanding its physics because both the plasma density and magnetic field strength vary strongly with distance from the pulsar. The above core/double-cone model provides consistent emission-height estimates of several hundred kilometers, but these are model dependent. Aberration/retardation provides a physical means of determining these heights (Blaskiewicz *et al.* 1991; Dyks *et al.* 2004), but only recently have procedures been developed to use this technique in a consistent and reliable manner. Emission-height measurements are now available for many pulsars (*e.g.*, Mitra *et al.* 2007; Mitra *et al.* 2016) and show that overall pulsar radio emission arises from altitudes of some 300-500 km.

Parent X-mode emission: Pulsar radio emission is highly linearly polarized, and this polarization provides fundamental clues to the emission processes. The nearly universal assumption that this emission would reflect a curvature-radiation process (*e.g.*, Ruderman & Sutherland 1975)—and thus be polarized parallel to the projected magnetic field in the emission region—was dashed by X-ray observations of the Vela 'arcs' that revealed the pulsar's rotation-axis orientation (Helfand *et al.* 2001). This showed that the pulsar's linearly polarized radio emission was mainly oriented perpendicular to the magnetic field (Johnston *et al.* 2006) and further that the proper motions of many pulsars were aligned $\parallel$ or $\perp$ to the projected rotation-axis direction Ω on the sky (Johnston *et al.* 2007; Rankin 2007). This work has been extended to pulsars with dominant core radiation to show that virtually all core emission is polarized $\perp$ to Ω and thus represents the extraordinary (X) propagation mode (Rankin 2015). This also shows that the supernova "kicks" responsible for pulsars' large space velocities and proper motions are mostly oriented parallel to Ω. Pulsar radiation must therefore reflect a dense-plasma process.

Radiation below the plasma frequency: This counter-intuitive property of pulsar radio emission now seems to obtain. Physical emission-height measurements facilitate modeling of the specific conditions within emission regions, and these in turn show that the radiation frequency is less or much less than both the plasma and cyclotron frequencies (*e.g.*, Mitra *et al.* 2016). A major theoretical question for years has been explaining how the radio emission could escape from a dense plasma magnetosphere, and indeed observational analyses now strongly reiterate that this is a major problem. However, X-mode radiation would have an easier time escaping compared to O-mode radiation that is strongly absorbed.

Conditions for backflow heating and thermal X-ray emission: Some normal pulsars emit thermal X-rays from small regions of their polar caps and others do not. Given that electric fields above the polar caps accelerate one sign of charge outward and the other downward, simultaneous radio /X-ray observations provide a means of studying the backflow heating produced by one species and the radio emission from the other. Radio/X-ray pulsars with two states or "modes"—such as B0943+10, B1822–09 and B0823+26—are very useful for studies to show the physical processes behind the modal changes (Hermsen *et al*. 2013, 2017, 2018).

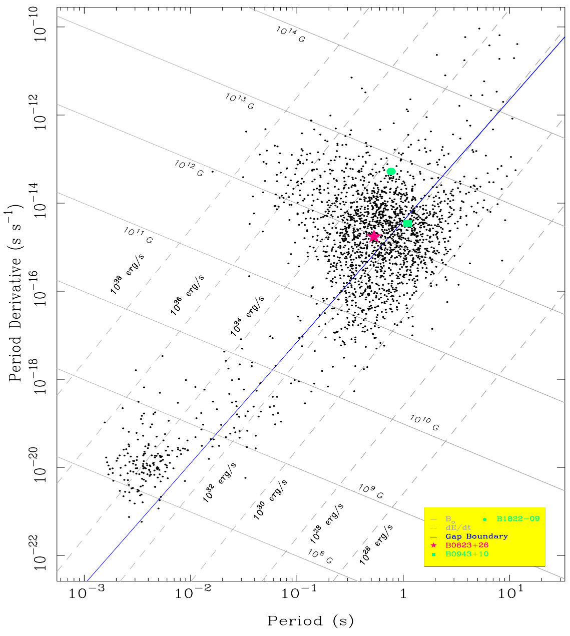

Fig. 1— P-$\dot{P}$ diagram showing the transition between 2-D and 3-D polar cap configurations. Notice that pulsars B0823+26 and B0943+10 both fall near this transition line—whereas pulsar B1822–09 falls well to the left of it. The magnitudes of surface magnetic field and spindown-energy loss rate $\dot{E}$ are also shown.

Core and conal, hot/cold types of polar caps: It has long been clear that the pulsar population divides into pulsars that are core-radiation dominated and those that emit mostly conal radiation. A new radio/X-ray study of pulsar B0823+26 shows how profound this difference is. Its bright radio mode also emits thermal X-rays (Hermsen *et al*. 2018), while its weak mode does not. Further, its bright mode emission is largely core radiation, whereas its 100-times fainter weak mode is mainly conal radiation (Rankin *et al*. 2019). The pulsar lies on the boundary between pulsars with core- and conal dominated emission (Rankin 1993a,b) in terms $B_{12}/P^2 > 2.5$, which in turn corresponds to a spindown-energy loss rate $\dot{E}$ of some $10^{32.5}$ ergs/s. Basu *et al*. (2017, 2019) also find a clear boundary in the drift modulation properties of pulsars at an $\dot{E}$ of some 10^{32} ergs/s.

Timokhin & Harding (2015) now show that pulsars generate the required pair plasma for emission in one of two polar cap configurations. For the younger, energetic half of the pulsar population, pairs are created above a flat (2-D) polar cap in a uniform (1-D) gap potential large enough to produce copious backflow heating. For older pulsars, however, the polar cap becomes cup shaped with a (2-D) gap potential and greatly reduced backflow heating. The boundary line between the flat and cup-shaped polar cap configurations—and thus pulsar populations—is plotted on the period period-derivative (P-$\dot{P}$) diagram of Figure 1, so that the energetic pulsars are to the top left and the slow ones to the bottom right.

An Observational/Theoretical Foundation for Pulsar Emission Physics:

A model of pulsar radio emission wherein the emitted frequency is lower than both the plasma and cyclotron frequencies ($\nu_{obs} < \nu_{plas} < \nu_{cycl}$) in the emitting region has been developed by

Melikidze, Gil & Pataraya 2000, Gil, Lyubarskii & Melikize 2004, Mitra, Gil & Melikize 2009, and Melikidze, Mitra & Gil 2014. The only instability known to operate at radio emission heights below 10% or so of the light-cylinder radius is the two-stream instability. Inner vacuum gap (IVG) non-stationary discharges lead to the generation of secondary plasma clouds with slight spreads in their particle velocities. The faster and slower velocities of successive clouds overlap at radio-emission heights to trigger strong Langmuir turbulence in the secondary plasma, which can become modulationally unstable. Melikidze *et al.* (2000) demonstrated that the non-linear growth of the modulational instability can lead to formation of charged solitons which are capable of emitting curvature radiation in curved magnetic fields. The soliton size must be larger than the linear Langmuir wave, and to maintain coherence the emission should have wavelengths larger than the soliton size, or in other words $\nu_{obs} < \nu_{plas}$ as observed. In order to radiate such solitons must of course be charged, and appropriate solutions of the Schroedinger equation were unknown until recently. However, Lakoba *et al.* (2018) have modeled such a solution to show how highly non-linear turbulence could generate such charged entities.

Promises of the Coming Decade:

Understanding the Plasma Physics of Pulsar Emissivity: Pulsar-emission studies are poised to connect the longstanding emission problem to plasma physics and indeed to expand knowledge of plasma physics to conditions of extreme non-linear turbulence. Many issues remain to be understood even within the coherent foundation sketched above: What is the plasma-physical origin of the distinction between core and conal radiation? How does the radio emission escape, and in particular how can we understand the observed O-mode radiation? How can circular polarization be understood, given the very different emission conditions of the O and X modes? Pulsar radiation, observed with the most sensitive instruments available offer nothing less than a unique laboratory for the study of plasma in extreme conditions, and while most effects involve only the pair plasma, ionic effects may be observable under certain conditions.

Delineating How the Pulsar Magnetosphere is "Wired": Abundant observational evidence now shows the interconnections between different parts of a pulsar's magnetosphere. The polar cap "accelerator" is only one such region; the two such regions show strong connections; and there is increasing evidence for radio and X-ray emission from high altitude "outer gap" regions within the magnetosphere. PiC simulations of pair plasma generation within the polar cap region (*e.g.*, Spitkovsky 2011, 2017), while exciting, do not yet extend to radio emission heights, nor do the models of pulsar wind acceleration regions outside the light cylinder yet assist in understanding the magnetic field configurations in the high magnetosphere. The legacy of early pulsar models viewing the polar cap region as completely dominant, though now obviously incorrect observationally, is still with us, and the future lies with conceptions that connect the bottom, middle, top and outside regions into a connected whole system.

Understanding MSP Emission: MSPs, though of primary importance for a variety of reasons have proven difficult to understand in terms of slow pulsar models. Many or most may be different due to the magnetic field destruction that occurs during accretion-driven spinup (*e.g.*, Ruderman 1991). Some, however, clearly exhibit properties that are parallel and compatible with those of slow pulsars (Rankin *et al.* 2017), and it is crucial to determine just why this is so. Efforts to understand the probably more complex magnetic field configurations of many MSPs will in turn provide foundation of investigating their emission characteristics. Most MSPs cannot be studied in the same manner as slow pulsars because even the brightest observed with the most sensitive instruments give inadequate signal levels, so little is yet known about how their dynamics and modulations affect their timing stability. Therefore, a hybrid approach is needed to better understand the physical issues that contribute to or limit their timing precision.

Giant pulses (GPs) and transients: While something of the physics behind the normal emission of slow pulsars is emerging, we as yet understand little about how some pulsars generate short occasional bursts of extremely intense emission—*e.g.*, the Crab pulsar's giant pulses, GPs in MSPs, RRATs or perhaps fast radio bursts (FRBs). Extensive studies of Crab pulsar GPs and from the first MSP B1937+21 revealed characteristics that are different from other kinds of single pulse emission (see review by Knight 2006). High time resolution observations revealed very short pulse widths, going down into the nanoseconds range (less than 0.4 ns in the case of the Crab pulsar, Hankins & Eilek 2007; less than 15 ns in the case of PSR B1937+21, Soglasnov *et al*. 2004). In spite of the fact that there is currently no uniform approach for the generation of giant pulses, recent advances in high performance computing show that kinetic simulations of complete pulsar magnetospheres can be carried out (Cerutti 2018). PiC simulations built by different groups agree that an equatorial current sheet forms just outside the light cylinder. In these sheets the relativistic reconnection converts magnetic field energy into plasma flows and highly energetic particles. The reconnection sites are by nature localized to small length scales and the reconnection bursts can fade in and out on time scales of the light travel time across such small regions. This also allows us to explain the existence of very short and very bright radio pulses. High time resolution observations and the capability of collecting a large number of single pulses are therefore crucial factors in unraveling the potential emission mechanism of the observed single pulses and in providing a deeper understanding of emission sites.

These lines of research are not only enriching to pulsar astronomy, but would also allows probe kinetic plasma physics. Reconnection in particular is of widespread astrophysical importance, and in a parameter regime not accessible by laboratory experiments. The comparison with kinetic simulations can also improve the fidelity of and the confidence in the corresponding numerical models which are also applied to other scenarios in space physics and astrophysics.

Observational Requirements:

- **Large collecting areas** allow us to do accurate polarimetry, see microstructure, and single pulses from fainter objects; etc.
- **Wider bandwidths**: more sensitivity; better measurements of dispersive effects (such as the Crab pulsar's giant pulse component-to-component DM variations) ; pulse profile evolution with frequency mapping to determine emission heights
- **Excellent polarization fidelity and calibration**: Important since polarization provides the best constraints on emission geometries.
- **High cadence, high sensitivity monitoring**: For many pulsar phenomena (*e.g.*, mode changes, RRATs), frequent monitoring is necessary to understand different emission behaviors and how they are correlated with timing/spin-down influences, quasi-periodicities underlying the emission—as well as simultaneous high-energy observations with NICER and future sensitive X-ray and gamma-ray telescopes.
- **Pulsar surveys**: to provide a larger census of pulsars with unusual emission properties. Statistics are needed to extrapolate from the particular to the general.

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