Phenomenology and the Problem of Pulsar Emission

The microwave radiation of pulsars is not well understood. Pulsar emission has been studied extensively by both observers and theorists, but the interaction between the theory and the observations has frequently been limited and unconstructive. We discuss the detailed phenomenological model of pulsar emission which has been developed from the observations. Through the catalytic effect of phenomenology, we believe, a comprehensive physical theory of pulsar emission can be constructed.

Key Words: *pulsars, radiation mechanisms, magnetospheres*

AN ADOLESCENT SCIENCE

In astronomy, we know the cosmos through its radiation. When we comprehend the detailed physical circumstances that prompt the emission of radiation by cosmic entities, we usually regard them as understood with some clarity. Why pulsars emit electromagnetic radiation, however, is not well understood.

Our conception that pulsars are rotating neutron stars has developed primarily through dynamical and structural considerations. The most fundamental observed properties of pulsar signals, their precise periodicity and secular spindown—as interpreted by physical theory—apparently exclude all other possibilities. "We know why pulsars pulse," as Sandra Faber remarked a few years ago, "but not why they shine."[1] While we have learned a great deal about pulsars in general, we paradoxically understand very

---

Comments Astrophys.
1989, Vol. 14, No. 1, pp. 1–10
Reprints available directly from the publisher
Photocopying permitted by license only

little about the sole agency through which we observe them—their radiation.

Neither observers nor theorists have been idle in the twenty years since the fortuitous discovery of pulsars. Observers worldwide have used an array of instruments and techniques to study pulsar radiation—to the point that it is now difficult to conduct a "fresh" observation. Theorists, for their part, have constructed detailed physical models of neutron stars and their magnetospheric emission, and they now speak with the confidence and caution that several cycles of elaboration and critique provide.

Nevertheless, the phenomenon of pulsar radiation is still poorly understood. If the hallmark of a "mature" science is the integrative and critical interaction of theory and observations, the field of pulsar emission remains distinctly adolescent. The respective observational and theoretical subfields have for some years now pursued almost independent development. Indeed, there is now so little interaction that pulsar theory and pulsar observations have virtually become irrelevant to each other.

PULSAR THEORY AND THE INDIVIDUAL PULSAR

A great deal of cogent theoretical work on pulsar emission and beaming is available in the literature. Physical models of their magnetospheric structure and emission regions have been developed to a high state of sophistication by a number of different theorists. In fact, certain magnetospheric emission theories *are* in general agreement with many features of the observations in an overall ensemble sense,[2] despite their known defects (such as the lack of a return current). Nevertheless, no one would now claim that we understand the physical principles of pulsar emission.

Magnetospheric theories are not automatically pulsar theories, however, any more than polytropes are models of stars. Severe difficulties arise in applying current theories to individual stars. Because individual pulsars are highly varied in their observed characteristics, it has not been at all clear just where and how the existing theory is applicable. Quantitative agreement of theory is poor with even the average emission characteristics of any individual pulsar, and there is as yet no theoretical consensus on primary qualitative features of individual-pulse sequences such as drifting subpulses, pulse nulling, profile or polarization mode-changing, and microstructure. When applied to specific individual stars, then, even the most successful physical theories provide few details or verifiable expectations.

In the concrete, practical terms of the observer, we thus have a theory of *pulsars*, but no remotely adequate theory of the individual stars which are necessarily the objects of our study. Or said differently, we have a theoretical *myth* of pulsar emission—that is, a wise but unverified tale—rather than an observationally grounded theory.

This is surely not to fault the theorists' efforts: The complexity and diversity of the observations are daunting, with the result that theorists have had little alternative to first principles as a standpoint for theory building. And the techniques of theoretical astrophysics are simply incapable of anticipating all the manifold phenomena of natural actuality.

Indeed, the history of our field suggests that we are simply not going to find that keystone fact or principle that renders everything else comprehensible. Illuminations then must necessarily come through integrative approaches that consider the full range of observational circumstances with which pulsars present us. In this sense, the pulsar emission problem is fully organic. We cannot fully understand an organism by studying its lung or brain or even its DNA, but once we have studied all these functions sufficiently, we can begin to understand the integrity of the overall organism although our comprehension of its individual organs may still be poor.

REVITALIZING A MORIBUND SCIENCE

What is to be done? Pulsar observers and theorists must again begin to work effectively together if we are to deepen our joint understanding of the pulsar phenomenon. Mere exhortations to this effect will not suffice, however. The objective conditions which prompted the divorce of our subfields must be confronted. For most of a decade we really have had little to say to each other; we have lost our long focus on the pulsar emission phenomenon, as each group has fixated myopically on the technical problems of their respective theories and observations. We have been reluctant to admit, to ourselves or to each other, that these efforts are unlikely to reward us with real understanding anytime soon.

Our impasse is not a new one. A century ago stellar classification facilitated the beginnings of a physical understanding of stars, and we are now in a similar position with regard to pulsars. We are only beginning to delineate those physical features around which the multiplicity of observations can be organized and classified. We are just learning to distinguish what is general and essential from what is specific and orientational (or evolutionary), what is physical from what is geometrical.

Nonetheless, observers worldwide have a well developed consensus on the primary phenomena of pulsar emission. We do not suggest that the observers are all of one mind—nor do we assume that this picture is necessarily correct physically. But a qualitative interpretation emerges from the observations which is more comprehensive and internally consistent than perhaps most theorists realize.

We are thus optimistic that profound insights into the pulsar emission problem can follow over the next several years from a new integration of the observational and theoretical approaches. In short, we are advocating phenomenology as a means of repairing the divorce of our field. If pulsar observers and theorists are not interacting constructively, let us not rudely force them together; let us rather take active steps to catalyze this essential synthesis.

Healthy new development on the pulsar emission problem necessarily depends on the systematic elaboration of the synthetic model inherent in the observations. To be effective, this empirical model must function both as a detailed and critical summary of the existing observations and as a foundation for theory building. It is important to note, however, that this model need not be physically or literally correct in itself.

Observers are only now beginning to provide the catalogue and contextual description of pulsar phenomenology on which comprehensive theory building must be grounded. In the concluding sections, we briefly review the empirical model that now exists, and make some suggestions about the directions of future work.

CLASSIFICATION AS A PHENOMENOLOGICAL TECHNIQUE

Classification of pulsar characteristics has long been recognized as a potential source of physical insight into the emission process. Inspired by Radhakrishnan and Cooke's hollow-cone emission model,[3] Huguenin *et al.*[4] first proposed a classification scheme for average profiles, and Backer[5] then greatly elaborated it. The latest system—which provides a starting point for the synthetic model or "theory" discussed above—builds directly upon these early ideas. It considers the morphological characteristics of *polarized* average profiles with particular attention to their formal *evolution* with radio frequency[6] as well as certain pulse-sequence properties, mode changing, drifting subpulses and pulse nulling.[7]

Two distinct classes of "single" profile are delineated: one typically broadens and bifurcates at low frequency, whereas the second adds pairs of adjacent components (or "outriders") at high frequency.

The first, the "conal" single (or $\mathbf{S}_d$) species is so denoted because of its close relation to the double (**D**) profiles. Both have polarization characteristics which are most simply explained by a hollow-conical emission zone (or "beam") which spreads weakly at low frequency. The conal double (**D**) profiles then reflect a central traverse of our line of sight through this conical emission pattern, and the $\mathbf{S}_d$ stars a tangential traverse, which becomes more central at low frequency as the cone grows larger.

In contrast, the "core" single (or $\mathbf{S}_t$) species is found to exhibit properties similar to those encountered in the central component of triple (**T**) profiles. Both often exhibit strong circular polarization, sometimes of symmetrically alternating sense. The leading and trailing components of the triple profiles have properties very similar to the double species, suggesting that the central component represents a "core" beam within the hollow cone.

Finally, "multiple" or five-component (**M**) profiles are observed which exhibit a central core component and a double set of conal outriders.

These properties provide the basis for a classification system in which the various species represent homogeneous groups of stars with similar physical, evolutionary, or orientational characteristics. Some 60% of the observed pulsar population have core-dominated profiles. Core emission, and especially the triple profile, emerge as most generally prototypical of pulsar emission. And the distinct polarization signatures of the outriding conal components and the quasi-axial core component of triple profiles suggest that two different physical mechanisms are involved in pulsar emission.

The isolated core components of stars with core single ($\mathbf{S}_t$) profiles exhibit little ordered modulation, nor do they null or show evidence of any sort of mode changing. Many have featureless ("white") fluctuation spectra, whereas others display low-frequency ("red") features (15–50 periods/cycle) with which no orderly drift is apparently associated. Similarly, the core components in triple (**T**), double (**D**; the "bridge" or "saddle"), and multiple (**M**) profiles also show these longitude-stationary, low-frequency fluctuations.

Drifting subpulses are then an exclusively conal phenomenon. Systematic subpulse modulation (P_3 2–15 periods/cycle) is associated with the conal components of stars with **D**, **T** and **M** profiles, but progressive, orderly drifting is observed only in conal single ($\mathbf{S}_d$) stars—that is, stars where the line of sight has a nearly tangential trajectory. Morover, the average P_3 values of conal single and double pulsars are identical, again suggesting that these species are orientation-specific manifestations of a single physical configuration.

Mode changing and nulling are associated with both core and conal emission, and thereby provide important clues to the relationship between them. Mode changing is most readily identified in stars with **T** and **M** profiles and manifests itself as a reorganization of the conal emission components about the profile's central core component. By their joint effect on both main-pulse and interpulse emission, mode changing and nulling suggest magnetospheric changes of global extent.

That all pulsars evidently emit a core beam suggests its primacy. The relatively small angular width of core components argues that they are generated very close to the stellar surface. Indeed, their circular polarization requires that the core be emitted by a population of low gamma particles in a region where the circular symmetry of the hollow cone is violated—again, almost certainly close above the polar cap.[8] The conal radiation then comes from greater heights and probably depends upon primary processes in the core to excite it.

We then have the following evolutionary picture: the core single (**S**$_t$) stars are by far the youngest, both in terms of spindown age and galactic scale height. Triple (**T**) stars are of intermediate age, and the remaining species (**S**$_d$, **D** and **M**) are all relatively old. These young **S**$_t$ pulsars emit a bright, steady core beam. As they age, their conal emission becomes competitive at ever lower frequencies (**T** stars), and the emission of the older species is primarily conal throughout their spectrum.

These results then provide the beginnings of a synthetic empirical model or "empirical theory" of pulsar emission—a comprehensive system for organizing the observations and gaining the physical insight needed to bring the theory and observations into constructive and critical contact. In viewing pulsar radiation as an amalgam of its core and conal constituents, we can begin delineating the geometry and evolution of the pulsar radiation processes. An understanding of beam topology promises to make existing pulsar theory applicable to individual stars, which in turn will facilitate the critical examination and revision of this theory.

TOWARD A SELF-CONSISTENT EMPIRICAL MODEL OF PULSAR EMISSION

If a phenomenological model presently represents our best approach to the pulsar emission problem, as we have argued above, then certain types of new observational, analytical, and theoretical work will be particularly helpful.

Observations bearing on the geometry of the emission beam are certainly one key to connecting the theory and the observations. We refer to the pioneering studies of Narayan and Vivekanand[9] as well as some of Smith's[10] and Gil's[11] work. Interpulse and off-pulse emission studies are also very useful,[12] and we hope that the exemplary interferometric work of Perry and Lyne[13] will be pursued and extended. Similarly, Hankins[14] has beautifully delineated the angular form of profile wings.

Several groups have also carefully studied the time-alignment of average profiles over wide frequency ranges.[15] These observations are intended to elucidate the geometry of the emitting region, and further work along these lines may well settle pivotal issues such as the extent of field-line sweepback and the importance of quadrupole fields near the stellar surface.

We hope that observers will consider the evidence and implications of the empirical model outlined above. At the outset, all existing observational evidence must be used to critique the conclusions drawn so far. But to the extent that the model does provide a correct summary and useful framework for the description of the observations, we hope that new work will incorporate it in a critical and constructive manner. As an example we note that Hankins and Wolszczan[16] recently extended the model by giving observational evidence for a new species of profile.

Analytically, much of the work in the literature is now of limited utility because the techniques used fail to distinguish between regions of core and conal emission. In a triple profile, for instance, it makes little sense to apply the usual Fourier transform technique of drift analysis across the entire profile; we know that conal components often exhibit a periodic fluctuation or P_3, core components almost never. We thus require entirely new techniques to unravel the characteristics of core emission. The brilliant study of the Vela pulsar by Krishnamohan and Downs[17] is very promising here as is also Wolszczan *et al.*'s new study[18] of pulsar 0611+22.

Similarly, it makes little sense to produce statistics on an entire pulsar population which includes highly dissimilar groups. If anything is true about the empirical model outlined above, it is that pulsars fall into species or classes. Once pulsars are divided, however, into species-homogeneous groups, statistical methods may very rapidly point the way to astrophysical insights.

Finally, we hope that theorists will also carefully consider the observational model and that it will indeed provide an observationally comprehensive foundation for building a physical theory of pulsar emission.

We all wish to construct a broadly based theory that joins the full spectrum of pulsar observations with the totality of astrophysical theory. In a word, we are seeking an organic theory, not one which is fully formed by quarrying the observations for a few keystone facts.

Throughout this process, theorists must give the model the kind of criticism they are best able to give, that is, to insure that it is both physical and internally consistent. Several recent studies have moved from close observational scrutiny to physical argument in just this manner; for example, Filippenko and Radhakrishnan[19] in their consideration of subpulse memory during nulls and Björnsson[20] in his discussion of polarization. In the near future, we hope that many such efforts will lead to the theory we are seeking.

JOANNA M. RANKIN
Department of Physics,
University of Vermont,
Burlington, Vermont 05405

JANUSZ A. GIL
Institute of Physics,
Pedagogical University,
55-069 Zièlona Gòra,
Poland

References

1. Quoted in J. Arons, Space Sci. Rev. **24**, 437 (1979).
2. For example, M. A. Ruderman and P. G. Sutherland, Ap. J. **196**, 51 (1975), and V. S. Beskin, A. V. Gurevich and Ya. N. Istomin, Sov. Phys. Usp. **29**, 946 (1986).
3. V. Radhakrishnan and D. J. Cooke, Ap. Lett. **3**, 225 (1969), and M. M. Komesaroff, Nature **225**, 612 (1970).
4. G. R. Huguenin, R. N. Manchester and J. H. Taylor, Ap. J. **169**, 97 (1971).
5. D. C. Backer, Ap. J. **209**, 895 (1976).
6. J. M. Rankin, Ap. J. **274**, 333 (1983a), Ap. J. **274**, 359 (1983b).
7. J. M. Rankin, Ap. J. **301**, 901 (1986).
8. V. Radhakrishnan and J. M. Rankin, Ap. J. (1988), in press, and J. M. Rankin, Ap. J. (1988), F. C. Michel, Ap. J. **323**, 822 (1987)
9. R. Narayan and M. Vivekanand, Astron. Astrophys. **113**, L3 (1980), Astron. Astrophys. **122**, 45 (1983a), and Ap. J. **274**, 771 (1983b).
10. F. G. Smith, M.N.R.A.S. **286**, 729 (1985).
11. J. A. Gil, Ap J. **127**, 262 (1983), Ap. J. **299**, 134 (1985), and Ap. J. **309**, 609 (1986).
12. For example, T. H. Hankins and L. A. Fowler, Ap. J. **304**, 256 (1986).
13. T. E. Perry and A. G. Lyne, M.N.R.A.S. **212**, 489 (1985).
14. T. H. Hankins (1988), private communication.
15. J. G. Davies, A. G. Lyne, F. G. Smith, V. A. Izvekova, A. D. Kuz'min and Yu. P. Shitov, M.N.R.A.S. **211**, 57 (1984), A. D. Kuz'min, V. M. Malofeev, V. A. Izvekova, W. Sieber and R. Wielebinski, Astron. Astrophys. **161**, 183 (1986), and T. H. Hankins and B. J. Rickett, Ap. J. **311**, 684 (1986).
16. T. H. Hankins and A. Wolszczan, Ap. J. **318**, 410 (1987).

17. S. Krishnamohan and G. S. Downs, Ap. J. **265**, 372 (1983).
18. A. Wolszczan, J. M. Cordes and L. A. Nowakowski (1988), preprint.
19. A. V. Filippenko and V. Radhakrishnan, Ap. J. **263**, 828 (1982).
20. C.-I. Björnsson, Ap. J. **277**, 374 (1984).