The Rest of the Story: Radio Pulsars and IR through $\gamma$-ray Emission

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Abstract. Recent observations have detected a number of young pulsars from the power peak in the $\gamma$-ray band to the incoherent photon peak in the optical/IR. We have made progress on the multiwavelength phenomenology of pulsar emission and beaming, but a wide variation of light curves between different objects and different energy bands makes the full story complex. I sketch here a ‘Unified Model’ of pulsar beaming and summarize the radiation mechanisms and their interplay in outer magnetosphere models of pulsar high energy emission.

1. Introduction

There has been much recent progress in detecting and modeling high energy ($\sim 10^9 - 10^7$eV) magnetospheric emission from spin powered pulsars. I will not discuss the coherent radio pulsations which provide the primary channel for pulsar discovery and dynamics/evolutionary studies (as our three honorees and their colleagues continue to teach us). The mechanism producing the radio has been very difficult to reconstruct (however see Gupta, Jenet, Melrose, these proceedings), but a well established phenomenology suggests that this is relatively low altitude emission above the magnetic polar cap. I will also only briefly describe the soft X-ray thermal emission from neutron star surfaces (for a recent review, see Pavlov, Zavlin & Sanwal 2002). Thus we focus here on the incoherent, non-thermal radiation, which is the product of magnetosphere gaps.

This radiation is highly pulsed and, hence, highly beamed. With pulse profiles having characteristic component widths $< 0.1$ in phase and the cusp of the Crab optical pulse extending over no more than $\delta \phi \sim 0.01$ we must have radiation dominated by $e^\pm$ with $N \geq 10 - 100$. We also must have relatively narrow radiating zones in the magnetosphere, where again the component widths restrict us to a few percent of the open field line volume.

2. Light Curves

To set the stage I plot a compilation of light curves from many sources, updated from Romani (2000). I have placed the closest approach of the radio pole at phase 0 and 1.5 pulse periods are shown for clarity. For Geminga the phase is set by the predicted outer magnetosphere pulses matched to the $\gamma$-ray. For PSR B1055-52, the radio polarization indicates that the pulse at $\phi = 0$ passes closest
to the line of sight; the interpulse is apparently stronger. In several cases the source has only an unpulsed detection; these are shown as flat lines.

In the outer magnetosphere picture (Morini 1983; Cheng, Ho & Ruderman 1986) the light curves displayed in this way make a fairly coherent set. The GeV pulses have double peaks which come from the pole at $\phi = 0.5$ and are beamed toward the spin equator ($\zeta = \pi/2$). Aberration shifts the peaks forward in phase and pulsars viewed at smaller $\zeta$ have a smaller GeV peak separation; the model provides a quantitative match to the observed profiles (Romani & Yadigaroglu 1995). The non-thermal optical and hard X-ray emissions lie largely within the $\gamma$-ray peaks and arise at lower altitudes, close to the null charge surface that serves as the inner boundary of the acceleration gap. The interpretation of the soft X-ray emission is complicated by the presence of thermal surface flux, which itself may be pulsed if the surface temperature is non-uniform. The radio emission, being more tightly beamed, shows narrow pulses covering a small portion of the sky. The exception to this picture is the Crab, whose strong non-thermal accelerators seem to keep pair production rates and particle densities so high that all emissions (radio-$\gamma$-ray) are dominated by the outer gap zone. This interpretation has encouraging successes, but is not unique. In particular, Harding and colleagues (e.g. Daugherty and Harding 1996) have described an aligned rotator polar cap model that can produce high energy hollow cone emission.

3. Physical Processes

Light curves locate the position of the radiation zones, but spectral energy distributions (SEDs) are the key to identifying the radiation processes. Thompson (1998) has compiled a useful set of broad-band SEDs for the young pulsars. The most striking feature of these $\nu F_\nu$ plots is the power peak at $> 100\text{MeV}$, with a rollover at several GeV. This component clearly arises from the radiati- reaction limit process for the primary magnetosphere $e^\pm$. Most recent models (e.g. Daugherty & Harding 1996, Romani 1996, Zhang & Cheng 1997, Hirotani & Shibata 1999) conclude that the particles are curvature radiation limited.

At present, outer magnetosphere spectral computations are more complex and less complete than near-surface polar cap models. The key difference is that at the polar cap $\gamma B \rightarrow e^\pm$ provides an efficient source of pair plasma to limit the gap potentials and provide the radiating plasma. Moreover, in modern polar cap models (Harding, Muslimov & Zhang 2002) the acceleration field is set by general relativistic frame dragging, providing some insulation from the details of gap electrodynamics. In contrast, outer gap models produce pairs via $\gamma - \gamma$, and rely on the charge gaps themselves to provide the acceleration field. In fact in some pulsars the soft target photons are provided by the gap as well. In this way gap luminosity and spectrum computations are (at least) doubly recursive (Figure 2). In effect, outer magnetosphere gaps are self-limiting: to provide the relatively large GeV efficiencies observed for some pulsars from curvature radiation of $\Gamma \sim 10^{7.5} e^\pm$ primaries the gaps must by definition be barely closed. Thus computations are difficult and to get the details right will likely require dynamic 3-D gap models, well beyond the state of the art today.

In brief, acceleration of the primary electrons is limited by curvature radiation reaction (CR). These curvature photons convert on soft thermal ($kT$)
or synchrotron (Sy) photons to make the pairs which limit the growth of the acceleration gap. The thermal emission produced by the general star surface and the pair-heated polar cap zone may dominate the target soft photons for Vela-like pulsars, but for younger pulsars and for MSP the synchrotron component should control the gaps. This synchrotron emission comes from cooling of the initial pitch angle of the $\gamma - \gamma$ pairs. Aside from the UV/soft X-ray band it dominates the spectrum in the MeV-eV range. For Crab-like pulsars this emission may be self-absorbed at sub-eV energies. There may also be IR-UV spectral features related to the local cyclotron energy; in general we expect a peak in the photon number flux in the optical/IR range. Interestingly, it seems likely that this radiation represents an unusual low pitch angle $\Psi < 1/\Gamma$ regime of synchrotron emission (Cruzius-Wätzel, Kunzl & Lesch 2001). The presence of these soft photons guarantees some Inverse Compton Scattering emission at multi-TeV energies, however the IR spectral break of the synchrotron component and the substantial beaming of this low energy flux greatly reduce the ICS optical depth and make computation of the ICS flux difficult.

Phase-resolved measurements of the spectral breaks provide the best test of these models. For example, while polar cap models predict a very abrupt GeV turnover from $\gamma - B$ absorption, in the outer magnetosphere the GeV cutoff is the more gradual rollover of the primary curvature spectrum for $\Gamma \sim 10^{7.5} e^\pm$. Existing EGRET data suggest mild (exponential) cut-offs for Vela and Geminga, but a definitive answer requires GLAST. The peak of the synchrotron spectrum is at $E \sim 0.5B_{12}^{5/2}(P/0.1s)^{-13/2}(r_i/0.1r_{LC})^{-2}\text{MeV}$ for $r_i \sim 0.1r_{LC}$ near the null-charge surface, where $\Psi \sim r_i/r_{LC}$ induced by aberration. Measurement of this component and its variation with pulse phase thus probes both the birth-site of the $\gamma - \gamma$ pairs and the field in the emission zone. Similarly measurement of the optical/IR spectral breaks (and polarization behavior) can probe the cooled population of $e^\pm$. However, except for Crab-like pulsars, this will be a challenge, as the emission is faint, typically $m_V > 25$ even for the nearest young objects.

4. A ‘Unified’ Beaming Model

Of course, the gap emissions described above are highly beamed, so the observed SED of a young, $\gamma$-ray active pulsar will depend on the magnetic inclinations $\alpha$ and Earth viewing angle $\zeta$. To illustrate how viewing geometry affects the source appearance, I present a ‘unified model’, in the spirit of the AGN unified model. There are four main cases, illustrated in Figure 3. First, with large $\alpha \approx \zeta \gtrsim \pi/3$, the object is visible as a radio pulsar and the active gaps dominate the high energy flux. A nearly isotropic thermal component (possibly with pulsations from a hot polar cap) is also visible. The bulk of the known $\gamma$-ray pulsars fall in this class, as the sample is highly biased to objects amenable to radio discovery. The other class of easily discovered, radio bright young pulsars has small $\alpha \approx \zeta$. For these objects the strong outer gap CR component will miss Earth. GeV emission may be present, but it will represent ‘off-pulse’ emission with fluxes a small $\lesssim 1\%$ fraction of that for the Vela-like objects. Evidence for such weak, more widely beamed flux comes from the low level gap emission seen for Crab and Vela through all pulse phases. One picture for such ‘Off-Beam’ emission in the polar cap scenario has been described by Harding & Zhang (2001). For
small \( \alpha \approx \zeta \) (e.g. PSR B0565+14) sources, the MeV synchrotron flux from the newly produced \( e^\pm \) with relatively large \( \Psi \) may still be visible. Not also that for this geometry, we expect to see \( \gamma \)-ray emission from near surface polar cap gaps, presumably with low flux.

For \( \alpha \ll \zeta \) neither the radio nor gap beams will be visible, although the neutron star can still be discovered via the nearly isotropic thermal emission. RX J1856-3754 provides a likely example of this geometry (Braje & Romani 2002). Finally when \( \zeta \) is appreciably larger than \( \alpha \), radio emission is not visible, but the non-thermal gap emission will be strong. Geminga is the archetype of this case. Since they lack radio pulses, we expect that the handful of such objects known today is much smaller than their true population.

Thus to understand individual SEDs, we need robust estimates of \( \alpha \) and \( \zeta \). The recent discoveries of equatorial tori in pulsar wind nebula (PWN) provide such estimates for the Crab and Vela pulsars. We have shown that even for fainter PWN useful constraints on \( \zeta \) can be obtained (Romani & Ng 2002). These measurements provide predictions of which pulsars will show bright non-thermal high energy emission and can also probe the relationship between neutron star linear and angular momenta (Lai, these proceedings).

5. Further Connections & Conclusions

While geometry offers a uniform interpretation of the phase-averaged SEDs of young neutron stars, as observation sensitivities increase, finer details in the pulse profiles and phase-resolved spectra provide continued challenges. For example Crab (Moffett & Hankins 1996) and Vela (Harding et al. 2002) multi-wavelength profile compilations show at least four components each. Clearly multiple regions are active in the pulsar magnetosphere. Of course, even if the bulk of the high energy emission is produced in the outer magnetosphere, some pairs and faint \( \gamma \)-rays associated with the radio-generating polar cap gaps must be present. [Mutual gap poisoning may prevent both being visible from the same pole; note that for outer gaps we automatically see the opposite pole in the radio.] It seems plausible that with the \( \sim 10^2 - 10^3 \times \) dynamic range available in the GLAST era, we may be able to identify \( \gamma \) activity from both gaps.

One further radio-high energy connection deserves comment. The Crab giant radio pulses must, of course, be a high altitude phenomenon. The discovery of similar pulses in millisecond pulsars, apparently aligned with strong narrow X-ray components, suggests a more general connection between such pulses and high energy emission (Romani & Johnston 2001, Johnston, these proceedings). With this zoo of behaviors, clearly the high-energy/radio connection will keep observers and theorists busy for some time to come.

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Figure 1. Young pulsar light curves (from many literature sources).

Figure 2. Physical processes in outer magnetosphere gaps.
Figure 3. Phase averaged pulsar SEDS. The line of sight is indicated in the magnetosphere images to the right (black lines).