Part 5
High Energy Phenomena

Section B
X- and gamma-ray emission

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Recent Gamma-Ray Observations

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Abstract. With the results from the Compton Gamma Ray Observatory, multiwavelength pulsar studies have taken on new importance.

1. Introduction

The Compton Gamma Ray Observatory (*Compton*) is the first comprehensive satellite mission to survey the sky at photon energies from about 100 keV to over 10 GeV. Among the wide range of results from the four instruments on *Compton* (see the recent review by Shrader and Gehrels, 1995) are the identifications of at least seven gamma-ray pulsars: Crab, PSR B1509−58, Vela, PSR B1706−44, PSR B1951+32, Geminga, and PSR B1055−52. These results have stimulated theoretical work on gamma-ray pulsars (e.g. Sturner and Dermer, 1994; Daugherty and Harding, 1996; Romani and Yadigaroglu, 1995; Harding, 1996). This article reviews the observational status and implications of gamma-ray pulsars independent of any particular theoretical model.

2. Gamma Ray Pulsars and Radio Pulsars

The quantity $\dot{E}/4\pi d^2$ (where d is the distance) is a useful measure of gamma-ray pulsar observability. All six known pulsars with $\dot{E}/4\pi d^2 > 3\times10^{-9}$ erg/cm^{2}s are gamma-ray pulsars. Five of these are also radio pulsars, implying a strong overlap between the radio and gamma-ray beams. PSR B1055−52, the seventh gamma-ray pulsar, is the exception. At least a dozen pulsars (more if the millisecond pulsars are included) have higher values of $\dot{E}/4\pi d^2$ without showing strong evidence of gamma-ray pulsation. Whether PSR B1055−52 is unusually efficient in producing gamma rays or has a preferred beaming geometry is an open question.

There are also "candidate" gamma-ray pulsars, all of which have $\dot{E}/4\pi d^2$ close to or larger than the value for PSR B1055−52. At present, none of these are considered as definite detections. PSR B0355+54 (Thompson et al., 1994), PSR B0656+14 (Ramanamurthy et al., 1996) and PSR J0631+10 (Zepka et al., 1996) all have gamma-ray light curves that are statistically improbable for a single trial, but they are part of a large sample of pulsars which have been examined for gamma-ray pulsation. PSR B1046-58 and PSR B1853+01 are radio pulsars positionally consistent with gamma-ray sources (though the error boxes are large), also having $\dot{E}/4\pi d^2$ in the same range as the known gamma ray

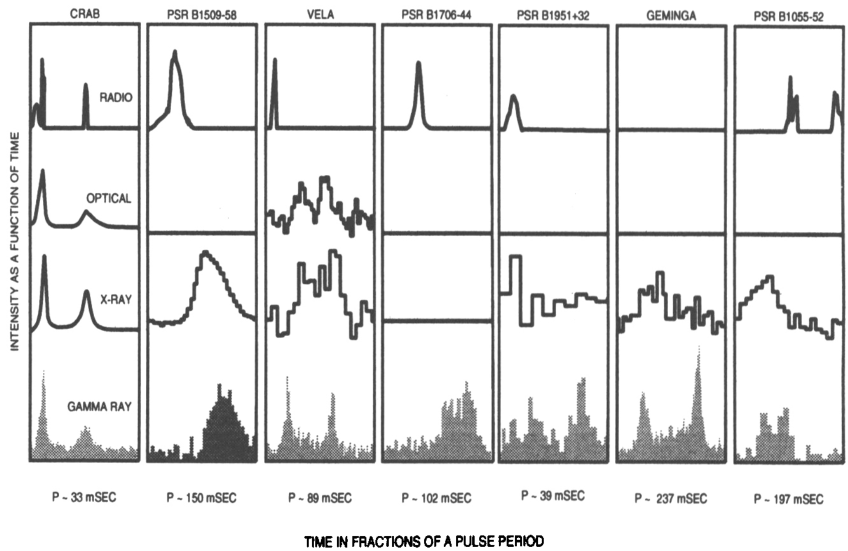

Figure 1. Multiwavelength light curves for the known gamma-ray pulsars. Crab: Manchester 1971 (radio), Groth 1975 (optical), Harnden & Seward 1984 (X-ray), Nolan et al. 1993 (gamma ray). B1509−58: Ulmer et al. 1993 (radio and gamma-ray), Kawai et al. 1991 (X-ray). Vela: Kanbach et al. 1994 (radio and gamma ray), Wallace et al. 1977 (optical), Ögelman 1994 (X-ray). PSR B1706−44: Johnston et al. 1992 (radio), Thompson et al. 1996 (gamma-ray). PSR B1951+32: Kulkarni et al. 1988 (radio), Safi-Harb et al. 1995 (X-Ray), Ramanamurthy et al. 1995 (gamma ray). Geminga: Bertsch et al. 1992 (gamma ray), Halpern & Ruderman 1993, and Halpern 1995 (X-ray). PSR B1055−52: Fierro et al. 1993 (radio and gamma ray), Ögelman and Finley, 1993 (X-ray).

pulsars. The gamma-ray energy spectra of these two sources are flat power laws like those of known pulsars (Fierro, 1995). These gamma-ray sources are not time variable. Gamma-ray pulsars are steady; many other gamma-ray sources are highly variable. They are energetically consistent with a pulsar origin (the gamma rays represent a small fraction of $\dot{E}$). Neither, however, shows any evidence of pulsation in gamma rays (Nel et al., 1996).

3. Pulsar Light Curves at Different Wavelengths

Figure 1 shows the light curves of the seven known gamma-ray pulsars at radio, optical, X-ray, and gamma-ray energies.

Among the features of this compilation are:

1. Only the Crab has pulses which are (nearly) aligned across the electromagnetic spectrum.

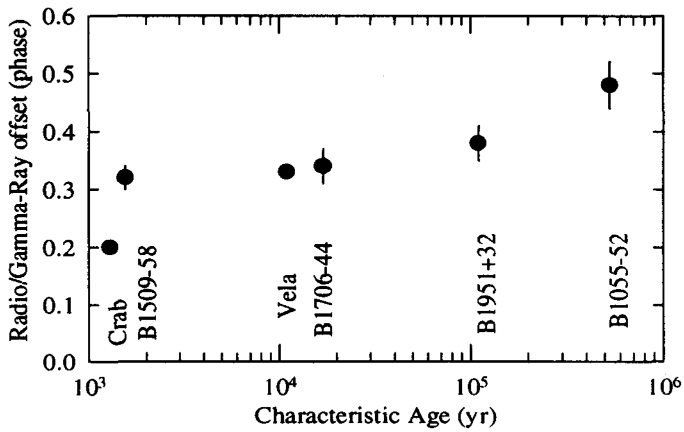

Figure 2. Radio/gamma-ray phase offset.

2. The gamma-ray light curves tend to show two pulses with a bridge of emission between. Only PSR B1509−58 is inconsistent with such a picture, although the statistics for PSR B1055−52 are too limited to draw any firm conclusions. The gamma-ray light curve for PSR B1706−44 contains at least two pulses, with possible evidence for a third between the two.

3. Only Geminga has gamma-ray pulses with a 180° separation.

4. The commonality of double pulses, coupled with the absence of many 180° separations, argues against orthogonal rotator models in which both poles are sources of gamma rays.

5. The gamma-ray light curves are consistent with single-pole, hollow-cone models of emission (see Harding, 1996).

4. Radio/Gamma-Ray Phase Offset

Figure 2 shows the phase offset between the main radio pulse (precursor pulse in the case of the Crab) and the midpoint of the gamma-ray emission. Except for PSR B1509−58, which is the only gamma-ray pulsar with no indication of two pulses, there is a trend for the radio/gamma-ray separation to increase with characteristic age. Assuming that the reference radio pulse is core emission which originates near the neutron star surface, the suggestion from this trend is that the gamma-ray emitting region moves away from the star as the pulsar ages.

5. Multiwavelength Spectra of Gamma-Ray Pulsars

Figure 3 summarizes the $\nu F\nu$ spectra for all seven known gamma-ray pulsars. This format shows the observed power per logarithmic energy interval. Pulsed emission is shown in all cases, with upper limits given for sources detected but without observed pulsation.

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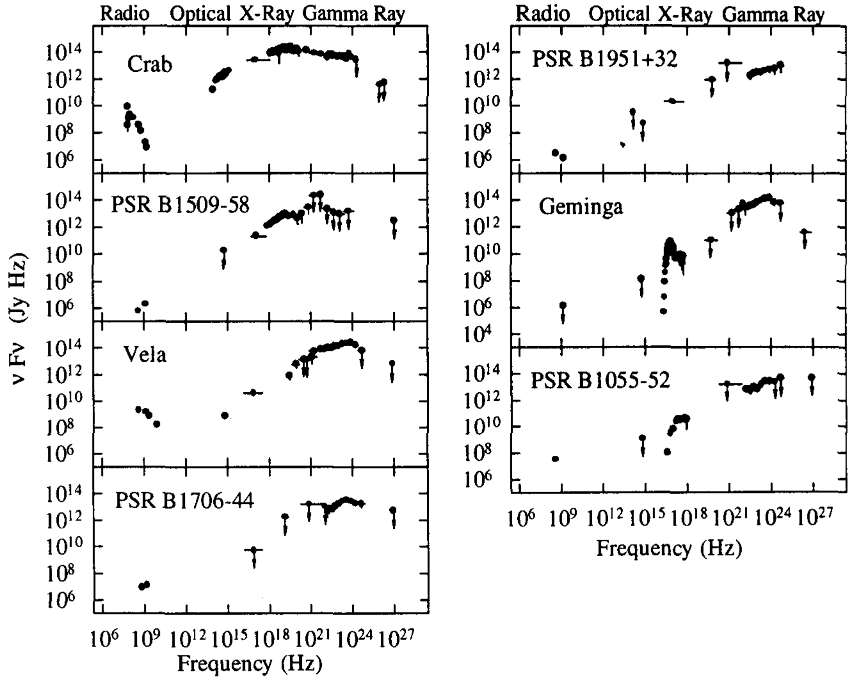

Figure 3. Multiwavelength energy spectra for the known gamma-ray pulsars. Crab: Rickett & Seiradakis 1982; Taylor et al. 1993; Rankin & Sutton 1970; Manchester 1971; Middleditch et al. 1983; Oke 1969; Percival et al. 1993; Davidson et al. 1982; Harnden & Seward, 1984; Pravdo & Serlemitsos 1981; Mahoney et al. 1984; Knight 1982; Ulmer et al. 1994; Much et al. 1995; Clear et al. 1987; Nolan et al. 1993; Vacanti et al. 1991, Akerlof et al. 1989. B1509−58: Taylor et al. 1993; Caraveo et al. 1994 (total emission from the optical counterpart treated as a pulsed upper limit); Seward et al. 1984, Kawai et al. 1993; Matz et al. 1994; Carramiñana et al. 1995; Nel et al. 1996; Nel et al. 1993. Vela: Taylor et al. 1993; Downs et al. 1973 ; Manchester et al 1980; Ögelman et al. 1993; Strickman et al. 1993; Hermsen et al. 1993; Kanbach et al. 1994; Nel et al. 1993. PSR B1706−44: Taylor et al. 1993; Johnston et al. 1992; Becker et al. 1995; Ulmer & Schroeder 1993; Carramiñana et al. 1995; Thompson et al. 1996; Kifune et al. 1995. PSR ! B1951+32: Taylor et al. 1993; K ulkarni et al. 1988 ; Safi-Harb et al. 1995; Ulmer & Schroeder 1993; Carramiñana et al. 1995; Ramanamurthy et al. 1995. Geminga: Seiradakis 1992; Bignami et al. 1993 (total emission treated as an upper limit to the pulsed optical emission); Halpern & Ruderman 1993; Ulmer & Schroeder 1993; Bennett et al. 1993; Mayer-Hasselwander et al. 1994; Fegan et al. 1993. PSR B1055−52: Taylor et al. 1993; Cheng & Helfand, 1983 (thought to be unpulsed, but matches the later pulsed results); Ögelman & Finley, 1993; Ulmer & Schroeder 1993; Carramiñana et al. 1995; Fierro et al. 1993

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COMMON FEATURES

1. In all cases, the maximum observed energy output is in the gamma ray band. The peak ranges from photon energies of 100 keV for the Crab to photon energies above 10 GeV for PSR B1951+32.

2. All these spectra have a high-energy cutoff or break. For PSR B1509−58, it occurs not far above 1 MeV photon energy; for PSR B1951+32 it must lie somewhere above 10 GeV (a $\nu F \nu$ spectrum cannot continue rising, because it would represent infinite energy).

INDIVIDUAL PULSARS

1. Crab – the spectrum could be continuous from optical to high-energy gamma-ray energies.

2. PSR B1509−58 – all the points above 1 MeV (about 10^{21} Hz) are upper limits. The spectrum must have a break between 1 and 100 MeV.

3. Vela – the pulsed X-ray emission is thermal. The gamma radiation is a separate, nonthermal component. The spectrum turns over sharply at a few GeV.

4. PSR B1706−44 – the gamma-ray spectrum is well described by two power laws, with a slope change at 1 GeV. An X-ray source at the position of the pulsar has a pulsed upper limit of 18%.

5. PSR B1951+32 – the gamma-ray spectrum can be represented as a single power law out to 30 GeV.

6. Geminga – like Vela, the gamma-ray spectrum has a sharp turnover in the few GeV energy range. The X-ray spectrum has two components, neither of which appears to connect to the gamma-ray spectrum.

7. PSR B1055−52 – limited gamma-ray statistics preclude a detailed study of this energy spectrum. The X-ray spectrum has two components, one of which may extrapolate to gamma-ray energies.

6. High-Energy Pulsar Luminosity

In terms of the observed energy flux F_E, the luminosity of a pulsar is

$$L = 4\,\pi\, f\, F_E\, d^2$$

where d is the distance and f is the fraction of the sky into which the pulsar radiates. The beaming solid angle $4\pi f$ for gamma-ray pulsars is highly uncertain and probably not the same for all pulsars. It must lie between the size of the neutron star polar cap and 4π. In the absence of a compelling argument for any particular value, I adopt a simple value for f, setting it equal to $1/4\pi$ (assuming that the pulsar radiates into 1 steradian).

The energy flux F_E is determined by integrating the broad-band energy spectra, making realistic assumptions about regions where no measurements exist. In most cases, the observed gamma-ray spectrum is itself a good approximation, because most of the observed energy falls in this band. For the Crab and PSR B1509−58, the X-ray spectra must also be considered. PSR B0540−69 in the Large Magellanic Cloud is not seen in gamma rays, but its hard X-ray component suggests that its spectrum may extend to higher energies. The X-ray flux then represents a lower limit. PSR B0656+14 has pulsed X-ray emission with a thermal spectrum. The higher-energy, nonthermal emission is no larger than this.

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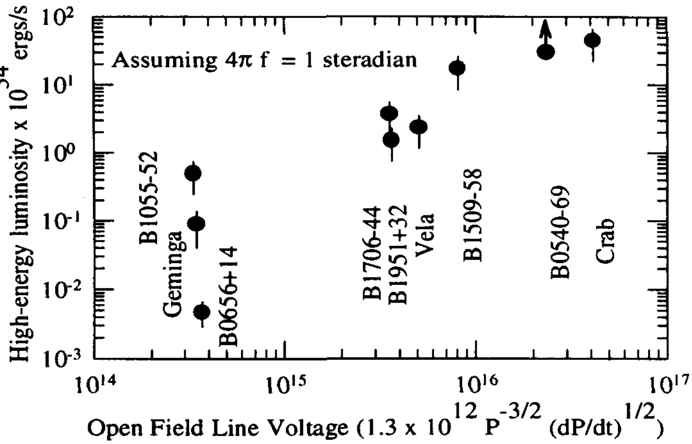

Figure 4. High-energy luminosity vs open field line voltage, for some X-ray and gamma-ray pulsars.

Figure 4 shows one possible pattern for pulsar luminosities. The high-energy luminosity increases with the open field line voltage ($\sim B/P^2$), which is also proportional to the polar cap current (Harding, 1981). Except for PSR B0656+14, a linear fit to the observed pulsars would be a reasonable approximation, extending over several orders of magnitude.

7. Geminga – Still a Puzzle?

The Geminga pulsar has several distinctive features:

1. The only radio-quiet pulsar
2. The only gamma-ray pulsar with pulses separated by 180°
3. The only gamma-ray pulsar (of 3 with adequate statistics) where a pulse has a flatter energy spectrum than the bridge (Fierro, 1995)
4. The closest and least luminous gamma-ray pulsar.

Because Geminga is unusual in more than one way, it is somewhat speculative to treat it as a prototype of radio-quiet pulsars. Extrapolating from a sample of one is strongly model dependent, and gamma-ray pulsar models have been much more successful at explaining existing observations than in predicting new results. Despite the uncertainties, Geminga is unlikely to be unique, and the potential for future studies of radio-quiet but gamma-ray-bright pulsars is high (Romani, 1996).

8. Conclusions

Gamma-ray studies are not about to replace radio as the way to study neutron stars, but they can be important to multiwavelength studies of these objects. Because there are no simple patterns that hold for all gamma-ray pulsars, the results present some challenges for theoretical work. Ultimately, we need another, larger gamma-ray telescope to follow up these observations.

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