NASA/CR-97- ~~TM~~-112998

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National Aeronautics and Space Administration

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FINAL TECHNICAL REPORT FOR NAG 5-3797

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Title of Research: **"Pair Production and Gamma-Ray Emission in the Outer Magnetospheres of Rapidly Spinning Young Pulsars"**

Report Period: 1 December 1996 – 30 November 1997

December 1997

Abstract

Electron-positron pair production and acceleration in the outer magnetosphere may be crucial for a young rapidly spinning canonical pulsar to be strong Gamma-ray emitter. Collision between curvature radiated GeV photons and soft X-ray photons seems to be the only efficient pair production mechanism. For Crab-like pulsars, the magnetic field near the light cylinder is so strong, such that the synchrotron radiation of secondary pairs will be in the needed X-ray range. However, for majority of the known Gamma-ray pulsars, surface emitted X-rays seem to work as the matches and fuels for an gamma-ray generation fireball in the outer magnetospheres. The needed X-rays could come from thermal emission of a cooling neutron star or could be the heat generated by bombardment of the polar cap by energetic particles generated in the outer magnetosphere.

With detection of more Gamma-ray pulsars, it is becoming evident that the neutron star's intrinsic geometry (the inclination angle between the rotation and magnetic axes) and observational geometry (the viewing angle with respect to the rotation axis) are crucial to the understanding of varieties observational properties exhibited by these pulsars. Inclination angles for many known high energy Gamma-ray pulsars appear to be large and the distribution seems to be consistent with random orientation. However, all of them except Geminga are pre-selected from known radio pulsars. The viewing angles are thus limited to be around the respective inclination angles for beamed radio emission, which may induce strong selection effect.

The viewing angles as well as the inclination angles of PSR 1509-58 and PSR 0656+14 may be small such that most of the high energy Gamma-rays produced in the outer accelerators may not reach the observer's direction. The observed Gamma-rays below 5 MeV from this pulsar may be synchrotron radiation of secondary electron-positron pairs produced outside the accelerating regions.

1. Introduction

The family of known high-energy gamma-ray pulsars (HEGPs) has grown from the original two (the Crab and Vela) to seven within last few years, thanks to high sensitivities of the GRO and Rosat. Although the mechanism of gamma-ray emission from young pulsars has been an active research area, there is no an agreement among the theorists.

Differences and similarities among the HEGPs have been used to classify them into Crab-like and Vela-like (Chen & Ruderman 1993; Ho 1993). Many unique features of the Crab pulsar suggest that it belongs to a separate group (with possibly PSR 0540-69 as another member which is seen in X-ray but not in Gamma-ray because of its large distance). The efficiencies of converting spin-down power into high energy Gamma-ray of Vela, PSR 1706-44 (Thompson et al. 1993) and PSR 1951+32 (Ramanamurthy et al. 1995) are similar (about 1%). The spectral indices of these three pulsars are also strikingly similar (1.7, 1.72 and 1.74, respectively). The similarities between Vela, PSR 1706-44 and PSR 1951+32 can be easily explained in this classification because their similar positions in the

Vela-type region. Two other HEGPs, Geminga (Halpern & Holt 1992; Bertsch et al. 1992) and PSR 1055-52 (Fierro et al.1993), have the longest spin periods and also the highest efficiencies of emitting Gamma-rays among the known HEGPs. The spectral indices of both pulsars are also the lowest. PSR 0656+14 is the HEGP with the lowest efficiency of converting spindown power into high-energy gamma-ray emission (Ramanamurthy et al. 1996) considering its position so close to Geminga and PSR 1055-52.

The above classification is not free of questions. PSR 1509-58 is not readily accommodated into the above classification scheme. It is located at the middle of the Vela type region, therefore, it is expected to be a high energy Gamma-ray pulsar with an efficiency of converting spin-down power into Gamma-ray luminosity comparable to that of the Vela pulsar. The non-detection of high energy Gamma ray above 5 MeV (Wilson et al. 1993; Bennett et al. 1995; Brazier et al. 1995) demands an explanation. Furthermore, the lower boundary (the "death line" of efficient Gamma-ray pulsar) of the Vela-like region is not very certain. Geminga, PSR 1055-52 and PSR 0656+14 are outside of the previously predicted Vela-like region (Chen & Ruderman 1993; Ho 1993), albeit very close to it. Furthermore, the efficiency of converting spin-down power into gamma-ray emission for PSR 0656 + 14 is uncomfortably low considering its closeness to other two very efficient Gamma-ray generators Geminga and PSR 1055-52.

2. Progresses Made in Last Year

We have made some progresses in the following area:

2.1. Pair Production in the Outer Magnetosphere and Death Line

Currents that go through the accelerating regions are generally assumed to be the energy extraction mechanism. To maintain a current in the outer magnetosphere, pair production is essential. However, the local magnetic field in the outer magnetosphere is too weak that g - B pair production process is not operating efficiently. Photon-photon collision seems to be the only effective pair production process (CHR) in the outer magnetospheres of HEGPs. For Crab, the observed keV X-ray and GeV Gamma-ray photons are sufficient to produce the needed current. Actually, the optical depth of a GeV photon within the magnetosphere of the Crab is more than ten -- the primary spectrum is significantly modified by pair production process.

For pulsars in the Vela-type region, the inability of producing the needed keV X-rays at the same location where GeV Gamma rays are produced significantly reduces pair production rate. Fortunately, all of the known HEGPs are modest X-ray emitters. Some of those soft X-ray photons will inevitably collide with curvature radiated GeV Gamma-rays (Ruderman et al. 1993) and can produce a electron/positron flux in the outer magnetosphere. It is easy to check that the current generated this way is comparable to that corresponding to the so-called Goldreich-Julian current for all of the HEGPs. Thus, it is likely that it is the main pair production mechanism in the outer gaps for pulsars in the Vela-like region. For an adolescent pulsar with a relatively long period like Geminga, it seems to be the only pair production mechanism in the outer gaps.

However, we are still uncertain about the origin of the surface emitted X-rays. If most of the observed X-ray is from the thermal emission of a cooling neutron star, then we expect significant reduction of pair production and associated Gamma-ray emission from the outer accelerators when thermal cooling flux drops rapidly. The typical X-ray photon will also soften to too low energy to make pairs with GeV photons. This happens when the age of a neutron star reaches 10^6 yr according to the standard cooling curve of a neutron star (Page & Applegate 1992).

There is another possibility that part of the neutron star surface could be kept hot either by internal by bombardment of the polar cap by energetic particles accelerated in the magnetosphere (Cheng & Ruderman 1980; Arons 1981; Halpern & Ruderman 1993). This could last the life of HEGPs by orders of magnitude. This process is going to be quenched when the curvature-radiated gamma rays are no longer energetic enough to make pairs with soft X-rays. The later point will be strongly supported if any millisecond pulsar is detected to be a strong gamma-ray pulsar. On the other hand, the former is favored at present stage, since no significant softening of gamma-ray spectrum has been observed when HEGP is approaching death region. Further studies in clarifying these uncertainties are warranted.

Considering uncertainties associated with these physical processes and the observations of PSR 1929 + 10 (Yancopoulos, Hamilton & Helfand 1994), it seems that these processes are not going to change much of the thermal history of a canonical pulsar around 10^6 yr. Thus, we define a working death line of the age 6×10^5 yr for canonical gamma-ray pulsars. Note that Gamma-rays from outer gaps are not going to quench to zero, but the efficiency of converting the spin down power into the Gamma-ray photons is expected to decrease rapidly after passing the death line.

2.2. *Geometry of Neutron Stars and Apparent Efficiency of HEGPs*

Among the known HEGPs, PSR 1055-52 is most certain to be orthogonal rotator. It also happens to have the highest efficiency of converting the spin down energy into Gamma-ray emission. The orthogonality of PSR 1055-52 provides us a useful tool in diagnosing surface magnetic field geometry and the Gamma-ray emission pattern. Like other pulsars in the Vela-like region and beyond, the X-ray light curve of PSR 1055-52 has a single broad peak. The X-ray emission seems to be thermal (Ogelman 1995) and may arise from hot spots on the surface of neutron star. In this case, only an off-centered dipole geometry can simultaneously explain the double peaked radio and single peaked X-ray light curves. If an off-center dipole geometry is typical among all pulsars, radio emission from the region close to the surface may be strongly influenced by the plasma effect in the magnetosphere and the radio polarization properties will be determined by plasma effect along the photon path. The Gamma-ray spectrum from polar cap region will be significantly modified,

On the other hand, two stranger HEGPs, PSR 1509-58 and PSR 0656-14, may happen to have small viewing angles. If the viewing angle of PSR 0656+14 is not much different from that inferred from radio data [8 degrees in Lyne & Machester (1988); 30 degrees in Rankin (1990)], then the curvature radiated high energy Gamma-ray flux from this pulsar in the direction of the Earth is small because of viewing selection effect. There are some indications that PSR 1509-58 may also have a small viewing angle. The inclination angle should not be much different from the viewing angle since it is a radio pulsar. (1) The single radio pulse of PSR 1509-58 has a FWHM about 35 degrees which can be broadened by small viewing angle if the radio emission is from nearby of the stellar surface (the so-called core emission: Rankin 1990). The single X-ray pulse is even broader, which however can hardly be used to constrain the neutron star geometry because the location of X-ray emission is not specified yet. But this is not inconsistent with the small viewing angle assumption, since the pulse from the opposite pole would have been seen otherwise. (2) The non-detection of glitches from this young pulsar with the largest known period derivative may also require a small inclination angle between the spin and magnetic axes. In this case, the flux tubes movement associated with the spin down process may be minimum.

Weak Gamma-ray emission for small viewing angles are expected in the original outer gap model (Cheng, Ho, & Ruderman 1986; hereafter CHR). In that model, Gamma-rays generated in the outer gaps can extend outward from the null surface to the light cylinder. How close the gaps can extend toward the stellar surface depends on the inclination angle. If the inclination angle is big, then the gap could extend almost down to the stellar surface. In this case, the variation of the magnetic field within the outer gaps would be very large and it would be hard to define a typical local field within the gaps. The Gamma-rays produced by curvature radiation and/or inverse Compton scattering by relativistic pairs in the outer gaps is emitted exclusively parallel to the local field line. As a result, the intensity of Gamma-rays produced in the outer gaps will have a large latitudinal coverage. For an observer at a small viewing angle, only radiation from open field lines near the light cylinder may be seen. However, the relativistic aberration effect, which is strongest near the light cylinder, further reduces the Gamma-ray intensity in the observer's direction.

If both the viewing and inclination angles of PSR 1509-58 and PSR 0656+14 are small, then high energy Gamma-ray emission from the outer gaps is expected to be rather weak in observer's direction.

All of the seven pulsars with highest spin down energy loss relative to the earth are known to be Gamma-ray pulsars. This fact states clearly that the Gamma-ray emission must have wide latitudinal coverage, at least much wider than the radio beams. However, all of the known HEGPs except Geminga are pre-selected in the radio band, a strong selection effect may arise if the radio emission is indeed strongly beamed. The efficiency of converting spin-down power into high energy Gamma-rays and the true energy spectrum may be subjected to this selection effect. In this regard, more HEGPs like Geminga are needed to reveal the importance of this selection effect. In principle, the inclination angle and the viewing angle of Geminga can be any value. It is interesting to note that the gamma-ray peaks of Geminga are exactly 180 degree apart. It is naturally expected in the CHR's inward and outward beams if the viewing angle is close to the equatorial plane.

2.3. Spectrum of PSR 1509-58: Synchrotron Radiation?

PSR 1509-58 also happens to have the largest period derivative of all known pulsars. The inferred magnetic field at the stellar surface, 1.6×10^{13} G, is also the highest. We have explored two physical processes associated with high surface magnetic field: photon-magnetic field pair production and single photon splitting (Chang, Chen, & Ho 1996). We conclude that neither of them can explain PSR 1509-58 satisfactorily.

However, even primary Gamma-rays of PSR 1509-58 may miss the observer's direction due to special viewing geometry, synchrotron radiation by secondary pairs produced by collision between primary Gamma-rays and soft X-ray outside the gaps may still be observable. The typical energy of photon emitted by curvature radiation is about 1 GeV. The optical depth of the primary gamma-rays within the magnetosphere of the neutron star is estimated as 0.5 for parameters of PSR 1509-58. The synchrotron radiation by these secondary pairs will have a high-energy turnover at about 10 MeV, which is comparable with observations. Furthermore, the spectral index of synchrotron radiation, roughly estimated is close to what has been observed. The low-energy turnover from synchrotron radiation due to the limit of radiation time within the magnetosphere (Chen & Ruderman 1993) is also comparable with the low energy cutoff of PSR 1509-58.

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