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Radio-quiet Gamma-ray Pulsars

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A radio-quiet γ-ray pulsar is a neutron star that has significant γ-ray pulsation but without observed radio emission or only limited emission detected by high sensitivity radio surveys. The launch of the *Fermi* spacecraft in 2008 opened a new epoch to study the population of these pulsars. In the 2nd *Fermi* Large Area Telescope catalog of γ-ray pulsars, there are 35 (30 % of the 117 pulsars in the catalog) known samples classified as radio-quiet γ-ray pulsars with radio flux density (S_{1400}) of less than 30 μJy. Accompanying the observations obtained in various wavelengths, astronomers not only have the opportunity to study the emitting nature of radio-quiet γ-ray pulsars but also have proposed different models to explain their radiation mechanism. This article will review the history of the discovery, the emission properties, and the previous efforts to study pulsars in this population. Some particular cases known as Geminga-like pulsars (e.g., PSR J0633+1746, PSR J0007+7303, PSR J2021+4026, and so on) are also specified to discuss their common and specific features.

Keywords: pulsars, gamma-rays, neutron stars, radiation mechanisms

1. INTRODUCTION

Pulsars are astronomical sources marked with "PSR", which stands for pulsating sources of radio. This given symbol is related to its historical discovery in 1967. Antony Hewish and Jocelyn Bell Burnell serendipitously detected a periodic signal when they tried to investigate the interplanetary scintillation through a radio telescope (Hewish et al. 1968). The observed target was soon connected to a rapidly rotating neutron star with a strong dipole magnetic field (Pacini 1967; Gold 1968). Therefore, a pulsar was defined as a neutron star with the significant radio pulsation in the early stage. However, the detection of the "Gemini gamma-ray source" (Geminga) overthrew the previous understanding of the pulsar. The γ-ray emission from Geminga was first discovered by SAS-2 (Fichtel et al. 1975) and COS-B (Bennett et al. 1977) in March of 1991. But the pulsation was not detected until the X-ray periodic signal of 237 ms was found in the soft X-ray band using the Roentgen satellite (*ROSAT*) observations (Halpern & Holt 1992), and now this source was also labeled as PSR B0633+17/PSR J0633+1746. The γ-ray pulsation of Geminga

was immediately confirmed by the energetic gamma ray experiment telescope (EGRET) on board Compton gamma ray observatory (*CGRO*) by Bertsch et al. (1992) and retrospectively in the COS-B and SAS-2 data. This detection not only revealed the nature of this target for 20 yr after its discovery, but also opened a new direction in studying pulsars. Although some literatures claimed the radio pulsation (Malofeev & Malov 1997; Vats et al. 1999) detected from Geminga (Sieber & Schlickeiser 1982; Caraveo et al. 1984) recently, the upper limit of the radio flux density @ 1,412.0 MHz (S_{1400}) for this pulsar was less than 0.507 mJy (Spelstra & Hermsen 1984) and it was concluded as radio-quiet (RQ) among general radio surveys. As shown in Table 1 summarized by Caraveo & Bignami (1997), Geminga has demonstrated many "firsts" for astronomers to further investigate RQ neutron stars or Geminga-like pulsars recently.

Because a pulsar/neutron star is expected to mainly emit neutrons in the X-ray band, the next RQ X-ray pulsar (RX J0720.4-3125 with 8.39 sec periodicity) was soon detected (Haberl et al. 1997) and this target was classified as X-ray dim isolated neutron stars (XDINS) or X-ray thermal isolated

Table 1. Many "firsts" for the detection of the Geminga pulsar (1973-present). Adopted from Caraveo & Bignami (1997)

- 1st unidentified γ-ray source
- 1st INS discovered through high-energy emission and identified through its X and γ-rays
- 1st INS identified without help of radio astronomy
- 1st INS optically identified through its proper motion
- 1st INS the distance of which is measured through its optical parallax
- 1st INS direct view in optical/UV of the surface/photosphere of a NS
- 1st evidence for an atmosphere surrounding NS crust
- 1st direct measurement of the surface magnetic field of an INS
- 1st INS the timing parameters of which are determined solely by high energy γ-ray data
- 1st optical measurement of absolute position of an INS within 40 mas (This leads to the first measurement of the braking index of a 10^5 yr old NS)
- 1st evidence (together with PSR 0656+14 and PSR 1055-58) of an INS with a two-component X-ray emission

neutron stars (XTINS) which belongs to the Magnificent Seven (Treves et al. 2001). However, due to the limited capability of γ-ray surveys to collect photons for temporal analysis, Geminga is the only RQ γ-ray pulsar among all the 7(+3) γ-ray pulsars (Thompson 2001) detected before the 21st century. The launch of the *Fermi* Gamma-ray Space Telescope efficiently increased the population of RQ γ-ray

pulsars. In the 1st *Fermi* Large Area Telescope (LAT) catalog of γ-ray pulsars, there are 17 γ-ray pulsars without known contemporaneous radio pulsed detection (Abdo et al. 2010a). Due to the improved techniques including weighting *H*-statistics (Kerr 2011) and the sliding coherence window technique (Pletsch 2011) that have been efficiently used for periodicity searches, 35 γ-ray pulsars were determined to be radio-quiet ($S_{1400} < 30\ \mu$Jy) in the 2nd *Fermi* LAT catalog of γ-ray pulsars, as shown in Fig. 1 (Abdo et al. 2013). Among 35 RQ γ-ray pulsars listed in 117 γ-ray pulsars of the 2nd *Fermi* LAT catalog, two of them (PSR J0106+4855 and PSR J1907+0602) are confirmed as radio-faint γ-ray pulsars (Abdo et al. 2010b; Pletsch et al. 2012b) and thus, "radio-quiet" does not completely indicate "radio-silent". Under this conception, astronomers started to consider whether a radio-silent pulsar exists or not. Furthermore, no RQ millisecond pulsar (MSP) was found in all previous efforts. Although PSR J1311-3430 is the first recycled rotation-powered pulsar that has been detected using *Fermi* data without known spin-modulated radio emission (Pletsch et al. 2012a), its radio pulsation was later confirmed with the green bank telescope (*GBT*; Ray et al. 2013). Even with a similar searching approach to detect
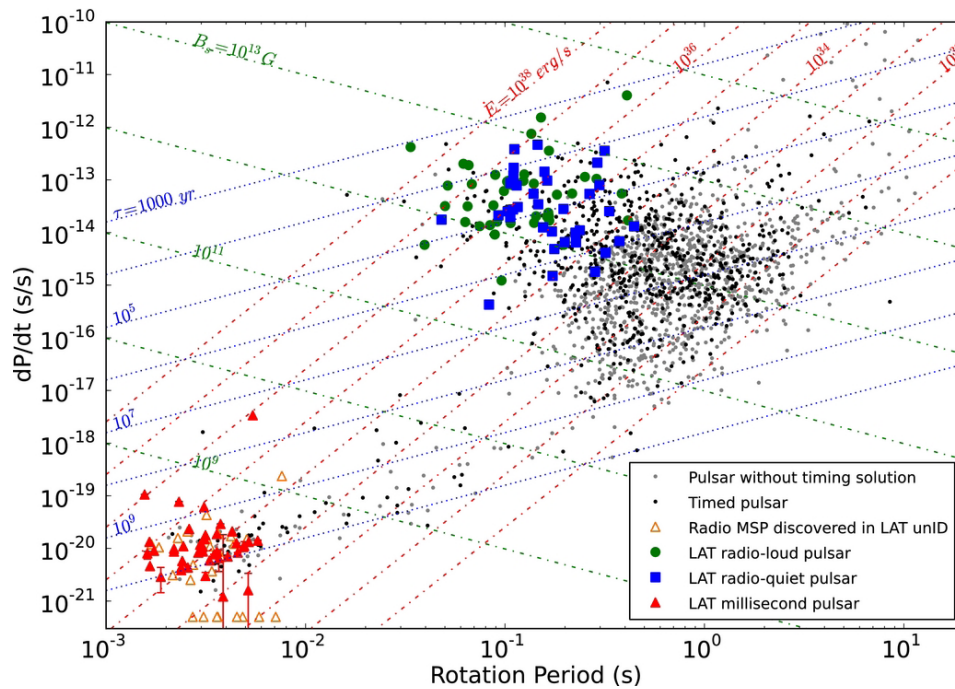

Fig. 1. Pulsars spin down rate, $\dot{P}$, vs. the rotation period P. Green dots indicate 42 relatively young, radio-loud γ-ray pulsars and blue squares show 35 "radio-quiet" γ-ray pulsars, defined as $S_{1400} < 30\ \mu$Jy. Red triangles are 40 γ-ray MSPs. 710 black dots indicate pulsars phase-folded in γ-rays using rotation models provided by "Pulsar timing consortium", for which no significant pulsations were observed. Phase-folding was not performed for 1,337 pulsars outside of globular clusters indicated by gray dots. Orange open triangles indicate radio MSPs discovered at the positions of previously unassociated LAT sources for which γ-ray pulsations have not yet been detected, and $\dot{P}$ is assumed as 5×10^{-22} when it is not detected yet. Shklovskii corrections to $\dot{P}$ have already been applied to pulsars with proper motion measurements. For clarity in this figure, error bars are shown only for γ-ray detected pulsars. Adopted from Abdo et al. (2013).

PSR J1311-3430, combining volunteer distributed computing via *Einstein@Home* and methods originally developed in gravitational-wave astronomy, we obtained 18 more γ-ray pulsars[1] before 2016, but none of them was a MSP. Therefore, accompanying the discovery of more and more RQ X-ray or γ-ray canonical pulsars, whether there is an RQ MSP is still an important issue to be solved in the future. Observers also have heeded that both X-ray and γ-ray pulsations can be yielded from the Geminga pulsar, but only a few RQ γ-ray pulsars have the same intriguing feature. These pulsars are usually recognized as Geminga-like pulsars and enable theorists to study the emission mechanism of RQ γ-ray pulsars.

This review article comprehensively discusses the possible origin causing a γ-ray pulsar to be quiet in the radio band, the similarities or dissimilarities among radio-loud (RL) & RQ pulsars, the environment in the vicinity of an RQ γ-ray pulsar, and some representatives in this population.

2. INTRINSICALLY OR GEOMETRICALLY RADIO-QUIET?

A pulsar without observable radio emission was rarely discovered due to the low significance of the limited high-energy photons collected for timing analysis before 1990s. However, the EGRET onboard *CGRO* launched in 1991 provided an opportunity to study particle acceleration and radiation in the magnetosphere of energetic pulsars, and 6 γ-ray pulsars were confirmed in the 30 MeV – 20 GeV γ-ray band (Nolan et al. 1996). Among 7 γ-ray pulsars (including PSR B1951+32 detected by the Compton telescope on board *CGRO*; Kuiper et al. 1998) of high significance level, Geminga and PSR B1055-52 have a relatively high radiation efficiency and old characteristic age (see Table 4 of Thompson et al. 1999). Because Geminga does not have obviously detectable radio emission, astronomers recognized that the radio emission from this middle-aged pulsar might be intrinsically weak because of a specific set for the spin period and magnetic field strength. For example, slow-spinning (> 0.3 sec) pulsars with low magnetic fields might form a population of low-luminosity pulsars (Narayan 1987). Detections of XDINs (e.g., The Magnificent Seven) were regarded as candidates of radio-silent cool neutron stars, and the birthrate of this specific population was compared with that of radio pulsars (Neuhäuser & Trümper 1999; Popov et al. 2003).

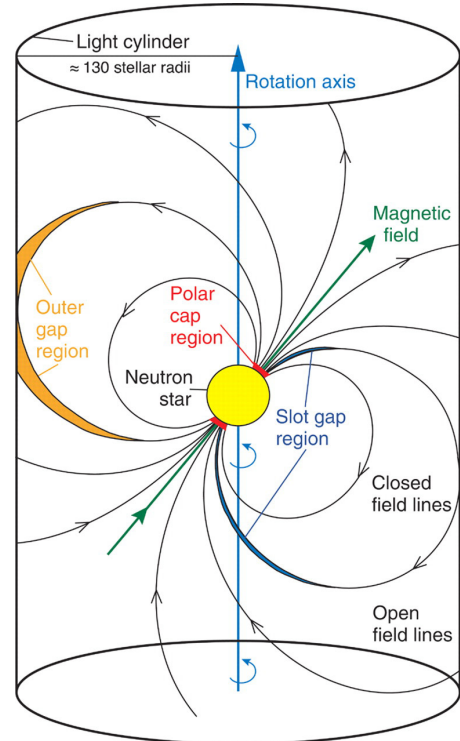The beaming geometry is another scenario to explain

Fig. 2. A sketch of the Crab's pulsar's magnetosphere: Electrons are accelerated along the magnetic field lines of the pulsar and emit electromagnetic waves from the vacuum gaps via the synchrotron or curvature radiation. Vacuum gaps or vacuum regions can occur at the polar cap, the slot gap or the outer gap. Adopted from MAGIC collaboration (Aliu et al. 2008).

the lack of radio emission for a high-energy pulsar. If the radio beam is apparently narrower than the γ-ray beam, one may expect to observe the RQ γ-ray pulsar in a particular viewing geometry. This concept motivated developments in investigating the high-energy emission from the magnetosphere of a neutron star. As shown in Fig. 2 for an example of the Crab pulsar (Aliu et al. 2008), the radio emission of a neutron star results in field lines tied to the magnetic pole, which is named the polar cap region with a size defined by the last open field lines (Lyne & Manchester 1988). The polar cap scenario was also proposed to explain the γ-ray pulsed detection. Inside the vacuum gap above the magnetic pole, its plasma density is lower than the critical Goldreich-Julian density (Goldreich & Julian 1969), where the magnetically induced electric field is saturated, and therefore the charged particles can be accelerated to very high energies. Under such a scenario, the polar cap model predicts strong correlations between radio and γ-ray pulse profile, and it is reasonable for some Crab-like pulsars (Kanbach et al. 2002). This model predicted a large amount of RL γ-ray pulsars to be detected, and only the weaker off-beam γ-ray emission would allow a small number of RQ γ-ray pulsars. However, except for the Crab pulsar, the other 4 EGRET pulsars that

have detected pulsation both in the radio and in the γ-ray bands do not show a phase-aligned profile (Thompson 2001). Recent investigations also confirmed that most canonical pulsars do not have strong correlation with their radio and γ-ray pulse profiles. In response, the slot gap (Gonthier et al. 2004; Muslimov et al. 2004) and outer gap model (Cheng et al. 1986; Hirotani 2007; Takata et al. 2008) were proposed to explain the observational results.

In the outer gap scenario, the particle acceleration region is characterized by a strong electric field along the magnetic field lines and the null charge surface, and it is located at the outer magnetosphere of a pulsar near the light cylinder, as shown in Fig. 2. The slot gap scenario presented in Fig. 2 is based on the electron acceleration along the edge of the open field region from the neutron star surface to the light cylinder, and the pair formation front across the polar cap forms a hollow shape as pairs are produced at higher and higher altitude approaching to the last open field line. Both of these models give observers a larger viewing angle to detect the γ-ray pulsation, and predict a greater number of RQ γ-ray pulsars (Gonthier et al. 2004). However, one could not discriminate whether RQ γ-ray pulsars are intrinsically RQ or a result of their beaming geometry before the launch of the *Fermi* observatory because only one sample in this population (i.e., Geminga) was confirmed. The discovery of the pulsar centered in CTA 1 (i.e., PSR J0007+7303) with the *Fermi* data (Abdo et al. 2008) and most RQ γ-ray pulsars listed in the 1st *Fermi* LAT catalog of γ-ray pulsars (Abdo et al. 2010a) do not present a shared feature on their physical parameters (e.g., spin periodicities, strength of the magnetic field, etc.) to form a characteristic population. This not only disfavors a physically intrinsic origin to explain the lack of radio emission but also suggests the outer gap or the slot gap model to describe its γ-ray pulsed detection. Comparing with the polar cap scenario, these outer magnetosphere models can both generate high-energy pulsation over a much broader range of phase and predict higher radiation efficiencies as inferred from the observed flux. Astronomers not only explained the absence of the radio signal from a γ-ray pulsar due to the particular geometry of the inclination angle and viewing angle, but also noticed some γ-ray pulsars are radio dim (e.g., PSR J0106+4855 and PSR J1907+0602). This phenomenon may be attributed to the line of an observer's sight just cut at the edge of the radio beam from a pulsar; moreover, the partially screened gap (PSG) model to interpret the origin of the radio emission from magnetars (Szary et al. 2015) may also provide further insight since magnetars are not powered by the rotational energy as in the case of general RL pulsars and only a few of them have weak, transient radio pulsed detection (e.g., XTE J1810-197; Camilo et al. 2006).

Due to the limitation of the sensitivity for a radio survey, it is difficult to confirm that one γ-ray pulsar is substantially radio-silent. An RQ γ-ray pulsar with a pulse profile of only narrow peaks and a low duty cycle, which cannot be modeled by the current outer magnetosphere models, might be a candidate. But in a scenario where radio-quietness is due to viewing angle, astronomers also expect to observe a significant number of RQ MSPs. However, contrary to the detection of a temporal signal from a solitary pulsar, a difficulty in the binary system is that the metric components determined on the search space explicitly change across the orbital parameters (Messenger 2011), and the inefficient blind search in a high frequency domain requires large trials, which seriously reduces the significance of a possible detection. Thus far, PSR J1311-3430 is the only (Pletsch et al. 2012a) recycled neutron star detected without a known contemporaneous radio ephemeris. However, its mean radio flux density of 60±30 μJy and the radio pulse of 10.3σ significance were detected by *GBT*@2 GHz observations (Ray et al. 2013). Whether there is an intrinsically radio-silent pulsar or an RQ MSP is still an open question. Addressing this question not only helps observers to test the current theories, but also will provide new insights for pulsar astronomy.

3. RADIO-LOUD AND RADIO-QUIET PULSARS

Among 117 γ-ray pulsars recorded in the 2nd *Fermi* LAT catalog (Abdo et al. 2013), 34 % of them are determined as MSPs; 30 % of them are classified as radio-quiet with the flux density of 1,400 MHz, smaller than 30 μJy; the rest are non-recycled radio-loud pulsars. A great number of RQ γ-ray pulsars expected to be discovered in the outer magnetosphere models naturally suggest that γ-ray emission sweeps over a larger viewing angle than the radio beam does, and they also provide astronomers a chance to investigate the differences between RL and RQ pulsars. For example, the distance of RL pulsars can be obtained through radio dispersion measures (DMs) of the pulses from a gas distribution model (Cordes & Lazio 2002) or directly evaluated by optical/radio parallaxes. A general formula to estimate the pulsar distance (d) of an RL one can be assessed by the time delay between two observing frequencies v_1 and v_2 using the relation to the dispersion measure,

$$\mathrm{DM} = \int_0^d n_e dl = \frac{2\pi m_e c}{e^2} \left(\frac{1}{\nu_1^2} - \frac{1}{\nu_2^2} \right)^{-1} \triangle t$$
$$\sim \frac{\triangle t}{4.15\ \mathrm{ms}} \left[\left(\frac{\nu_1}{\mathrm{GHz}} \right)^{-2} - \left(\frac{\nu_2}{\mathrm{GHz}} \right)^{-2} \right]^{-1} \tag{1}$$

where n_e represents the integrated electron number density from the Earth to the source; m_e, e, and c label the electron mass, charge and the speed of light, respectively. Since RQ pulsars do not have any information at the radio band, usually the distance can only be estimated by the study on the line-of-sight galactic absorption column (N_H) in the direction of the pulsar (Dickey & Lockman 1990). However, the correlation between DM and N_H is closely connected to different phases of interstellar medium (ISM). Thus, even several literatures adopted an average ionization fraction of 10 % in the ISM (e.g., Seward & Wang 1988; Camilo et al. 2012), such a decision has unclear justification and causes a large uncertainty in the measurement of distance. Nonetheless, this estimate can still be refined by the comparison of X-ray absorption column density derived from the atomic and molecular gas (e.g., more details can be referred to Section 4 of Marelli et al. 2014) or if other bright X-ray-emitting and optical-emitting stars (with known distances) were also present. But if a pulsar has an observed energy flux > 100 MeV, its pseudo-distance can be determined using an empirical function between the intrinsic γ-ray luminosity and spin-down power provided in Saz Parkinson et al. (2010) as well.

Except for 40 γ-ray MSPs detected by *Fermi* observatory, the other 77 young or middle-aged γ-ray pulsars have shared properties with respect to characteristic age, surface magnetic field, and spin-down luminosity, as shown in Fig. 1. Even if we further consider the spin down efficiency in γ-ray, no obvious correlation between RL and RQ γ-ray pulsars can be concluded (Abdo et al. 2013). Most of the young or middle-aged γ-ray pulsars have conversion efficiency of less than 20 %, and only a few cases exceeding 100 % (e.g., PSR J2021+3651 for RL and PSR J2021+4026 for RQ) result from overestimated distances or the assumed beaming factor. The spectral behavior for all the γ-ray pulsars can be well described with a power-law with an exponential cutoff (PLE),

$$\frac{dN}{dE} = K \left(\frac{E}{E_0} \right)^{-\Gamma} \exp\left(-\frac{E}{E_{\text{cut}}} \right)^{-b} \qquad (2)$$

where K is the normalization factor, Γ is the photon index in the low energy range, E_{cut} is the cutoff energy, b represents the sharpness of the cutoff with a default setting of 1, and the energy E_0 can be set arbitrarily. 35 RQ and 42 RL γ-ray pulsars recorded in the 2nd *Fermi* LAT catalog that provide acceptable spectral fits to the exponential cutoff power-law give a mean photon index of 1.45±0.02 and 1.52±0.05, and a mean cutoff energy at 2.58±0.07 GeV and 2.65±0.20 GeV, respectively. Comparing with a LAT-detected MSP giving an obvious harder spectrum with the mean photon index

of 1.29±0.04, γ-ray emission from RQ and RL pulsars can be concluded to be from the same non-thermal origin/geometry with a photon index distributed among 0.6-2.0 and breaks down at several GeVs. If we further consider the dependence of Shklovskii-corrected spin down power ($\dot{E}$) and the spectral fit parameters (Γ and E_{cut}) using a simple measurement on the fit with $\Gamma = A\log(\dot{E}) + B$, a similar trend for RQ and RL γ-ray pulsars can be described with $A \sim 0.2$ and $B \sim -5$. However, the Pearson correlation coefficient in this relation derived for RL pulsars (0.4) is lower than that for RQ pulsars (0.68). This indicates that RL γ-ray pulsars have a dispersed distribution of Γ and $\dot{E}$, and the known samples may be obtained from different sub-populations.

Since the blackbody emission of pulsars/neutron stars is expected to mainly radiate in the X-ray band, X-ray investigations, especially those obtained through *Chandra* and X-ray multi-mirror mission (*XMM-Newton*) space telescopes with high spatial and timing resolutions, are also crucial for further investigating RQ γ-ray pulsars. In general, RQ pulsars have fainter X-ray counterparts than RL pulsars (e.g., XDINS is an important population of RQ pulsars). Among 117 γ-ray pulsars catalogued by *Fermi*/LAT (Abdo et al. 2013) and 4 more RQ γ-ray pulsars recently detected via *Einstein@Home* (Pletsch et al. 2013), 30 radio-loud, 28 radio-quiet, and 18 millisecond pulsars have a confirmed X-ray counterpart. Among these 76 γ-ray pulsars, the X-ray flux distribution for RL γ-ray pulsars is less concentrated than for RQ γ-ray pulsars, and this phenomenon is similar to the correlation coefficient inspected for the relation of the spectral photon index and spin-down power. The distance-independent ratio of the γ-ray to X-ray flux (F_γ/F_x) for a pulsar might be a useful parameter to investigate the differences between the young-to-middle-aged RQ and RL γ-ray pulsars (Marelli et al. 2015). As shown in Fig. 3, $\log(F_\gamma/F_x)$ of RQ γ-ray pulsars is on average 3.38±0.10, while that of RL pulsars is in 2.24±0.10; an order of magnitude lower. The RL γ-ray pulsars obviously spread with a wider distribution of F_γ/F_x, although a single Gaussian can still marginally fit the distribution with a null hypothesis probability of 0.05 in 8 degrees of freedom (DOF) using a peak of the standard deviation of 0.72±0.11. A single Gaussian gives a much better fit to the distribution of $\log(F_\gamma/F_x)$ for RQ γ-ray pulsars using a peak with a smaller standard deviation of 0.43±0.09, and the null hypothesis probability of this fit is 0.62 in 3 DOF. If we consider fitting the distribution of $\log(F_\gamma/F_x)$ for RL γ-ray pulsars with two Gaussians, a better result with peaks located at ratios of 1.81±0.11 and 3.20±0.14 (standard deviation is 0.29±0.09 and 0.34±0.05, respectively) gives a null hypothesis probability of 0.38 in 5 DOF. This analysis not only directly demonstrates a scattered distribution on γ-to-X-ray energy flux ratio for RL γ-ray pulsars, but also
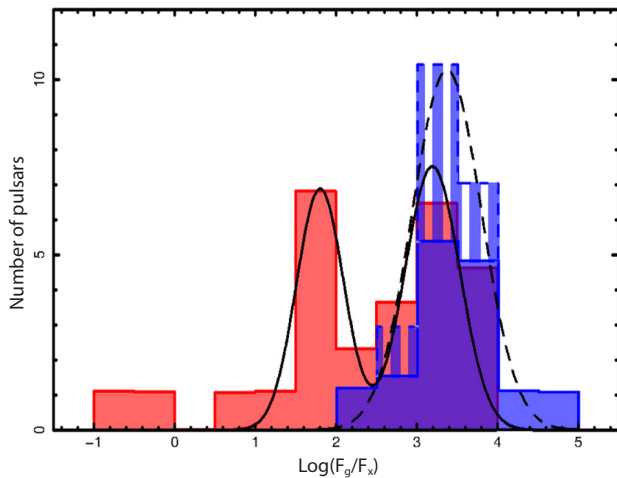
Fig. 3. Histogram of the logarithm of the γ-to-X-ray flux ratio (F_γ/F_x) of *Fermi*/LAT pulsars with high-confidence X-ray detections. Histograms for RL and RQ pulsars are shown in red and blue, respectively. 8 radio-quiet pulsars detected in X-rays for the first time in Marelli et al. (2015) is shown in dashed blue. The X-ray flux for these pulsars was measured with fitting to a simple power-law. The continuous and dashed lines are the best Gaussian fit for the distributions of RL and RQ γ-ray pulsars, respectively. Adopted from Marelli et al. (2015).

indicates the known samples might be collected from two groups; one of them similar spectral behavior and high-energy radiative efficiency to the known RQ γ-ray pulsars. However, one cannot totally exclude the possibility of a single Gaussian fit for RL γ-ray pulsars in Fig. 3 because only low statistical significance (~0.03) for the improvement can be obtained from current limited samples. γ-ray MSPs are not included in the aforementioned analysis because their magnetospheres estimated from the radius of the light cylinder are smaller than those of young or middle aged γ-ray pulsars and it will lead to a different story in their high-energy emission mechanisms. Owing to a more complicated evolution scenario and neighboring environment (3/4 of the LAT detected γ-ray MSPs are in a binary system), the high-energy radiation process of γ-ray MSPs is expected to be more complex but it can easily be resolved from the spectral fit.

Some radio-faint pulsars (e.g., PSR J1741-2054 and PSR J1907+0602) were found to have the highest F_γ/F_x belonging to the population of RL γ-ray pulsars (Marelli et al. 2015), and this might also suggest that radio-faint γ-ray pulsars, similar to RQ γ-ray pulsars, have higher F_γ/F_x values than radio-bright ones. The same examination as shown in Fig. 3 can be applied using the photon indices ratio, Γ_γ/Γ_x, where Γ_x was yielded with a single power-law fitting to the X-ray spectrum. Among 58 young-to-middle aged γ-ray pulsars, a single Gaussian can both provide an acceptable fit to RL and RQ γ-ray pulsars. The peaks of the Γ_γ/Γ_x distribution for RL and RQ γ-ray pulsars are -0.09±0.03 and -0.14±0.08, respectively. The consistent peak locations obtained from

the examination of photon indices ratio suggest the different distributions for RL and RQ γ-ray pulsars seen in Fig. 3 are not due to an intrinsic difference between the spectral slopes of these two populations. If we believe the out gap model or the slot gap model as the origin of γ-ray photons, there is no reason for a smaller luminosity, spin-down conversion efficiency or a different γ-ray beaming factor for RQ γ-ray pulsars, and the illusion of such differences can be caused by the large uncertainty on the distance estimation for RQ pulsars. Hence, different F_γ/F_x ratios for RL and RQ γ-ray pulsars inspected from Fig. 3 might connect to different major X-ray emitting features. An RQ γ-ray pulsar detected with a large magnetic impact angle may have X-ray emission mainly originating from the outer magnetosphere, which presents similar radiation geometry (or a beaming factor) to the γ-ray pulsation. But the polar cap scenario introduced in the previous section may provide another interpretation to the X-ray emitting origin for RL γ-ray pulsars. X-rays are expected to be emitted from a low-altitude cone, and the cone is formed by tangents to magnetic field lines at the rim of an open volume with angular size equaling $(r/R_{lc})^{1/2}$ (R_{lc} is the radius of the light cylinder) at a distance r. The radio beam is concentrated on the center of the X-ray cone, and the X-ray peak emission can distribute inside the polar cap rim. This emitting geometry illustrates the luminous X-ray emission centered on the magnetic axis can only be seen for small magnetic impact angles, and RL pulsars can usually have a small F_γ/F_x ratio. This X-ray polar cap emission component should also present large variability in luminosity and beaming factor for RL pulsars, and the wide dispersion in F_γ/F_x is expected to be detected, as shown in Fig. 3.

The aforementioned inference will be seriously challenged if the RL γ-ray pulsars have two groups on the distribution of the γ-ray to X-ray energy flux ratio. In addition, pulsation of an RL pulsar can be detected via the contemporaneous radio ephemeris, but RQ pulsars can only be discovered through a blind periodicity search. This means that it is impossible to confirm a low-luminosity RQ γ-ray pulsar due to the limitation of the sensitivity for the current instruments (cf. *Fermi*/LAT), and we can speculate that the known RQ γ-ray pulsars will concentrate with relatively high γ-ray flux. To further extend the possible discrimination of the high-energy flux ratio to be adopted for all the known RL and RQ pulsars, more known RQ isolated neutron stars including XDINS (e.g., Magnificent Seven), central compact objects (CCOs) are found near the center of supernova remnant SNR (e.g., RX J0822-4300; Hui & Becker 2006), and RQ magnetars (e.g., SGR 1806-20; Woods et al. 2007) should be taken into consideration. In reality, many RQ pulsars are

bright in X-rays, but no obvious γ-ray counterpart can be discovered. This clearly indicates a very low F_γ/F_x for these RQ pulsars. Even if we exclude magnetars with an extremely powerful surface magnetic field of 10^{14} G, the major X-ray emission of XDINs and CCOs can be well described with the thermal emission from a hot spot. To build a global theory to explain the specific emission mechanism for all RQ pulsars or to compare the emitting pattern with RL ones, more complete samples of the known RQ neutron stars and a simultaneous fitting to multi-wavelength pulse profiles (e.g., Pierbattista et al. 2015) may help us to clarify the realistic emission geometry of pulsars in multi-bands.

4. GEMINGA-LIKE PULSARS

Since radio emission from RQ γ-ray pulsars is below or close to the sensitivity limitation of the current radio instruments and neutron stars are typically faint in the optical band, the only way to extensively investigate these objects depends on studies in the X-ray band. Deep X-ray observations not only constrain the distance of a pulsar via the interstellar absorption column density but also provide more clues to inspect the difference between RQ and RL pulsars, like those discussed in the previous section of this article. To investigate the morphology of the surrounding SNR or pulsar wind nebula (PWN) for one RQ γ-ray pulsar, the high spatial resolution X-ray observations also allow us to measure the size of the nebula (Hui et al. 2015; Marelli et al. 2016) or to estimate the proper motion of a pulsar (e.g., PSR J0357+3205; De Luca et al. 2013; Marelli et al. 2013). However, among all the 28 RQ LAT pulsars with identified X-ray counterparts, only seven were observed with enough exposure to obtain the X-ray pulsation. Because Geminga is the first RQ pulsar confirmed with both X-ray and γ-ray

pulsations, the other 6 RQ pulsars with the same feature are usually recognized as Geminga-like pulsars for a simple comparison to other pulsars. The other known Geminga-like pulsars are PSR J0007+7303, PSR J0357+3205, PSR J1813-1246, PSR J1836+5925, PSR J2021+4026, and PSR J2055+2539. This article will introduce related interesting stories and several observational properties of these pulsars. Table 2 also summarizes physical parameters for these RQ γ-ray pulsars.

4.1 The 1st Known RQ Pulsar - PSR J0633+1746 (Geminga)

Geminga has its historical position in studying RQ pulsars, as mentioned in Section 1 of this article and also is listed in Table 1. It has the shortest distance away from the Earth (0.25 kpc; Faherty et al. 2007) among all the known young-to-middle aged LAT pulsars (taking into account the uncertainty range, only PSR B1055-52 and PSR J1836+5925 have comparably small distances; cf. Table 5 of Abdo et al. 2013) and we can detect its optical radiation of $V \approx 25.5$ (Bignami et al. 1988) and it is the only RQ γ-ray pulsar confirmed by *CGRO*/EGRET as well (Bertsch et al. 1992). The pulsation of Geminga can not only be detected both in the X-ray and γ-ray bands, but also was confirmed by the observation of extreme ultraviolet explorer (*EUVE*) satellite in UV band (Halpern et al. 1996). The *EUVE* folded light curve presents an indication of the second peak, and a similar feature was also presented in the far-ultraviolet (FUV) pulse profile obtained from the far-ultraviolet multi anode microchannel array (FUV-MAMA) detector of the space telescope imaging spectrometer (STIS) onboard the Hubble space telescope (*HST*). However, the near-ultraviolet (NUV) pulsations obtained from the NUV-MAMA detector only appear as a single sinusoidal-like structure (Kargaltsev et al. 2005). Because STIS provides

Table 2. Parameters of the known Geminga-like pulsars. Column 2, 3, and 4 denote the spin period, characteristic age, and the spin down power for each pulsar. Columns 6 and 7 present the photon index and the cutoff energy obtained from the best fit to the γ-ray spectrum using a power-law model with an exponential cutoff (PLE). Column 5 is the resultant γ-ray flux in 0.1-100 GeV derived from the PLE model. Column 9 is the spectral photon index of a power-law obtained from the non-thermal component of the X-ray spectrum. Column 8 is the unabsorbed X-ray flux in 0.3-10 keV derived from the power-law. Column 10 is the distance and Column 11 shows the magnetic field at the light cylinder (Abdo et al. 2010a). Except for columns 9 and 11 and the spectral behavior of PSR J1813-1246, all the information can be found in Abdo et al. (2013). Spectral parameters of PSR J1813-1246 are obtained from Marelli et al. (2014) to update the obvious results provided in Abdo et al. (2013). X-ray flux in column 8, X-ray photon indices in column 9, and some distances in column 10 are updated with the latest report noted in Section 4 of this article. The magnetic field at the light cylinder for PSR J2055+2539 can be found in Saz Parkinson et al. (2010).

Name PSR	P (ms)	τ (10^3 yr)	$\dot{E}$ (10^{34} erg s^{-1})	F_γ (erg cm^{-2} s^{-1})	Γ_γ	E_{cut}^γ (GeV)	F_X^{nt} (erg cm^{-2} s^{-1})	Γ_X	d (kpc)	B_{LC} (kG)
J0007+7303	315.9	14	44.8	$(4.01 \pm 0.04) \times 10^{-10}$	1.4 ± 0.1	4.7 ± 0.2	$(9.8 \pm 0.1) \times 10^{-14}$	1.5 ± 0.1	1.4 ± 0.3	3.1
J0357+3205	444.1	590	0.6	$(6.4 \pm 0.2) \times 10^{-11}$	1.0 ± 0.1	0.8 ± 0.1	$6.4 ^{+0.9}_{-0.6} \times 10^{-14}$	2.25 ± 0.20	0.6 ± 0.3	0.2
J0633+1746	237.1	340	3.3	$(4.23 \pm 0.01) \times 10^{-9}$	1.2 ± 0.1	2.2 ± 0.1	$4.97 ^{+0.09}_{-0.27} \times 10^{-13}$	1.7 ± 0.1	$0.25 ^{+0.23}_{-0.08}$	1.1
J1813 - 1246	48.1	43	624	$(2.53 \pm 0.06) \times 10^{-10}$	2.15 ± 0.02	3.6 ± 0.3	$(1.08 \pm 0.01) \times 10^{-12}$	0.85 ± 0.03	≥ 2.5	76.2
J1836+5925	173.3	1,800	1.1	$(6.06 \pm 0.04) \times 10^{-10}$	1.2 ± 0.1	2.0 ± 0.1	$3.1 ^{+0.4}_{-2.1} \times 10^{-14}$	1.8 ± 0.3	0.5 ± 0.3	0.9
J2021+4026	265.3	77	11.4	$(9.55 \pm 0.09) \times 10^{-10}$	1.6 ± 0.1	2.6 ± 0.1	$(3.3 \pm 1.1) \times 10^{-14}$	$1.2 ^{+0.3}_{-0.2}$	1.5 ± 0.4	1.9
J2055+2539	319.6	1,230	0.5	$(5.4 \pm 0.2) \times 10^{-11}$	1.0 ± 0.1	1.1 ± 0.1	$(3.43 \pm 0.27) \times 10^{-14}$	2.36 ± 0.14	0.60 ± 0.15	0.3

phase-resolved measurements that can help to separate the thermal and non-thermal fluxes, the corresponding spectral analysis suggests that FUV radiation of Geminga is mainly contributed from the surface thermal emission of a neutron star, and its near-infrared (NIR) through the NUV spectrum is clearly non-thermal.

Both Caraveo et al. (2004a) and Kargaltsev et al. (2005) investigated the X-ray radiation of Geminga with the same *XMM-Newton* observation in detail. The X-ray folded light curves obtained in three energy ranges (0.15-0.7 keV, 0.7-2.0 keV, and 2.0-8.0 keV) clearly have different structures with a single sinusoidal shape, double sinusoidal components, and double-peaked pattern respectively. The background-subtracted spectrum also shows that X-rays from Geminga have three components; a cool thermal emission with temperature of ~43 eV covering a region of $>7d_{0.16}$ km in radius ($d_{0.16}$ denotes the distance to Geminga in unit of 160 pc measured by parallax with earlier *HST* observations; Caraveo et al. 1996), a hotter thermal emission with temperature of ~170 eV covering a smaller region at the magnetic poles of ~$40d_{0.16}$ m in radius, and a non-thermal emission with a photon index of 1.7 (as listed in Table 2) originating from the particle acceleration region in the magnetosphere. The analytical results yielded from the X-ray spectra give a proper interpretation to the observed pulse profiles in the different energy range. The X-ray phase-resolved spectroscopy clearly shows a strong variability of the hot thermal emission tracing a hot spot on the surface co-rotating with Geminga. The total unabsorbed X-ray flux in 0.3-8 keV detected for Geminga is 1.1×10^{-12} erg cm^{-2} s^{-1}, which is larger than the non-thermal contribution only summarized in Table 2. In contrast to the FUV emission from other neutron stars, the FUV spectrum of Geminga lies slightly below the extrapolation of the soft X-ray thermal component, and the thermal FUV radiation is strongly pulsed, showing a narrow dip at a phase close to that of a broader minimum of the soft X-ray (< 0.7 keV) pulse profile. The partial occultation of the thermal UV radiation by regions of the magnetosphere filled with electron/positron plasma might be the origin of such strong FUV pulsations. On the other hand, the NUV pulsations do not show any obvious correlation with the hard X-ray pulsations, though the spectrum can also be well modeled with a non-thermal power-law.

Geminga is indeed a low luminosity pulsar comparing to other γ-ray sources, given that their galactic distributions are at least 10 times more distant and usually can be hundred times the luminosity of the Geminga. But due to its short distance away from Earth, Geminga is still the 2nd brightest non-variable GeV source on the γ-ray sky. Its double-peaked

pulse profile varies with energies. Beyond 18 GeV, only a single peak can be resolved from the γ-ray folded light curve, and this detection precludes high-energy radiation below 2.7 stellar radii because of the magnetic absorption (Abdo et al. 2010c). The γ-ray spectrum fitted with a PLE model is summarized in Table 2. The detailed phase-resolved spectroscopy investigated with *Fermi*/LAT data in Abdo et al. (2010c) shows a clear evolution of the spectral parameters, with the spectral index reaching a minimum value just before the leading peak and the cutoff energy having maxima around the peaks. They also showed that the γ-ray emission from Geminga exists at all spin phases. The spectral shape, broad pulse profile, and maximum photon energy of this pulsar can find reasonable explanations from the outer gap or slot gap scenarios.

The power in optical and radio emission of Geminga is lower than that in the γ-ray emission, by more than 6 orders of magnitude, designating a critical characteristic for an RQ pulsar. The spin periodicity of ~237 ms for Geminga has two known phase jumps in its history. The first glitch occurred in late 1996 confirmed by the advanced satellite for cosmology and astrophysics (*ASCA*) observations (Jackson et al. 2002), and the second event resolved by *XMM-Newton* observations in 2002 was estimated to be 3×10^{-9} in the change of pulse frequency ($\Delta f/f$), which is 5 times the size of the 1996 glitch (Jackson & Halpern 2005). Deep *XMM-Newton* observation of 2002 discovered that two elongated parallel tails are aligned with the supersonic motion of Geminga, extended for 2' (Caraveo et al. 2004b). The non-thermal emission of the tails can be explained by the synchrotron emission in the bow shock between the pulsar wind and the surrounding ISM. This bow shock detection in the X-ray band also allows us to evaluate the pulsar electron injection energy and the shock magnetic field if the angle of Geminga's motion and the local density can be determined.

4.2 Next Geminga - PSR J1836+5925

PSR J1836+5925 was usually called the "NEXT GEMINGA" (Mirabal & Halpern 2000a; Halpern et al. 2002, 2007; Lin et al. 2014) because of its physical parameters, similar to Geminga and the discovery history. The γ-ray emission from this pulsar was first discovered by *CGRO*/EGRET (GRO J1837+50; Nolan et al. 1994). This unidentified γ-ray source was recorded in the 3rd EGRET catalogue as 3EG J1835+5918 (Hartman et al. 1999) and GeV J1835+5921 using data with energies greater than 1 GeV (Lamb & Macomb 1997) only. 3EG J1835+5918 caught the attention of astronomers because it (at b~25°) is the brightest source outside the Galactic plane, and it reveals several features (e.g., a photon spectral index ~ 1.7; Hartman

et al. 1999; and steady γ-ray flux; Reimer et al. 2000) similar to a neutron star. Mirabal et al. (2000b) tried to identify the counterpart of the unidentified γ-ray source; no flat-spectrum radio sources are found in the vicinity and they derived a lower limit for the γ-to-X-ray energy flux ratio of 10⁴, which is similar to that of Geminga (cf. Table 2). RX J1836.2+5925, the brightest X-ray source in the EGRET error circle resolved by *ROSAT* observations, was finally determined as the X-ray counterpart of 3EG J1835+5918 because of the absence of optical emission (Mirabal & Halpern 2001). The upper limit on the optical flux from RX J1836.2+5925 implied that the X-to-optical energy flux ratio (F_X/F_V) is greater than 300; such a larger value is seen only among neutron stars. The X-ray spectrum of RX J1836.2+5925 also behaves like a thermally emitting neutron star, and therefore this high Galactic latitude source is a critical candidate of an old radio-quiet neutron star if we assume pulsars were born in the Galactic plane and scattered outside following their evolutions. 3EG J1835+5918 was estimated to be older than 300 kyr based on the surface cooling scenario (Mirabal et al. 2000b), and it is similar to the characteristic age of 340 kyr for Geminga as well. Considering all the aforementioned factors comprehensively, 3EG J1835+5918 was thought to be the "NEXT Geminga" even no pulsation was detected before the launch of *Fermi* observatory.

γ-ray pulsation of 3EG J1835+5918 was finally confirmed with a periodicity of ~173.3 ms by *Fermi*, and the determined characteristic age of ~ 1,800 kyr is older than that of Geminga (Abdo et al. 2009). The upper limit of the radio flux density at 1,400 MHz is 4 μJy (Ray et al. 2011), and it characterizes PSR J1836+5925 as an RQ γ-ray pulsar. The surface magnetic field (~5×10¹¹ G) and the spin-down power (1.1×10³⁴ erg s⁻¹) of PSR J1836+5925 is about one-third of those of Geminga. The distance claimed to be larger than 250 pc for this pulsar was obtained from the X-ray measurements (Halpern et al. 2002). The γ-ray spectrum of PSR J1836+5925 satisfies the fit with a PLE model (cf. Table 2). Although its efficiency converting spin-down power to γ-ray is one order of magnitude higher than that of Geminga (Abdo et al. 2013), all other physical parameters of Geminga and PSR J1836+5925 are typically in the same order of magnitude. Deep STIS imaging of the *HST* failed to detect this source to an optical limit of *V* > 28.5 (or *I* > 26.5), and it refined the measurement of F_X/F_V > 6,000 (Halpern et al. 2002). A detailed investigation of its γ-ray pulse profile reveals a large off-pulse emission component, which might be attributed to the magnetospheric radiation due to no evidence of a surrounding PWN seen in the γ-ray image and a 2-3 GeV cutoff required for the pulse minimum spectrum. The behavior of the γ-ray spectrum can be well modeled by the emission from the slot gap with a distance

of ~250 pc; however, only the outer gap model provides an acceptable interpretation to the observed γ-rays if PSR J1836+5925 has a larger distance of ~750 pc (Abdo et al. 2010d).

Efforts to search for the X-ray periodic signal from RX J1836.2+5925 gained successful detection using two *XMM-Newton* observations in 2013 (Lin et al. 2014). The X-ray pulsation can be firmly detected in 0.2-0.7 keV (i.e., soft X-ray band) with a sinusoidal structure and marginally found in 0.7-2 keV (i.e., medium X-ray band). No indication of the hard X-ray (i.e., > 2 keV) pulsation was yielded for this target. The pulsed fraction of 35 % obtained in 0.2-12 keV is comparable to the similar ratio (~30 %) determined from the γ-ray folded light curve with energy > 100 MeV. Only a multi-component model can provide an acceptable fit to the X-ray spectrum of PSR J1836+5925. X-rays from the pulsar comprise a non-thermal component with a photon index of ~1.8 (as listed in Table 2) and a thermal blackbody component with the temperature of ~60 eV emitted from a region of ~1.5$d_{0.8}$ km in radius, where $d_{0.8}$ represents the maximum assumption of the distance of 800 pc. The total flux in 0.2-5 keV estimated from the fit of a non-absorbed spectrum is ~ 5.6×10⁻¹⁴ erg cm⁻² s⁻¹. The unabsorbed non-thermal flux is (3.1-3.7)×10⁻¹⁴ erg cm⁻² s⁻¹ with the assumed absorption distributing between zero and the galactic value. The contribution of the non-thermal emission should occupy a substantial fraction of the total observed X-ray flux, but no strong evidence of a surrounding PWN was ever detected, either in the γ-ray or X-ray bands, even with the high-resolution *Chandra* images (Abdo et al. 2010d). To account for the non-thermal component, the synchrotron emission from the relativistic electron pairs in the outer magnetosphere provides a reasonable explanation (Takata et al. 2008). In the soft X-ray band, the sinusoidal shape seen in the pulse profile suggests X-rays originate from the modulation of a heated polar cap. The structure of folded light curves in 0.7-2 keV and in the γ-ray band is apparently different from that in 0.2-0.7 keV, which suggests a different emitting origin. The previous proposition can also be proved by the findings that the non-thermal flux takes ~15 % in 0.2-0.7 keV and its contribution is > 99 % in 0.7-2 keV (cf. Fig. 3 in Lin et al. 2014). Based on the current X-ray investigations, the proper motion of PSR J1836+5925 determined by *Chandra* astrometry is less than 0.14" yr⁻¹, corresponding to a projected velocity < 530 km s⁻¹ at a distance of 800 pc.

4.3 First *FERMI*/LAT Detected RQ Pulsar - PSR J0007+7303

Similar to the history in identifying Geminga and PSR J1836+5925, a high-energy emitting source centered in the

CTA 1 (G119.5+10.2), was concluded as a neutron star before the confirmation of its pulsation. Related investigations of this source started from its discovery by *CGRO*/EGRET (GeV J0008+7304; Lamb & Macomb 1997; or 3EG J0010+7309; Hartman et al. 1999) and the search of its X-ray counterpart (RX J0007.0+7302; Slane et al. 1997). The steady flux detected by EGRET and the continuity of the spectral index from X-rays to γ-rays are consistent with a typical neutron star (1.58±0.18 @ 70-200 MeV for 3EG J0010+7309; Brazier et al. 1998, and 1.5±0.2 @ 0.5-10 keV for RX J0007.0+7302; Slane et al. 2004) gave indirect evidences to identify this source. The X-ray nebula, CTA 1 seen in the neighborhood of 3EG J0010+7309/RX J0007.0+7302, has been explained as an SNR powered by the pulsar wind of a fast rotating neutron star (Brazier et al. 1998). Because of the lack of radio emission ($S_{1400} < 5\,\mu$Jy; Ray et al. 2011), the high-energy pulsation of this pulsar candidate can only be yielded from a blind search; however, no positive result was reported until 2008. The inferred age of the pulsar candidate was assumed as ~ 13,000 yr based on Sedov's model (Sedov 1959) to describe the morphology of CTA 1. A kinematic distance of ~1.4 kpc was estimated based on the HI observations to CTA 1 (Pineault et al. 1993).

The LAT onboard *Fermi* and the improved technique (time-differencing fast Fourier transform; Atwood et al. 2006) provided an opportunity to directly obtain the pulsation from the RQ γ-ray pulsar. Because 3EG J0010+7309 has a large photon flux of ~4.2×10⁻⁷ ph cm⁻² s⁻² (except for Vela and Geminga pulsars, this target also has the largest photon flux of 3.23×10⁻⁶ ph cm⁻² s⁻¹ detected by *Fermi*/LAT; Abdo et al. 2013), *Fermi* observatory started to trace it in the commissioning phase and the initial days of routine operations. It then became the 1ˢᵗ LAT γ-ray pulsar detected through a blind search (Abdo et al. 2008). The γ-ray spectral behavior of PSR J0007+7303 is summarized in Table 2, and the inferred characteristic age is similar to that derived from CTA 1. The inferred surface magnetic field of PSR J0007+7303 is ~1.1×10¹³ G, which is about an order of magnitude larger than other known Geminga-like pulsars. The broad range of the pulsed phase with superimposed sharp peaks agrees well with the emitting geometry from the outer magnetosphere of a pulsar. A glitch of PSR J0007+7303 with a change in pulse frequency ($\Delta f/f$) of ~ 6×10⁻⁷ was detected on May 1, 2009 (Abdo et al. 2012). No significant flux variability was detected before or after the glitch under a systematic examination. Deep optical observations were also proposed to observe PSR J0007+7303, but only an upper limit of $r' > 27.6$ and $V > 26.9$ can be acquired (Mignani et al. 2013). The upper limit on the non-thermal unabsorbed r'-band flux is 1.22×10⁻¹⁶ erg cm⁻² s⁻¹, corresponding to an unabsorbed non-thermal X-ray-

to-optical flux ratio $F_X/F_{r'} > 800$ that is usually obtained from other young pulsars.

With the known ephemeris identified by *Fermi*/LAT, X-ray pulsation of PSR J0007+7303 was simultaneously detected by Lin et al. (2010) and Caraveo et al. (2010) using the *XMM-Newton* observation. The X-ray spectral behavior can be attributed to the emission from the associated nebula and the pulsar, and therefore a multi-component model is required to give an acceptable fit. The X-ray emission from PSR J0007+7303 can be described with a single power-law or a composite model with both non-thermal and thermal components. The blackbody or the neutron star atmosphere (NSA) model is favored to be included since the X-ray pulse profile demonstrates a sinusoidal structure, which provides a perfect interpretation with the thermal surface emission from a neutron star. The origin of the major pulsation in a thermal component can also be confirmed with phase-resolved spectroscopy (Caraveo et al. 2010). The best fit of the thermal component gives a temperature of ~5×10⁵ K of a 10 km radius neutron star, suggesting rapid cooling for this young RQ γ-ray pulsar. The X-ray flux obtained from the non-thermal component is larger than 80 % of the total flux, indicating a substantial contribution for the synchrotron emission from the outer magnetosphere of the pulsar or the surrounding nebula. The non-thermal emission related to the pulsar and the surrounding nebula have similar photon indices of ~1.5 (Table 2; Lin et al. 2010). The upper limit of the optical emission for PSR J0007+7303 is compatible with the extrapolation of the X-ray power-law component determined by *XMM-Newton* observations. High spatial resolution *Chandra* (Halpern et al. 2004) and deep *Suzaku* observations (Lin et al. 2012) provide an opportunity to survey the morphology of the surrounding nebula. A torus plus a jet feature resolved by the *Chandra* image and the spectral fit with a single power-law resemble the morphology of a PWN, as seen in other bright γ-ray pulsars. With deep *Suzaku* exposures, a large structure with an extent of ~10' appears to extend eastward from PSR J0007+7303. The morphology of this extended feature is asymmetric, which can be explained as a bow-shock nebula. Such features are usually along the direction of the pulsar motion and behind the bow-shock. The X-ray spectrum of the extended emission can be described by the synchrotron radiation from the flow of particles coming out of the PWN.

4.4 First Pulsar to Have a Turtle's Tail - PSR J0357+3205

PSR J0357+3205 is one of 16 γ-ray pulsars obtained through blind frequency searches in the earliest *Fermi*/LAT observations (Abdo et al. 2009). Among 117 γ-ray pulsars recorded in the 2ⁿᵈ

Fermi LAT catalog of γ-ray pulsars, it has the slowest rotational speed, with a period of 444.1 ms, and therefore was nicknamed "Morla" (cf. "The Neverending Story"). This pulsar has a low spin-down luminosity and the inferred characteristic age is similar to Geminga (cf. Table 2). Morla is located off the Galactic plane, at a latitude of *b* ~ -16°. In the error region of Morla, no radio counterpart can be confirmed and the upper limit of the radio flux density at 1,400 MHz is 4 *μ*Jy (Ray et al. 2011). Deep optical and near-infrared observations were also proposed to search for the emission of Morla at other wavelengths; however, no coincident optical/infrared sources were resolved on the images. The 5*σ* upper limits of *B* > 25.86, *R* > 25.75, and *I* > 23.80 can be set with the *Isaac Newton Telescope* observation (De Luca et al. 2011).

The γ-ray spectrum of Morla can be well described with the PLE model, as shown in Table 2, and the production of γ-rays in the outer magnetosphere along open field lines can lead us to understand its 3-dimensional emitting structure. The X-ray counterpart of Morla was identified by De Luca et al. (2011) using *Chandra* observations. The deep *XMM-Newton* observation performed in 2011 gave a better constraint on the X-ray emission from the pulsar with a magnetospheric non-thermal radiation plus a thermal origin from the hot spot (Marelli et al. 2013). The photon index derived from the non-thermal component is ~2.05-2.45, as shown in Table 2, and the thermal hot spot can be fitted using the blackbody model with a temperature of ~94 eV from a circular emitting region with the radius of ~0.45 km or the NSA model with a lower temperature of ~41 eV from a larger emitting region with a radius of ~3.77 km (Marelli et al. 2013) assuming the pseudo-distance of Morla as 500 pc (Saz Parkinson et al. 2010). The total X-ray flux derived for the pulsar is in agreement with the results obtained from *Chandra* data (De Luca et al. 2011). According to the X-ray measurements, the inferred γ-ray-to-X-ray (F_γ/F_x) and X-ray-to-optical (*V* band; F_x/F_V) ratios are ~1,000 and ~520. F_γ/F_x of Morla is well below the mean for other RQ γ-ray pulsars (~9,000; Marelli et al. 2015). The absorption column density derived from the best spectral fits is fully compatible to the galactic absorption column in the direction of Morla inferred from the H_I distribution, and this result points to a lower limit for the pulsar distance of ~300 pc. The upper limit for the distance of ~900 pc can be estimated from the observed correlation between the intrinsic γ-ray luminosity and the spin-down power of the pulsar by assuming the γ-ray efficiency to be less than 1. Pulsations in the X-ray band (0.2-6 keV) can both be detected with a significance ≥ 3.5*σ*. The X-ray pulsed fraction both in soft (0.2-0.8 keV) and hard X-ray (0.8-6 keV) bands is ~85 %, and 80 % of the 0.8-6 keV photons come from the non-thermal pulsar component

while 50 % of the soft X-ray photons are attributed to a thermal origin. This result clearly demonstrates that the emission from a hot spot of Morla mainly contributes to soft X-rays while the synchrotron radiation occurring in the outer magnetosphere mainly provides hard X-rays.

The most intriguing feature of Morla is not the pulsar itself, but the X-ray tail detached from the pulsar. The high-resolution *Chandra* image clearly presents an extended structure protruding from Morla, corresponding to a size of >9′ in length and ~1.5′ in width. This tail is apparently separated from the pulsar with no detection of nebula counts until 50″ away, and it shows an asymmetric morphology with the brightest part far away from Morla. The spectrum of the tail/nebula can be fitted with a single power-law; however, the derived absorptions for the nebula and the pulsar are in conflict at the 3*σ* level and therefore reject an origin from the classical bow shock, ram-pressure-dominated pulsar wind. Comparing with the description with a non-thermal spectrum, the spectrum of the tail lacks any spatial variation and can be well modeled with the thermal bremsstrahlung emission (or other similar thermal models) with a temperature of ~3.75 keV, absorbed by a consistent column density applied to the X-ray spectrum of Morla (Marelli et al. 2013). Different from the traditional scenario of the PWN for a pulsar, Morla's nebula is believed to be the first example of a new "turtle's tail" class of pulsar bremsstrahlung nebula (PBN; Marelli et al. 2016). The cooling time for the PBN is orders of magnitude longer than for the traditional PWN, and it also explains a lack of spectral variation along the tail. The proper motion of Morla measured by Chandra observations is 165±30 mas yr^{-1}, resulting in a lower speed limit of 390 km s^{-1} if the distance of Morla is assumed as 500 pc (De Luca et al. 2013). Under the scenario of a strong shock front to heat ISM up to emit X-rays, we can also directly estimate the upper limit of the velocity as 1,900 km s^{-1} for Morla from the temperature of the shocked ISM material at the head of the bow shock. Although the existence of this extended feature is problematic for Morla with such a low spin-down power, the bremsstrahlung-emitting tail can still be inferred from the thermal radiation of ISM, shocked by a supersonically moving neutron star.

4.5 RQ γ-ray Pulsar with Only Non-thermal X-ray Pulsation – PSR J1813-1246 & PSR J2055+2539

The surface thermal emission of a neutron star is usually expected to contribute in the soft X-ray band, and therefore a broad sinusoidal modulation was always observed to dominate the X-ray pulsation. Comparing with the thermal

component, only ~25 pulsars clearly show non-thermal X-ray pulsed detection in the literature (e.g., Kuiper & Hermsen 2015). If we focus on the target of radio-quiet γ-ray pulsars, 4 Geminga-like pulsars (Geminga, Morla, PSR J1813-1246 and PSR J2055+2539) have non-thermal pulsations, while PSR J1836+5925 only has very marginal non-thermal pulsation obtained in 0.7-2.0 keV. Geminga, Morla, and PSR J1836+5925 have known thermal pulsations either from the entire surface or a hot spot, but X-ray pulsations detected in PSR J1813-1246 and PSR J2055+2539 have no indication of a thermal component, making these two RQ γ-ray pulsars incomprehensible objects to the theoretical modeling of their high-energy emission.

PSR J1813-1246 was discovered in a blind search during the first three months of *Fermi*/LAT scanning (Abdo et al. 2009) while PSR J2055+2539 is the only known Geminga-like pulsar that was not recorded in the 1st *Fermi* LAT catalog of γ-ray pulsars. Timing ephemeris of PSR J2055+2539 was confirmed by an analysis with about one year of data (2008 Aug. 4th - 2009 Jul. 4th; Saz Parkinson et al. 2010). Based on *GBT* observations, these γ-ray pulsars have no radio counterparts detected down to 17 μJy (Ray et al. 2011) and 7 μJy (Saz Parkinson et al. 2010) flux limits at 1.4 GHz. The field of PSR J2055+2539 was observed with the BTA 6 m telescope at the *Special Astrophysical Observatory* (Beronya et al. 2015), and no conclusive optical counterpart (*V* > 20.13) or H_α bow shock emission could be identified. According to the timing parameters determined by *Fermi* data, PSR J1813-1246 is the known RQ γ-ray pulsar with the fastest spin period and the second most energetic spin-down power while PSR J2055+2539 has the lowest spin-down power (that is compatible to Morla) among the known Geminga-like pulsars. PSR J1813-1246 is also characterized by its young age, similar to the pulsar centered in CTA 1, but PSR J2055+2539 is as old as PSR J1836+5925 with age of more than one million years. The γ-ray pulse profile of PSR J1813-1246 reveals two broad peaks with phase separation of ~180°, while that of PSR J2055+2539 has one major peak. The γ-ray spectra for both pulsars can be well described with the PLE model, as listed in Table 2, but the photon index obtained for PSR J1813-1246 is much softer than that for PSR J2055+2539. The emitting geometries for both cases can be proposed to fit all the popular outer magnetospheric models with different viewing and inclination angles (Pierbattista et al. 2015), although the slot gap is slightly favored. A clear asymmetric bridge emission exists between two peaks of the pulse profile of PSR J1813-1246, and the γ-ray spectrum becomes harder during this bridge phase. No off-pulse γ-ray emission has been detected for PSR J1813-1246, but this component is very strong for PSR J2055+2539. The off-pulse

emission of PSR J2055+2539 can also be fitted with the PLE model, which shows a magnetospheric origin, and a similar feature was observed for PSR J1836+5925 as well (Marelli et al. 2016). Two significant phase changes (glitches) were reported for the profile of PSR J1813-1246 with Δ*Phase* ≈ -0.037 and 0.345 on Sep. 20th, 2009 (Ray et al. 2011) and Dec. 29th, 2012 (Marelli et al. 2014), but no similar detection was reported for PSR J1813-1246.

Deep *XMM-Newton* observations provide the opportunity to further study the X-ray pulsation and the surrounding environment of these two pulsars. A comparison of the X-ray absorption along the line of sight with the column density derived from HI or ^{12}CO (*J*=1→0) gas can be used to estimate a lower limit on the distance of >2.5 kpc for PSR J1813-1246 and >450 pc for PSR J2055+2539 (Marelli et al. 2014, 2016). With the empirical relation of the intrinsic γ-ray luminosity and the spin-down power for PSR J2055+2539 (Saz Parkinson et al. 2010), an upper limit of the distance of ~750 pc can also be determined by requiring the γ-ray efficiency to be less than 1. No indication of a nebula was found down to 1.5" close to PSR J1813-1246; however, two nebulae associated with PSR J2055+2539 were detected with a physical size of ~2.1×0.05 pc and ~0.7×0.09 pc derived from the distance of nebulae at 600 pc away. Both nebulae have elongated tails and present uniform brightness profiles, corresponding to fractions of 2.4×10^{-3} and 3.0×10^{-4} of the pulsar spin-down luminosity. Although both nebulae can be fitted by either a single power-law or a thermal bremsstrahlung model, at least one of them cannot be applied to a classical synchrotron nebula explanation. The most plausible scenario is that the brighter tail is related to a collimated ballistic jet, and a similar feature, misaligned with the pulsar proper motion, was also discovered in the vicinity of PSR B2224+65 (Guitar nebula; Bandiera 2008). The fainter/smaller nebula is most likely a bow-shock PWN due to the spatial spectral variability. The proper motion of ~350 km s^{-1} for PSR J2055+2539 can be estimated by *Chandra* observations separated by two years; however, no such series of high-resolution images is provided to derive the proper motion of PSR J1813-1246.

The young-aged PSR J1813-1246 and middle-aged PSR J2055+2539 indeed have several different features but they share similarity in the non-thermal X-ray spectral origin. Comparing with the PSR J1813-1246 has the softest γ-ray photon spectrum among all the RQ γ-ray pulsars (cf. Abdo et al. 2013), but it also has the hardest X-ray spectrum among all the known Geminga-like pulsars (cf. Table 2). This result also leads to a γ-ray-to-X-ray flux ratio of ~230, three times less than the lowest value of other known RQ γ-ray pulsars (Marelli et al. 2015). The detection of PSR J1813-1246 in 30-500 keV obtained from international gamma-ray astrophysics

laboratory (*INTEGRAL*) IBIS/ISGRI also perfectly matches the entire spectral energy distribution from the soft X-ray to the *γ*-ray band (Marelli et al. 2014). On the contrary, PSR J2055+2539 has a hard *γ*-ray photon index, but it owns the softest X-ray spectrum among all the known Geminga-like pulsars. This result gives PSR J2055+2539 a *γ*-ray-to-X-ray luminosity ratio of ~1,600 and an X-ray efficiency of 3×10⁻⁴ (for an assumed distance of 600 pc), typical values derived for other RQ pulsars. No thermal component was significantly detected in the X-ray band for these two pulsars, although the structure of the pulse profiles is quite different. PSR J1813-1246 exhibits two peaks on the X-ray folded light curve while PSR J2055+2539 has a sinusoidal profile. Similar to the *γ*-ray pulse profile, PSR J1813-1246 also has no significant off-pulse emission in the X-ray band with a pulsed fraction of (96±3) %, but the X-ray peaks lag behind the *γ*-ray ones by a quarter of phase (Marelli et al. 2014). The most plausible interpretation for this detection is that *γ*-rays are emitted from the outer magnetosphere while X-rays come from the polar cap rim at an altitude of ~40 neutron star radii. Although the pulsed fraction detected for PSR J2055+2539 is only ~25 % (Marelli et al. 2016), this fraction remains a consistent value in the soft X-ray (0.3-1.5 keV) and the hard X-ray (1.5-10 keV) bands. This characteristic suggests a single component pulsation with a non-thermal origin because the X-ray spectrum behaves like a power-law. Comparing with the similar broad peak with a sinusoidal shape detected both in soft and hard X-ray bands, the pulse profile obtained in the *γ*-ray band has a narrower peak and a slightly larger pulsed fraction of ~30 % (Abdo et al. 2013). The polar cap model applied to explain the non-thermal X-ray pulsation detected for PSR J1813-1246 may also provide a similar X-ray emitting scenario for PSR J2055+2539, and this interesting result deserves deep investigation to test high-energy emission models.

4.6 The First Variable *γ*-ray Pulsar – PSR J2021+4026

γ-ray emission related to PSR J2021+4026 and its SNR, *γ* Cygni (G78.2+2.1), was discovered by *CGRO*/EGRET before 2000 and it was recorded as 3EG J2021+4017/GeV J2020+4023 (Lamb & Macomb 1997; Hartman et al. 1999). 3EG J2021+4017 is the brightest unidentified *γ*-ray source detected by EGRET and is located close to the center of an extended nebula that is generally recognized as a SNR (Higgs et al. 1977), and hence it is similar to the case of 3EG J0010+7309 mentioned in Subsection 4.3, which was connected to a pulsar candidate. Due to the limitation of the EGRET data, there have been many efforts involving a multi-wavelength search for a counterpart to conclusively identify 3EG J2021+4017 (Becker et al. 2004; Weisskopf et al. 2006).

Because 3EG J2021+4017 is one of 43 unidentified EGRET sources having counterparts in the *Fermi*/LAT first year catalogue, it was soon confirmed to be a LAT *γ*-ray pulsar with the first three months of data (Abdo et al. 2009). The correct X-ray counterpart was resolved using the *Chandra* image (Weisskopf et al. 2006), but complete studies in the X-ray band to this source (Trepl et al. 2010; Weisskopf et al. 2011), with a given name of 2XMM J202131.0+402645, could only be started after the pulsation was confirmed in the *γ*-ray band because of the lack of sufficient exposures. No radio and optical/infrared counterpart was found for PSR J2021+4026 or 2XMM J202131.0+402645, and hence 2XMM J202131.0+402645 was also recognized as a Geminga-like pulsar when the X-ray pulsation was confirmed (Lin et al. 2013). The upper limit on the undetected optical/infrared flux for the source can be determined by observations taken at *Kitt Peak National Observatory* with $I' > 23.0$ and $r' > 25.2$ (Weisskopf et al. 2011) and the undetected radio emission can be constrained by *GBT* with $S_{1400} < 20$ *μ*Jy (Ray et al. 2011). The association with the *γ* Cygni supports a distance of ~1.5 kpc for this pulsar (Landecker et al. 1980), and its proper motion is estimated to be ~340 (d/1kpc) km s⁻¹ (Trepl et al. 2010).

The *γ*-ray spectrum of PSR J2021+4026 can also be described with a PLE model, as shown in Table 2 (Abdo et al. 2013). But long-term monitoring with *Fermi*/LAT unveils another surprising phenomenon of a sudden decrease in energy flux by ~18 % over a time span shorter than one week. The basic feature to characterize a pulsar is its steady high-energy emission, but the *γ*-ray flux of PSR J2021+4026 has an obvious jump near Oct. 16ᵗʰ 2011 (MJD 55850). It indeed overturns the previous understanding to determine a pulsar candidate (Allafort et al. 2013). Not only the *γ*-ray flux, but also the pulse profile and the spectral behavior have changed simultaneously with different significance levels of > 5*σ* and < 3*σ*. Similar to the occurrence of a glitch, the rotational frequency of PSR J2021+4026 in this event also had a sudden change in the spin-down rate increasing from ~7.8×10⁻¹³ Hz s⁻¹ to ~8.1×10⁻¹³ Hz s⁻¹, which is a 4 % increase over a period shorter than one week. Although mode changes and intermittent behavior have been found for some radio pulsars (e.g., Lyne et al. 2010), this is the first time to have a similar event detected in the *γ*-ray band and makes PSR J2021+4026 the first known variable *γ*-ray pulsar. The decrease in flux rate associated with an increase in spin down rate might be caused by the shift of the magnetic field structure. The minor change of the magnetic inclination angle leads to a reconfiguration of the beaming geometry of *γ*-rays and a substantial fractional change on the emission efficiency.

Due to the instability of PSR J2021+4026, it is difficult to build a long-term global ephemeris without taking into account the timing noise. The strong periodic signal of 2XMM J202131.0+402645 was yielded from the long exposures (>100 ks) of *XMM-Newton* observation of 2012 and is consistent with that determined by the local ephemeris obtained from the 1 yr *Fermi* archive. Comparing to the double-peak feature seen in the γ-ray folded light curve, the X-ray pulse profile only has only one major peak with a broad FWHM and an obvious phase lag of ~ -0.14 (Lin et al. 2013). Another interesting feature is that all the pulsed X-rays concentrate in the medium X-ray band (0.7-2 keV), and the absence of indication of the pulsation obtained in the soft X-ray band (< 0.7 keV) is completely different from the major X-ray pulsed detections of other Geminga-like pulsars, and even the major pulsed component is non-thermal (e.g., PSR J1813-1246 and PSR J2055+2539). Only the multi-component model of a blackbody plus a power-law can give a reasonable fit to the X-ray spectrum. The thermal component obtained that is twice as powerful as the non-thermal flux can be described by the surface emission from a hot spot with the temperature of ~250 eV and a circular radius of ~$280d_{1.5}$ m, where $d_{1.5}$ denotes the distance to PSR J2021+4026 in units of 1.5 kpc. This result is consistent with the fit of the pulsed spectrum (Hui et al. 2015) and the polar cap heated by the return current injected from the outer magnetosphere (Cheng & Zhang 1999). Neither the pulsed thermal X-ray component nor the unpulsed non-thermal component is found to be variable before and after the epoch (MJD 55850) to discover the flux jump of γ-rays. The inferred flux ratio of F_x/F_V is ~ 250 and that of F_γ/F_x is > 2.5×10^4 (Weisskopf et al. 2011), which is the largest among those RQ γ-ray pulsars with known X-ray counterparts. Because no obvious pulsation was detected in the hard X-ray band, one possible origin for the power-law component is the PWN. A non-thermal extended feature can be resolved by the *Chandra*/ACIS image (Hui et al. 2015), and high-resolution deep X-ray observations are required to constrain the nature of the possible PWN.

5. DISCUSSION AND SUMMARY

Current understanding of RQ γ-ray pulsars is based on different emission geometry at different energy bands. A radio beam is expected to be radially emitted from magnetic poles within a narrow angle; however, high-energy photons are generally believed to be emitted through the synchrotron-curvature radiation or the inverse Compton scattering from the magnetosphere close to the light cylinder (Watters et al. 2009). Since the outer magnetosphere model supports the radiation over a broad phase with superposed sharp tips causing by caustics of the emission pattern, the amount of RQ γ-ray pulsars should be more than that of RL pulsars due to a relatively lower opportunity to observe the radio beam from a neutron star. According to the updated pulsar catalog[2] provided by the *Fermi* LAT Multiwavelength Coordinating Group on Feb. 22th 2016, now we have 205 γ-ray pulsars and 45 % of them are MSPs. Among 112 young-to-middle aged γ-ray pulsars, 54 were directly discovered through the improved technique (Pletsch et al. 2013) for a periodicity search with LAT data. If we follow the same criterion (S_{1400} < 30 μJy) used for the 2nd *Fermi* LAT catalog of γ-ray pulsars (Abdo et al. 2013) to determine RQ, then 47 % (including Geminga) of the young-to-middle aged γ-ray pulsars can be specified as RQ. Although the current known RQ γ-ray pulsars are still fewer than RL γ-ray pulsars, this ratio in the known young or middle-aged pulsars has already increased by 2 % to fit the speculation of the theoretical modeling in pulsar astronomy. But the aforementioned discussion does not take into account that an intrinsically RQ or a radio-silent pulsar may exist; astronomers are still trying to propose a plausible scenario to examine any possibility. In addition, no RQ MSP has been detected yet. Although those recycled pulsars are believed to have a smaller magnetosphere and a more complicated high-energy emission mechanism than young pulsars, the radio emission is believed to have the same origin. The limitation of the efficiency in periodicity search is the key reason to prevent the discovery of an RQ MSP, and this constraint is expected to be overcome with the modern AI of a high performance computing collaboration.

From the observational aspect, there is no clear correlation between the radio flux and X- or γ-ray fluxes was concluded. Nevertheless, the γ-to-X-ray energy flux ratio (F_γ/F_x) might be an indicator to discriminate an RQ pulsar from the known γ-ray pulsars owing to its relatively larger value (Marelli et al. 2015). In this article, the X-ray flux is mainly contributed to the non-thermal component of a pulsar because only a few cases (e.g., Geminga and PSR J2021+4026) have thermal emission dominating in the X-ray spectral behavior and the computation of the total X-ray flux would usually result in the ratio of a similar value/order. But to extend the relation of F_γ/F_x to all the RQ pulsars, we must take into account the selection bias of samples. Due to the technique to examine the periodic signal for an RQ γ-ray pulsar, it is impossible to detect an RQ γ-ray pulsar with a very low luminosity. For

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example, the faintest RL γ-ray pulsar recorded in 2nd *Fermi* LAT catalog of γ-ray pulsars, PSR J1531-5610, has photon flux (~10^{-9} ph cm^{-2} s^{-1}) and energy flux (~2×10^{-12} erg cm^{-2} s^{-1}) in the energy range of 0.1-100 GeV, which are both one order of magnitude lower than those for the faintest RQ γ-ray pulsar (cf. PSR J0106+4855). Because one can confirm an RL γ-ray pulsar using the known radio ephemeris to avoid an inefficient blind search, RL γ-ray pulsars can possibly have weak γ-ray flux and plainly lead to lower F_γ/F_xs. In order to build a firm connection of the observational feature yielded in multi-wavelength for RQ pulsars, RQ X-ray pulsars (e.g., Magnificent Seven; Treves et al. 2001) should be included in a complete inspection.

RQ γ-ray pulsars with deep X-ray observations to confirm their X-ray pulsations are named Geminga-like pulsars as well. We have 7 known Geminga-like pulsars, as listed in Table 2. Although all of them have relatively strong X-ray emission leading to F_γ/F_x in a similar order of magnitude, the major pulsed X-rays detected from these pulsars show clearly different origins. Only Geminga clearly presents X-ray pulsation originating from the star surface, a heated polar cap, and the outer magnetosphere, which results in an aligned pulse pattern, as seen in the γ-ray band. Although the entire surface radiation of a neutron star is expected to emit in the soft X-ray band, only Geminga and PSR J0007+7303 exhibit this thermal component. Thermal pulsations obtained from PSR J0357+3205 (Morla), PSR J1836+5925 and PSR J2021+4026 are concluded to emit from a small hot spot with temperature of ~1.1×10^6 K, ~7.2×10^5 K, and ~2.9×10^6 K. If we propose the blackbody model on a 10 km-radius neutron star for a distance 0.5 kpc away to fit Morla's X-ray spectrum, the 3σ upper limit of the surface temperature is less than 4.4×10^5 K, making Morla cooler than other coeval RQ pulsars (e.g., RX J1856-3754; Sartore et al. 2012). This may indicate that no significant contribution of the whole surface X-ray emission can be detected on a relatively old pulsar. However, PSR J2021+4026 is relatively young and hence such an inference is contentious. PSR J1813-1246 and PSR J2055+2539 only have non-thermal pulsed detection, proposed to be synchrotron radiation generated from secondary e^+/e^- pairs. Obtained X-rays emitted from polar cap cascades can extend from a few tenths keV to hundreds of MeV (Dyks & Rudak 1999), and have a different origin compared to the observed γ-rays. A slight change of the line of sight may make PSR J1813-1246 a bright radio pulsar, as presumed in Marelli et al. (2015).

Deep X-ray observations of Geminga-like pulsars also provide a chance to investigate the nebula in the vicinity. Geminga, PSR J0007+7303, PSR J2021+4026, and PSR J2055+2539 were found to have classical bow shock, ram-pressure dominated PWN while another brighter jet-like feature associated with PSR J2055+2539 should belong to a collimated ballistic jet, similar to those discovered for AGNs. The most interesting result is the discovery of a tail-like nebula detached from Morla. This feature is now concluded to be a new type PBN with thermal bremsstrahlung radiation coming from the shocked ISM heated to emit X-rays. Studies of RQ γ-ray pulsars in multi-band campaigns offer a key not only to discriminate different emission models but also to understand the details of this pulsar population including their neighboring environments. With deep investigation of more RQ and RL pulsars in multi-wavelengths, important contributions are expected to be obtained by comparison of theoretical analysis and observation results. As mentioned in Marelli et al. (2015), *XMM-Newton* observations of 130 ks exposures may provide a substantial possibility to have 8 more Geminga-like pulsars to extend our understanding of RQ (γ-ray) pulsars to a new level. The upcoming mission, extended Roentgen survey with an imaging telescope array (*eROSITA*) on-board the Russian "spectrum Roentgen gamma" (SRG) satellitie which will perform the first imaging all-sky survey in the X-ray band of 0.2-10 keV and be launched in 2017, will be devoted to the study of galactic compact objects including the population of isolated neutron stars (i.e., XDINS and magnetars). *eROSITA* has FOV comparable to *RXTE* (~1°), effective area comparable to EPIC-PN carema onboard the *XMM-Newton* (~1,400 cm²@1 keV), angular resolution comparable to *ROSAT* (15"@1.5 keV) and the time resolution of 50 ms, so the *eROSITA* All SKy Survey (eRASS) system is allowed to detect 60-100 new X-ray thermally emitting pulsars and thus extend the members in this population by an order of magnitude (Merloni et al. 2012). Because XDINs and some magnetars are also radio-quiet with very low (or none) γ-ray emission, such discoveries may bring a new understanding on RQ (γ-ray) pulsars comparing with those known cases detected at *Fermi* observatory. The launch of the advanced telescope for high energy astrophysics (*ATHENA*) in 2028 will be another important event for studying RQ pulsars with very dim pulsation, and the corresponding achievements like those we have obtained from the *Fermi* observatory may open another era for pulsar astronomy.

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