Radio and gamma-ray emission from pulsars

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Abstract.
The radiation of pulsars have been observed for many years. A few pulsars are discovered to have both radio and gamma-ray emission. Many models on pulsar radiation have been developed, but so far we are still lacking an elaborate model which can explain the emission from radio to gamma-rays in detail. In this paper we present a joint model for radio and gamma-ray emission, in which both the dominate emission mechanisms are inverse Compton scattering. The pulse profiles at radio and gamma-ray bands are reproduced for the Crab-like, Vela-like and Geminga-like pulsars, in good agreement with observations.

1. Introduction
A wealth of observational data on radio pulsars has accumulated in the last three decades. So far, seven gamma-ray pulsars have been discovered, of which six are also radio pulsars. The general properties of gamma-ray pulsars could be summarized as follows (Kanbach 2002): (1) the light curves of most gamma-ray pulsars show two major peaks with pulse widths close to 50 percent of the rotation period, (2) the gamma-ray spectra are hard, normally with a luminosity maximum around 1 GeV, but a spectral cutoff above several GeV is found; (3) the spectra vary with rotational phase indicating different sites of emission; (4) the gamma-luminosity scales with the particle flux from the open regions of the magnetosphere (Goldreich-Julian current). Except in the case of the Crab pulsar, the gamma-ray pulses are mostly much wider than the radio mean pulses and often show remarkable phase offsets from the radio pulses (e.g., the Vela pulsar).

In history, models for pulsar radio and gamma-ray emission have been developed within two separated domains, namely, the polar cap model for radio emission, either the polar cap or the outer gap models for gamma-ray emission. Since both radio and gamma-ray emissions can be observed simultaneously from a same pulsar, there come the questions: is there any relationship between radio and gamma-ray radiation? Is there any interaction between the acceleration processes in the polar and outer-gap accelerators? Can we have a model for both radio and gamma-ray emission?

There have been some efforts to fit the observations. It is suggested that in the outer gap model the gamma-ray emission altitude should be lower (Cheng & Zhang 1999), whereas in the polar cap model the altitude should be higher (Harding & Muslimov 1998), in order to explain well the observations. However,
the phase shifts of Crab-like and Vela-like pulsars, between radio and gamma-ray pulses, can not be explained simultaneously with either the outer or the polar cap models. If the emission is located between the null surface and the polar cap, a lot of observational facts (including the relative phase shifts) may be understood. Null surface plays a vital role in such a scenario.

This paper is an effort of such a joint model. Radio emission altitudes and pulse profiles are figured out under the ICS model (e.g., Qiao & Lin 1998), gamma-ray pulse profiles are calculated by assuming a second acceleration region above the polar gap (that is produced by space-charge limited flow of secondary particles).

2. A short statement for radio emission

We have proposed an inverse Compton scattering (ICS) model for pulsar radio emission (Qiao & Lin 1998, Xu et al. 2000, Xu et al. 2001, Qiao et al. 2001). Some main observational features can be understood under this model: (1) the central or 'core' emission beam and the conal beams; (2) emission altitude for each emission component; (3) linear and circular polarization of individual and integrated pulses; (4) pulse profiles changing with frequency. The equations what we used in this paper can be found in the papers above.

3. Equations for gamma-ray emission

Owing to there is a strong acceleration process through space charge limited flow near null surface, Gamma-rays would be produced there by synchrotron and Inverse Compton scattering mechanisms.

The emission location with distance \( r = \lambda R_{\text{null}} \) from the stellar center, where \( R_{\text{null}} \) is the minimum distance from the center to the intersection of null charge surface and the last open field lines, \( \lambda \) is a constant which is supposed to be less than but close to 1 (so that the acceleration region is not far from the null surface), e.g., 0.8 in this paper. Here we only show an analytical approximation for a small inclination angle (\( \alpha \)). For a large \( \alpha \) we perform numerical methods.

The emission location could be determined by

\[
\theta_e = \arcsin(\sqrt{\lambda} \sin(\frac{1}{2}(\arccos(-\frac{\cos \alpha}{3}) - \alpha))),
\]

where \( \theta_e \) is the angle between the magnetic axis and position vector \( \vec{r} \), and \( \alpha \) is the inclination angle. The angle between the radiation direction and the magnetic axis, \( \theta_\mu \), is given by

\[
\theta_\mu = -\alpha - \arctan(\frac{\cos(\alpha) + 3 \cos(\alpha + 2\theta_e)}{\sin(\alpha) + 3 \sin(\alpha + 2\theta_e)}) + \frac{\pi}{2}.
\]

With the emission angle we can calculate the phase separation between two emission components. Supposing that each emission component is Gaussian, we fit the mean pulse profiles with observations (see next section for results).
4. Results

The observed pulse profiles in gamma-ray and radio bands are fitted for seven pulsars, i.e., the Crab, PSR B1509-58, the Vela, PSR B1706-44, PSR B1951+32, the Geminga and PSR B1055-52. The profiles and fitted curves are shown in Figure 1. It is found that the observational profiles can be reproduced when reasonable parameters are chosen in our simulations.

5. Conclusions and discussions

The pulse profiles at both radio and gamma-ray bands are calculated under the joint model as it is shown here. In principle, the main observational features can be reproduced with this model. More details, such as phase resolved spectrum at gamma-rays, X-ray emission from pulsars, and so on, are need to be investigated in the future. For the inner gap sparking, a strange star model is benefit(Xu et al.2001).

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Figure 1. The observed and the simulated mean pulse profiles for seven pulsars. The dash lines are for simulations, and the solid lines for the observations.