Recent developments of inverse Compton scattering model of pulsar radio emission

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Abstract. Many theoretical efforts were made to understand the core and conal emission identified from observations by Rankin (1983) and Lyne and Manchester (1988). One of them, named as inverse Compton scattering (ICS) model (Qiao & Lin 1998), has been proposed. It is found in the model that: there are central or 'core' emission beam, and one or two hollow conical emission beams; the different emission components are emitted at different heights; owing to different radiation components emitted from different height, the observed emission beams can be shifted from each other due to retardation and aberration effects; the sizes of emission components change with frequencies. Recent developments of the model include: simulations of pulse profiles at different frequencies; studying the basic polarization properties of inverse Compton scattering in strong magnetic fields; computing the polarizations and spectrum of core and cones. A new classification system was also proposed. The main results calculated from the model are consistent with the observations.

1. Introduction

The emission beams of a radio pulsar have been identified as two (core, inner conal, Lyne & Manchester 1988) or three parts (plus an outer conal, Rakin 1983) through careful studies of the observed profiles and polarization characteristics. Many theoretical models can only explain the hollow cone beam. It is necessary to understand the core emission theoretically. Some theoretical efforts have been made, one of them is inverse Compton scattering model (ICS) model, which can get both core and conal emission beams (Qiao and Lin 1998, Liu et al. 1999; Qiao et al. 1999b; Xu et al. 1999a). Up to now, following issues have been investigated for the model:

(1). Inner gap structure and the explanation of some phenomena (Zhang & Qiao 1996; Qiao & Zhang 1996; Zhang et al. 1997a,b), such as mode-changing, nulling.

(2). Emission beams and emission regions of radio pulsars (Qiao & Line 1998).

(3). Frequency behaviour of pulse profiles (Liu & Qiao 1999; Qiao et al. 1999b).

(4). The polarization properties of the ICS model in strong magnetic fields (Xu et al. 1999a);

(5). Depolarization and position angle jumps (Xu et al. 1997);

(6). Coherent ICS process in magnetosphere (Liu et al. 1999; Xu et al. 1999a).

2.   Basic idea of the ICS model

The basic idea of the model can be found in Qiao & Lin (1998), Qiao et al. (1999b), Xu et al. (1999a) and Liu et al. (1999). In the model, low frequency electromagnetic waves are supposed to be produced near the star surface due to the violent breakdown of RS type vacuum gap (Ruderman & Sutherland 1975). The waves are assumed to propagate freely in pulsar magnetospheres and inverse Compton scattered by the secondary particles produced in gap sparking processes. The upscattered photons are in the radio band, i.e., the observed radio emission. With the simple dipole field, the incident angle of the ICS decreases first, and then starts to increase above a critical height. The Lorentz factor of the secondary particles, however, keeps decreasing due to various energy loss mechanisms (mainly the ICS with the thermal photons near the surface). The combination of the above two effects naturally results in the feature that on a given field line, the emission has the same frequency at three heights, corresponding to one core and two conal emission components.

One basic ingredient of the ICS model is the vacuum gap, which has been opposed by binding energy calculations. However, the idea that pulsars are bare strange stars can solve the binding energy problem completely (Xu & Qiao 1998; Xu et al. 1999b). If the vacuum gap could be formed, the ICS of the primary particles off the thermal photons actually take an important role in the inner gap physics, both within and above the gap (Zhang & Qiao 1996; Zhang et al. 1997a,b). The energy loss behaviour of the secondary particles is also influenced by ICS process (Zhang et al. 1997b).

3.   Emission beams and their properties

The central or 'core' emission beam, inner cone and outer cone beams have been simulated in the ICS model. We found that:

(1). 'Core' emission should be a small hollow cone in fact, which can be identified from de-composited Gaussian components (Qiao et al. 1999a).

(2). Different emission components are emitted at different heights: 'core' emission is emitted at a place near the surface, 'inner cone' at a higher place, and 'outer cone' at the highest. Due to the retardation and aberration effects caused by different heights, polarization position angle can have two or three modes at a given longitude (Xu et al. 1997).

(3). The beam size changes with frequencies. As observing frequency increases, the 'core' emission beam becomes narrow, the 'inner cone' becomes slightly wider or has little change, and the 'outer cone' also becomes narrow (Qiao & Lin 1998).

4.   Classification and frequency behaviour of pulse profiles

Based on the ICS model and the multi-frequency observations, radio pulsars could be devided into two categories:

Type I: Pulsars with core and inner cone. These pulsars has a shorter period P, and their polar caps are larger (e.g. Fig.6b in Qiao & Lin 1998). As the impact angle of the line of sight gradually increases, they are grouped into two sub-types, namely Ia (e.g. PSR B1933+16) and Ib (e.g. PSR B1845-01).

Type II: Pulsars with all three parts of beam. These pulsars have normal periods, and the low frequency waves should be strong enough at high altitudes to produce the radio emission. They can be further grouped into three sub-types as the impact angle gradually increases. Type IIa: pulsars with five or six components at most observing frequencies when the line of sight cut the core beam. The prototype is PSR B1237+25. Type IIb: the impact angle is larger so that at higher frequencies the line-of-sight missed the core beam. An example is PSR B2045-16. Type IIc: The line of sight has the largest impact angle, so that only the outer conical branch can be observed. A typical pulsar is PSR B0525+21.

The profiles of most these types or subtypes have been simulated, and typical examples were selected and compared its multi-frequency observations (Qiao et al.1999b, Liu & Qiao 1999). Here are two examples.

Type Ia: The multi-frequency observations of PSR B1933+16 show that it belongs to Type Ia pulsars. It has a single component at low frequency, but becomes triple at higher frequencies. Such behaviour can be simulated in the model, since the radius of the 'inner' cone increases towards higher frequencies. This may be an important feature of the ICS model distinguished from the other models.

Type IIa: For such pulsars, we simulate a typical example, PSR B1237+25. It is worth mentioning that the ICS model can interpret an important characteristics of this pulsar: five components in most frequency bands, but three components at very low frequencies. This can hardly be explained by any other model.

5. Polarization

The polarization features of scattered emission by relativistic electrons in the *strong* magnetic field were calculated from the Stokes parameters of scattering emission (Xu et al. 1999a). (1). When $\omega_{in} \ll \frac{eB}{mc}$, both ω_{in} and ω_{out} (the angular frequency of incident and outgoing photons, respectively) are in radio band, the scattered photons are *completely* linearly polarized, and its polarization position angle is in the co-plane of the out-going photon direction and the magnetic field. (2). For resonant scattering at high energy bands, significant circular polarization appears in the scattered emission. The position angle of linear polarization is perpendicular to the co-plane of out-going photon and the magnetic field, different from the case in radio band.

The inverse Compton scattering of a bunch of particles outflowing in pulsar magnetosphere should be coherent in order to produce significant circular polarization for beamed radio emission (Xu et al 1999a). At a certain time an observer can only see a small part of an emission beam radiated by a particle bunch, which we called 'transient beam'. (1). In ICS model, at a given frequency the transient beam have three parts (core, inner and outer cones), each of them is called 'mini-beam', and their polarization feature are quite differ-

ent. (2). Circular polarization is very strong (even up to 100%) in the core mini-beam and it is much less in the inner cone mini-beam. (3). If the line of sight sweeps across the center of a core (or inner conal) mini-beam, the circular polarization will experience a central sense reversal, or else it will be dominated by one sense, either the left hand or the right hand according to its traversing line relative to the mini-beam. (4). The position angles at a given longitude of *transient* 'sub-pulses' have diverse values around the projection of the magnetic field. The variation range of position angles is larger for core emission, but smaller for conal beam. When many such 'sub-pulses' from one mini-beam is summed up, the mean position angle at the given longitude will be averaged to be the central value, which is determined by the projection of magnetic field lines. (5). Stronger circular polarization should be observed in sub-pulses with higher time resolution according to our model.

6. Conclusion

Besides the natural appearance of core and conal components, some observational properties of radio pulsars can also be explained in the ICS model, such as the frequency-dependent pulse profiles, the polarization nature of mean pulses and individual pulses. We propose here a classification method for grouping pulsar integrated pulses, which may help to understand the multi-frequency pulse data.

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