On the inverse Compton scattering model of radio pulsars

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Abstract.

Some characteristics of the inverse Compton scattering (ICS) model are reviewed. At least the following properties of radio pulsars can be reproduced in the model: core or central emission beam, one or two hollow emission cones, different emission heights of these components, diverse pulse profiles at various frequencies, linear and circular polarization features of core and cones.

1. Introduction

"The crisis today, over twenty years later, is that theory has produced nothing more useful to compare observations with in order to interpret them" (Radhakrishnan 1992). On observational aspect, emission beam of a radio pulsar can be divided into two (core, inner conical) or three (plus an outer conical) components through careful studies of the observed pulse profiles and polarization characteristics (Rankin 1983; Lyne & Manchester 1988).

Many pulsar profiles at meter wavelength are dominated by core components. In the usual models of radio pulsars which are related to polar cap, it is difficult to get a central or "core" emission beam. Considering such obvious discrepancy between observations and theory, several authors (e.g., Beskin et al. 1988; Qiao 1988a,b; Wang et al. 1988, Lyutikov et al. 1999) presented their models for the core emission. In the following, we discuss some characteristics of the inverse Compton scattering (ICS) model (Qiao 1992; Qiao and Lin 1998, hereafter as QL98; Liu et al. 1999; Qiao et al. 1999; Xu et al. 2000).

2. On Emission beams

2.1. Basic idea of the ICS model

The basic idea of the ICS model (Qiao 1988a,b; QL98) can be briefly described as following. Low-frequency electromagnetic waves are produced in the polar cap due to gap sparking and afterwards propagate out freely; Such low energy photons are then inverse-Compton-scattered by the secondary particles from the pair cascades, and the up-scattered waves are the radio emission observed from pulsars.
With the conditions $B \ll B_q = 4.414 \times 10^{13}$ Gauss and $\gamma \hbar \omega_0 \ll m_ec^2$, the frequency formula of the ICS mechanism (Qiao 1988a,b; QL98) is

$$\omega \simeq 2\gamma^2 \omega_0 (1 - \beta \cos \theta_i),$$

(1)

where $\omega_0$ and $\omega$ are the frequencies of incident and scattered waves, respectively. The Lorentz factor of the secondary particles is $\gamma = 1/\sqrt{1 - \beta^2}$, and $\theta_i$ is the incident angle (the angle between the direction of motion of a particle and an incoming photon). Using the formula above, we have obtained so called “beam-frequency figure” (see QL98, Qiao et al. 1999), which is the plot of the beaming angle $\theta_\mu$ (the angle between the emission direction and the magnetic axis) versus observing frequency $\nu$. The shape of emission beams, emission heights and other emission properties can be derived from the “beam-frequency figure”.

2.2. The central emission beam and hollow cones

Two distinct types of emission components were identified from observations, namely, ‘core’ or central emission beam near the center and one or two hollow cone(s) surrounding the core. The ICS model can reproduce one core and two cones at the same time. The emission beam in the model could consist of (1) Core + inner cone emission, for pulsars with shorter rotational periods; (2) Core + inner and outer cones, for pulsars with longer periods. Furthermore, the core emission may be a small hollow cone in fact, i.e., not be fully filled. This can be identified from some pulsar profiles through “Gaussian decomposition” (Qiao et al. 1999).

In the model, we found that these emission components are emitted at different heights. The ‘core’ emission is emitted at the place closed to the surface of neutron star, the ‘inner cone’ at a higher place, and the ‘outer cone’ at the highest place.

We also found that the sizes of the emission beams should change with frequency. As observing frequency increases, the ‘core’ emission beam becomes narrow; the ‘inner cone’ size increases or at least keeps constant; but the ‘outer cone’ size decreases. For given magnetic inclination and impact angles, we can figure out how the shape of pulse profiles vary with frequency (see Qiao et al.1999). This is the theoretical base for the classification of radio pulsars.

2.3. Classification for radio pulsars

The pulse profile shapes, especially the variation of profiles with the observing frequencies are very important for understanding the emission mechanism of pulsars. In the ICS model, various pulse profiles and its evolution over a wide frequency range can be well simulated. As the impact angle gradually increases, pulsars can be grouped into two types (and further sub-types) according to the ICS model (Qiao et al. 1999).

Type I – Pulsars with only core and inner conical emissions. Such pulsars usually have shorter periods (thus have larger polar caps). There are two sub-types. Type Ia: Pulsars of this type have very small impact angle, and normally show single pulse profiles at low frequencies, but triple profiles at high frequencies. Prototype in this form are PSR B1933+16, PSR B1913+16. Type Ib: Pulsars of this type have larger impact angle than that of Type Ia. Though at low
frequencies the pulsars also show single profiles, they will evolve to double profiles at higher frequencies, since the lines-of-sight only cut the inner conical beam. An example of this type is PSR B1845-01.

Type II – Pulsars with all three emission beams. Pulsars with average period often have such a feature. IIa: Pulsars of this type have five components at most observing frequencies, since the small impact angle makes the line-of-sight cut all the three beams (the core, the inner cone and the outer cone). One important point is that in the ICS model, the five pulse components will evolve to three or even one component at very low frequencies (see QL98, Fig. 6a, line A). Such a feature have been observed from PSR B1237+25 (Kuzmin et al. 1998). IIb: For this type, the impact angle is larger than IIa, so that at higher frequencies, the line-of-sight does not cut the core beam. Thus the pulsars show three components at low observing frequencies, but four components when frequency is higher, and finally just double profiles at highest frequencies. PSR B2045−16 is an good example. IIc: Pulsars of this type have the largest impact angle, so that only the outer conical beam is cut by the line-of-sight. The pulse profiles of this type are double at all observing frequencies, with the separation between the two peaks decreasing at higher frequencies. This is just the traditional radius-to-frequency mapping which has also been calculated in the curvature radiation (CR) picture. The prototype is PSR B0525+21. Alternative situation of this type is that pulsars have single profiles at most of observing frequencies, but become double components at very low observing frequencies. An example is PSR B0950+08.

3. Linear and circular polarization

Pulsar radio emission is generally found to be linearly polarized over all longitudes of profiles, sometimes as high as up to 100%. The position angle sweep is in an ‘S’ shape, which can be well understood within the rotating vector model. However, depolarization and position angle jumping are often found in the integrate profiles of some pulsars. Considering the retardation effect due to relative phase shift between pulsar beam components (the core and conal emission components are retarded from different heights in ICS model), we find that the phase shift of beam centers of the different components could cause the depolarization and position angle jump(s) in integrated profiles (Xu et al. 1997).

3.1. Basic idea for polarization in ICS model

We have calculated the polarization feature of the ICS model. Now we would like to present one key point about how the circular polarization is produced in the ICS model.

As many authors (Ruderman & Sutherland, 1975; QL98) argued, there may exist the inner gap above the pulsar polar cap. The continuous gap formation and breakdown provide both low frequency waves with $\omega_0 \sim 10^5$ s$^{-1}$ and out-streaming relativistic particles with $\gamma \sim 10^3$. The low frequency waves will be up-scattered by relativistic particles (moving direction $n_e$) to observed radio waves. The frequency ($\omega$) of out-going waves is determined by eq.(1), while their
complex amplitudes \( E \) are determined by (Liu et al. 1999)

\[
\begin{split}
E &= C \frac{\sin \theta'}{\gamma^2 (1 - \beta \cos \theta')^2} e^{i(\omega_0 t R - \frac{\omega}{c} R \cdot n + \phi_0)} e_s,
\end{split}
\]

(2)

where \( n \) is the observing direction, \( R \) is the low frequency wave vector, \( \theta' \) is the angle between \( n_e \) and \( n \), \( C \) is a constant, \( e_s \) is an electric unit-vector in the co-plan of \( n_e \) and \( n \), and \( \phi_0 \) is the initial phase determined by incident wave.

Moving out and losing energy via inverse Compton scattering, the particle undergoes a decay in \( \gamma \), which is assumed to be (QL98)

\[
\gamma = \gamma_0 [1 - \xi (r - R_0)/R_e].
\]

(3)

The electric field of the total scattered wave at a direction \( n \) is the sum of \( E \) of each electron if such electrons are scattered coherently.

The emission region for a certain \( \omega \) can be obtained by eq.(1). As pointed out in QL98, there are generally three possible emission zones, corresponding to core, inner and outer cones. The scattered electromagnetic waves can be superposed coherently if the low-frequency waves are from same sparking and the emission region is smaller than \( 2\pi c/\omega_0 \). The coherent superposition of scattered waves will result in circular polarization as well as linear polarization (Xu et al. 2000).

3.2. Further considerations and numerical results

*Subpulse* circular polarization patterns

When the line of sight sweeps across a mini-beam, we can see a transient "subpulse". 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 left hand or right hand according to its traversal relative to the mini-beam.

Subpulse Position Angles

Subpulse position angles show diverse values, which are generally centered at the projection of the magnetic field. The variation range is quite small for subpulses from outer cone emission zones, and becomes larger when emission height decreases, that is, larger for inner cone and core component. The position angles values are scattered around the value of the projection of the magnetic field lines. When emission of all the sub-pulses are summed up, the mean position angle will have the mean value. So naturally the mean position angle is related to the projection of magnetic field lines, exactly as assumed by the rotation vector model.

Circular and linear polarization of mean profiles

An observer can see bunches of particles all around his line of sight. The polarization he receives from individual bunches is different. When the magnetic axis is inclined from the rotation axis, the probability of the sparkings was assumed to decrease exponentially with the azimuthal angle from the projection of the rotational axis in our simulation. We then get significant (but smaller than in subpulse) circular polarization for core components of mean pulses. But this is not the case for the cone components.
4. Conclusion

The ICS model can reproduce many observational properties of radio pulsars. There are emission beams of core, inner and outer cones. These beams are emitted from different heights. The pulse profiles change with frequencies, similar to what observed from many pulsars. The transient 'sub-pulses' have very high circular polarization (sometimes as strong as 100%). In mean pulse profile, circular polarization is much higher in core than that in inner cone and outer cone.

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References

Beskin, V.S., Gurevich, A.V., Istomin, Y.N., 1988, Ap&SS, 146, 205
Liu, J.F., Qiao, G.J., Xu, R.X., 1999, Chin. Phys. Lett., 16, 541
Lyne A.G., Manchester R.N., 1988, MNRAS, 234, 477
Lyutikov, M., Blandford, R.D., Machabeli, G., 1999, MNRAS, 305, 338
Qiao, G.J., 1988a, Vistas in Astronomy, 31, 393
Qiao, G.J., 1988b, in: High Energy Astrophysics, ed. G.B. Borner, p.88, Berlin: Springer-Verag.
Qiao, G.J., 1992, in: IAU Colloq. 128, eds. T.H. Hankins et al., p. 239, Poland: Pedagogical Univ. Press
Qiao, G.J., Lin, W.P., 1998, A&A, 333, 172 (QL98)
Qiao, G.J. Liu, J.F., Zhang, B. Han, J.L., 1999, ApJ, submitted
Radhakrishnan V. 1992, in: IAU Colloq. 128, eds. T.H. Hankins et al., p. 267, Poland: Pedagogical Univ. Press
Rankin J.M. 1983, ApJ, 274, 333
Ruderman, M.A. Sutherland, P.G., 1975, ApJ, 196, 51
Wang, D.Y., Wu X.J., Chen H., 1988, Vistas in Astronomy, 31, 399
Xu, R.X., Liu, J.F., Han, J.L., Qiao, G.J., 2000, ApJ, in press
Xu, R.X., Qiao, G.J. Han J.L., 1997, A&A, 323, 395