

What Causes the Circular Polarization in Pulsars?

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Abstract

A plausible explanation for the the circular polarization in radio pulsars is in terms of propagation effects in the inhomogeneous birefringent pulsar plasma. The escaping radiation has the polarization characteristic of the natural wave modes in a polarization limiting region, probably associated with the cyclotron resonance region.

1. Introduction

The circular polarization (CP) of pulsar radio emission is an embarrassment. Data on the complete polarization of integrated pulses has long been available, and the characteristics of the CP are well documented (Han et al. 1998). Data on the complete polarization of single pulses (Ekers & Moffat 1968; Clark & Smith 1969) imply that the CP can be large and variable from pulse to pulse. Evidence was found for a systematic swing of the polarization across the Poincaré sphere (Lyne, Smith & Graham 1971), and it is of considerable interest to have this possible characteristic feature explored in further detail. The CP in single pulses correlates partially, but not completely between different frequencies (Karastergiou et al. 2001). There is no simple theory that explains the observed features of the CP in a natural way.

The possible explanations for CP (cf. Radharkrishnan & Rankin 1990) can be separated into three classes: CP intrinsic to the emission process, CP imposed through cyclotron absorption, and CP imposed as a propagation effect. The third of these is favored here. It is argued that the CP is associated with orthogonal modes (Stinebring et al. 1984) that are elliptically polarized at a polarization limiting region.

2. Intrinsic CP and CP due to cyclotron absorption

Two possibilities are that the CP is intrinsic to the emission process, and that the CP is imposed by cyclotron absorption. However, one encounters major difficulties in explaining all the observed CP in terms of either.

If curvature emission is the emission process then incoherent emission (Gil & Snakowski 1990) can have a CP that is large for a single particle and reverses as the line of sight crosses that plane of the curved path. The CP in incoherent emission from a distribution of particles is small due to a strong cancelation of the positive and negative CP. However, pulsar emission must be coherent and

maser curvature emission can occur only at a nonzero angle to the plane defined by the curve, implying that it has a preferred handedness (Luo & Melrose 1992). While maser curvature emission has not been ruled out as the pulsar emission mechanism, it is sensitive to magnetic field strength, B , and could not explain CP in both millisecond and ordinary pulsars.

Cyclotron absorption occurs where the wave frequency is equal to the (Doppler shifted) cyclotron frequency of the ambient particles. All the particles are thought to be in their lowest Landau level (no motion perpendicular to the magnetic field), and a particle jumps to its first excited state on absorbing a cyclotron photon. Cyclotron absorption by electrons and positrons affects radiation with opposite handedness. If the incident radiation has no CP, a nonzero CP develops provided that the distributions, notably the number densities, n_{\pm} , of electrons and positrons are different. Luo & Melrose (2001) estimated the importance of the effect, and concluded that it may be important for some pulsars. The cyclotron resonance should be more important when it occurs at lower heights, which corresponds to higher frequencies. Hence, this mechanism might be most favorable for explaining an increase in the CP at high frequencies. However, the estimates suggest that cyclotron absorption cannot explain all the observed CP.

3. Birefringence in pulsar plasma

The observational evidence on orthogonal mode changes in the polarization of some pulsars (Stinebring et al. 1984) points strongly to birefringence playing an important role in propagation of radio waves through the pulsar magnetosphere (McKinnon & Stinebring 2000). Granted that this is the case, the interpretation of the polarization must be based on the polarization of the natural modes as they escape from the pulsar magnetosphere. A plausible model involves the following three ingredients: an emission mechanism that generates radiation in one of the natural modes; a propagation region in which the two modes propagate independently, except for specific locations where mode coupling occurs; and a 'limiting polarization' region beyond which the birefringence is ineffective in causing further changes in the polarization of the natural modes.

The pulsar radio emission mechanism must be coherent, in the sense that it involves growing waves, and wave growth strongly favors the fastest growing mode. The most favorable mechanism so far suggested involves a nonresonant beam instability (Gedalin, Gruman & Melrose 2002), which generates only the L-O mode. Although the other mode (X mode) can be generated in principle for $n_+ \neq n_-$ (Luo & Melrose 2001), its growth rate is always much smaller. To explain the orthogonal polarizations, one requires that some mode coupling process generates a mixture of the two modes. Ignoring mode coupling, as the radiation propagates outward through the magnetosphere, the polarization adjusts continuously so that it always coincides with that of the natural mode at that point. The most important changes in the polarization are due to changes in the angle, θ , of propagation relative to the magnetic field, and the modes becoming more circular near the cyclotron resonance. In particular, the handedness of the modes (for $n_+ \neq n_-$) reverses sense at the angle $\theta \sim 1/\gamma_p$, where γ_p is the bulk Lorentz factor of the plasma, that corresponds to $\theta = \pi/2$ in

the rest frame of the plasma. The polarization also becomes more circular at frequencies where cyclotron absorption occurs.

The polarization ceases to change at a polarization limiting region. The condition for limiting polarization is simply that the two modes cease to get significantly out of phase, but the practical estimation of where this occurs is not straightforward. In effect, changes in the medium must cause the polarization of the natural modes to change faster than the components in the two modes get out of phase: separating into two modes is then physically irrelevant, and the two modes are said to be strongly coupled. The data on CP in pulsars may be interpreted in terms of the limiting polarization occurring where the modes are nearly linearly polarized in pulsars where the CP is weak, and where the modes are substantially circularly polarized in pulsars where the CP is strong. A polarization limiting region in the cyclotron absorption region is favorable for high CP for two reasons. First, the circular polarization of the natural modes tends to be highest near the cyclotron frequency. Second, the polarization ellipses are changing shape, as a function of frequency, relatively rapidly, thereby favoring strong mode coupling.

4. Generation of orthogonal modes

Granted that any instability in the birefringent pulsar plasma favors one mode or the other, a separate mechanism is required to produce a mixture of the two modes, as required to explain the orthogonal mode changes. "Mode coupling" is the generic name for the effect of inhomogeneity causing a transfer of energy between the modes. When mode coupling is weak, the inhomogeneity slightly modifies the propagation allowing energy in one mode to leak slowly into the other. When mode coupling is strong, the inhomogeneity dominates the birefringence, and the polarization transfer of the radiation is as in an isotropic medium. Petrova (2001) discussed mode coupling associated with propagation of pulsar radiation in the presence of large-scale gradients in the pulsar magnetosphere.

A more effective way of coupling the modes is through reflection off a sharp boundary. In general, an incident ray in one mode generates reflected and transmitted rays in both modes. The effectiveness of this process depends primarily on the presence of sufficiently sharp gradients: specifically one requires the plasma parameters to change over a distance shorter than that in which the two modes get out of phase. One model that allows this is localization of the pair plasma into columns (Deshpande & Rankin 1999). A model in which pulsar emission is generated in underdense regions between dense plasma columns and is ducted outward through reflections off the columns has several favorable features. First, it allows for emission at lower frequencies than in a smooth magnetosphere at the same mean density, thereby overcoming a difficulty in accounting for the lowest frequencies in the pulsar emission (Melrose & Gedalin 1999). Second, reflection of the walls of the duct allows pure L-O mode radiation to become a mixture of L-O and X-mode radiation, as is required to account for the observed orthogonal polarizations. The model of reflection of sharp boundaries proposed here is motivated partly by models to explain the directivity, depolarization and ducting of solar radio bursts (cf. Bougerest & Steinberg 1977, Duncan 1979).

5. Conclusions

It is highly desirable that the well-documented properties of the CP in integrated pulses (Han et al. 1998) be complemented by corresponding properties of CP in single pulses. For example, confirmation of a possible characteristic sweep of the polarization across the Poincaré sphere (Lyne et al. 1971), the statistics of the variation in CP from pulse to pulse, and the correlation of the CP at different frequencies (e.g., Karastergiou et al. 2001) should all provide important additional clues to the origin of the CP.

The properties of the CP are most plausibly interpreted as a propagation-induced effect. A plausible model involves several stages: waves are generated by an instability that strongly favors a single mode of the birefringent plasma; this radiation in a single mode is converted into a mixture of the two modes due to mode coupling, and the polarization of the escaping radiation is determined by that of the natural modes at a polarization limiting region. It is suggested here that effective mode coupling might be due to reflection of the wall of underdense ducts, in which the radiation is generated, defined by the regions between overdense, field-aligned plasma columns. The polarization limiting region may be located in the cyclotron resonance region. This seems to be required that for those pulsars that exhibit substantial CP because the CP of the natural modes is a maximum and the shape of the polarization ellipses is changing most rapidly as a function of frequency at this location. For pulsars that exhibit no significant CP, the polarization limiting region must be located where the modes have no significant CP.

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