DOPPLER PERIOD VARIATIONS OF HIGH-VELOCITY PULSARS

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Abstract. The effect of the source motion on the period variation of pulsars is investigated. For some pulsars, a velocity 100-300 km/s can give a Doppler contribution to the second period derivative $\dot{P}$ which is comparable or larger than the intrinsic variation predicted by theoretical models, whereas larger velocities are required in order to give an appreciable kinematic effect on the first derivative $\dot{P}$. The possibility of experimental detection of $\dot{P}$ and proper motion for known pulsars is discussed.

1. Introduction

The original suggestion that at least some pulsars might possess high velocities relative to the local standard of rest (Shklovskii, 1969; Burbidge and Hoyle, 1969) is now receiving some observational support, and seems to agree with theoretical ideas on the process of pulsar formation in supernova explosion. We briefly summarize some of the relevant data: (1) The optical pulsar NP 0531 in the Crab Nebula has a measured proper motion $\mu = (0.^{\prime}0.9 \pm 0.^{\prime}0.3) \ (\text{year})^{-1}$, which corresponds to a tangential velocity $v_t \sim 100$ km/s. (2) Observations of pulsar dynamic spectra (Ewing et al., 1970) gave evidence for systematic drifting of spectral features of CP 0328, CP 0834, CP 1133, and CP 1919. The observations are consistent with an interstellar scintillation effect, and allow to deduce transverse velocities of $\sim 100$ km/s (within a factor two) of the sources with respect to the interstellar medium and Earth. (3) Prentice (1969) found a spatial correlation between some pulsars and young supernova remnants, but no correlation with older remnants; this led him to suggest that pulsars might possess very high velocities, possibly of the order of 1000 km/s. (4) Shklovskii (1969), noticing the uncommon fact that all pulsars are 'single', considered the possibility that they were formed from a multiple system: when one of the components undergoes a supernova explosion, the system can disrupt, and the remnant neutron star (pulsar) can be ejected with high velocity (the orbital velocity plus a possible contribution from the asymmetry of the explosion). Arnett (1969) independently suggested, from theoretical considerations, that pulsars are produced from O–B stars, which are usually binary massive stars with radial velocities $v \sim 100–200$ km/s. Arnett noticed that pulsars would also be expected to form from 'runaway' stars, that, according to Zwicky (1957) and Blaauw (1961), are high-velocity objects ($v \sim 40–200$ km/s) left over after the explosion of their companion in a binary system. (5) Gott et al. (1970) considered the possibility that the Crab pulsar NP 0531 and the pulsar NP 0525, located at $1.^{\circ}2$ angular separation from the Crab, arose from two distinct supernova events of stars originally belonging to a binary system in the nearby association I

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Geminorum, and estimated for both pulsars a space velocity $v \sim 150$ km/s. Reifenstein et al. (1969), and Burbidge and Hoyle (1969), earlier suggested that NP 0525 could have been ejected from the Crab Nebula itself: but this requires a velocity $v \sim 0.15$ c, and we shall see that this possibility can be ruled out. (6) Gunn and Ostriker (1970) presented evidence for a positive correlation between pulsar periods and their distances from the galactic plane. If, as predicted by current pulsar models, the pulsation period increases with age, and if pulsars are born near the galactic plane, this correlation could be interpreted by assuming that younger pulsars are located near their birth places, while older ones have moved far away with high velocity. Gunn and Ostriker fitted the data with a scale height at birth $|z| \sim 80$ pc (that associates pulsars with $B$ stars of Population I), and with a mean space velocity at birth $v \sim 170$ km/s.

(7) Michel (1970) analyzed the asymmetrical collapse of a massive star, whose core could fragment into several objects, including neutron stars. The system becomes unbound, and runaway pulsars with $v \sim 1000$ km/s could be generated. (8) Shklovskii (1969) and Detre (1969) suggested that the observed slowing down of pulsar periods could be due to the Doppler effect from the high velocity of the object.

In the present note, we shall give a general discussion of the kinematic effects on the period variation, taking into consideration the contribution to the first and second time derivatives of the period.

2. Estimate of the Time Derivatives $\dot{P}$ and $\ddot{P}$ from the Doppler Effect

Let us consider a pulsar at a distance $R$, with intrinsic period $P_0$, moving with (non-relativistic) velocity $v$ relative to the Earth, in a direction at an angle $\theta$ with the line of sight (Figure 1). The period received at the Earth is

$$P = P_0 \left(1 + \frac{v_r}{c}\right),$$

($v_r = v \cos \theta$ is the radial component of the velocity). By differentiating with respect to time we have

$$\left(\frac{dP}{dt}\right)_k = -\frac{P_0 v_r}{c R} \sin^2 \theta = -\frac{P_0 v_r}{c R},$$

Fig. 1. Geometry of the system.