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# Simulations of the generation of partial nongyrotropy of newborn ions

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## Abstract

The nongyrotropy of newborn ions in solar wind plasmas is studied by means of one-dimensional electromagnetic hybrid computer simulations of homogeneous plasmas. It is found that, contrary to the previous theory of nongyrotropy, the homogeneous injections of newborn ions can also produce the nongyrotropy of newborn ions (partial nongyrotropy). However, the inhomogeneous injections of newborn ions can make the ion nongyrotropy stronger. The newborn ion nongyrotropy is different within different perpendicular velocity range, and is strongest in the velocity range close to the injection velocity of newborn ions $V_{\mathrm{in}}$.

*Keywords:* Nongyrotropy; Newborn ions; Phase-angle diffusion; Generation mechanism

## 1. Introduction

A very important phenomenon concerning newborn ions at comet Grigg–Skjellerup is the nongyrotropic velocity distribution of newborn ion (Coates et al., 1993). The so-called nongyrotropic structure of particles refers to the velocity distribution that is dependent on the gyrophase angle in the perpendicular plane with respect to the ambient magnetic field. Such velocity distributions are also observed and reported in many other space regions, such as at collisionless shocks (Gurgiolo et al., 1981; Eastman et al., 1981; Anderson et al., 1985; Thomsen et al., 1985; Sckope et al., 1990), near the space shuttle orbiter (Cairns, 1990), in the earth's distant magnetotail (Frank et al., 1994; Saito, 1994), in the solar wind (Astudillo et al., 1996), and in some active experiments.

The instabilities driven by nongyrotropic rings ions have been studied for parallel propagation (Sudan, 1965; Fredricks, 1975; Gurgiolo et al., 1981, 1993; Fruchtman and Friedland, 1983; Freund et al., 1987; Wu et al., 1988; Gary, 1991a,b; Tsurutani, 1991; Brinca et al., 1993; Glassmeier and Neubauer, 1993; Motschmann and Glassmeier, 1993; Neubauer et al., 1993a,b; Cao et al., 1995, 1999, 2000; Motschmann et al., 1997; Brinca and Romeiras, 1998; Convery et al., 2002) and for oblique propagation (Cao et al., 1998; Motschmann and Glassmeier, 1998).

Both theoretical analysis and observations show that the waves excited by the newborn ions are mainly parallel (Brinca et al., 1993; Gurgiolo et al., 1993; Motschmann and Glassmeier, 1993, 1998; Neubauer et al., 1993a,b; Cao et al., 1995, 1998, 2000; Motschmann et al., 1997; Brinca and Romeiras, 1998; Convery et al., 2002). The theoretical analysis shows that the growth rate of parallel propagation wave is much larger than that of oblique propagation wave in the nongyrotropic plasma

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(Cao et al., 1998; Motschmann and Glassmeier, 1998). The simulation results also show that the wave excited by nongyrotrpic ions is parallel propagation wave (Convery et al., 2002). The observation shows that wave propagation directions are approximately parallel (or antiparallel) to the magnetic field (about 10° with respect to $\pm B_0$) (Neubauer et al., 1993a). However the oblique propagating fluid mirror waves may occur for cases of large temperature anisotropies of new injected ions and or in high $\beta$ regions (Tsurutani et al., 1982).

In addition, the nongyrotropic ions always produce a zero-order electrical current. This zero-current is dependent on the nongyrotropic coffeicient $\Phi_{n\neq 0}$ (see Cao et al., 1995). Generally, if the density of the implanted ions is very small, this current is also correspondingly very small, and consequently its effect can be neglected (Fredricks, 1975; Cao et al., 1995).

The nongyrotropy of newborn ions can be observed at inactive comets such as Comet Grigg–Skjellerup. Compared to comet Halley's environment, the interaction region of comet Grigg–Skjellerup shrinks since its production rate of newborn ions is very low (about $7.5\times 10^{27}\ \mathrm{s}^{-1}$) (Johnstone et al., 1993; Neubauer et al., 1993b); this small size of the comet environment, compared to the gradient in the density of implanted ions ($n \propto r^{-2}$) may cause strong deviation from gyrotropic ion distribution due to inhomogeneous injection of newborn ions.

Thus it seems that only inhomogeneous injection rates of newborn ions can produce the nongyrotropy of newborn ions (for example Grigg–Skjellerup comets), and the homogeneous injection rates of newborn ions cannot produce the nongyrotropic distribution of new born ions (for example Halley comets). It is true if all the ions with different velocities are considered in the phase-angle space. However, recently, our studies show that the nongyrotropy of newborn ions can exist even in the case of homogeneous injection of newborn ions, and the inhomogeneous injection of newborn ions at inactive comet only enhance the nongyrotropy of newborn ions. In fact, even for homogeneous injection rate, the nongyrotropy of new born ions may exist for the ions with velocities close to the injection velocity. The newborn ions with velocities close to injection velocities are very active and is the main source of free energy. Thus we call this kind of nongyrotropy "partial nongyrotropy".

The purpose of this paper is to study the generation mechanism of nongyrotropy of newborn ions by computer simulation of one-dimensional homogeneous hybrid code. Newborn ions are continuously injected at a constant rate with a specified initial pitch angle 90° and thus almost invariable low frequency waves are guaranteed. In Section 2, we will present briefly the simulation model. In Section 3, the results of the simulations and some discussions are presented. Section 4 gives a conclusion.

## 2. Simulation model

The simulations are carried by means of a hybrid code, which is the same as that in Cao et al. (1999, 2000) and similar to that used by Winske and Omidi (1993) and Gary et al. (1988). The interactions between the particles and (the electric and magnetic) fields are calculated self-consistently. The ambient magnetic field is $\mathbf{B}_0 = B_0\mathbf{e}_x$ and the system is assumed to be periodic in the $x$-direction. There are two ion populations in the simulation model: core protons and injected newborn ions. The core protons are constant in number and distributed uniformly in space with a zero drift Maxwellian velocity distribution at $t = 0$. The injected ions are introduced into the simulation randomly in space with constant initial velocity $\mathbf{v}_{\mathrm{in}} = -V_0\mathbf{e}_z$, which have a small thermal spread. This small thermal spread is represented by the $\beta$ value of plasma. The injection rate of the newborn ions is defined by $\Lambda_{\mathrm{p}} \equiv (\mathrm{d}n_{\mathrm{p}}/\mathrm{d}t)n_{\mathrm{c}}^{-1}$, where $n_{\mathrm{c}}$ is the density of the core protons and $n_{\mathrm{p}}$ is the density of the injected ions. The phase angle $\phi$ is measured from $e_y$. Thus the initial angles of newborn ions are 270°. $f(\phi)$ is the phase-angle distribution function and satisfy the condition $\int_0^{360} f(\phi)\,\mathrm{d}\phi = 1$.

Time is normalized to $\Omega_{\mathrm{p}}^{-1}$, spatial length is normalized to $c/\omega_{\mathrm{p}}$ ($\omega_{\mathrm{p}}$ is the proton plasma frequency), and velocity to Alfven speed. The time step $\Delta t$ is $0.05\Omega_{\mathrm{p}}^{-1}$ and the cell size $\Delta x$ is 1. The simulation box has 512 cells. The ratio of the plasma frequency to the proton cyclotron frequency $\omega_{\mathrm{p}}/\omega_{\mathrm{p}}$ is 12,000, roughly the value in the solar wind. The injection velocity $V_{\mathrm{in}}$ is $4V_{\mathrm{A}}$. Therefore, $V_{\mathrm{in}}\Delta t = 0.2 < \Delta x/2$. The small warm velocity spreads of particles can be deduced from plasma betas ($\beta_{\mathrm{e}} = \beta_{\mathrm{p}} = 0.4$). For the injected ions, it is assumed that $T_{\mathrm{in}} = 0.2T_{\mathrm{p}}$.

50,124 total particles are used in the system and correspondingly there are 98 particles per cell, which can ensure that simulations can give good statistical results.

## 3. Simulation results

We present results of three simulations. In these simulations, we change only one parameter: the injection rate. The injection rate is $2\Lambda_{\mathrm{p}}(10^{-5}\Omega_{\mathrm{p}})$ in Simulation 1 and $4\Lambda_{\mathrm{p}}(10^{-5}\Omega_{\mathrm{p}})$ in Simulation 2 and $8\Lambda_{\mathrm{p}}(10^{-5}\Omega_{\mathrm{p}})$ in Simulation 3. The other parameters used in simulations are all same for three simulations.

### *3.1. Nongyrotropy for newborn ions with different velocities*

In Simulation 1, the initial velocity of newborn proton particles $V_{\mathrm{in}}/V_{\mathrm{A}}$ is equal to 4. The injection rate $\Lambda_{\mathrm{p}} = 2\times 10^{-5}\Omega_{\mathrm{p}}$.

Newborn protons are injected in the system at an injection pitch angle $\alpha = 90°$, and excite low-frequency