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Note

Spoke formation under moving plasma clouds—The Goertz–Morfill model revisited

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Abstract

The plasma cloud mechanism of spoke formation in Saturn's rings, proposed by Goertz and Morfill in 1983, is revisited in the light of new data and the criticisms raised by Farmer and Goldreich [Farmer, A.J., Goldreich, P., 2005. Icarus. This issue]. It is concluded that the plasma cloud model satisfies all available observational and physical constraints.

Keywords: Saturn; Saturn's spokes; Dusty plasmas

1. Introduction

New information about Saturn's spokes, their temporal variability, particle sizes and topology has recently been assembled (McGhee et al., 2005). At the same time, a great deal of research has been carried out in over 3000 publications in the last 10 years about complex (dusty) plasmas, including dust-plasma boundaries, dynamics, self-organisation and physical processes (see, e.g., Shukla et al., 1997; Horanyi et al., 1998; Nakamura et al., 2000; Bharuthram et al., 2002; Shukla and Stenflo, 2004). It is the purpose of this paper to review the physics of the Goertz and Morfill (1983) (thereafter called GM) spoke formation model in the light of the advancement of the field of complex (dusty) plasmas and, in particular, with reference to the criticisms raised by Farmer and Goldreich (2005) (thereafter called FG). We briefly review the underlying assumptions of the FG model, then we describe the GM model and the new research results that bear on the physics (some of which unknown in 1983) and finally we derive the conditions for spoke production and comment on the results.

2. The FG model

The model is describes by the authors as a 2D strip of material (representing dust grains plus ions) located at $z = 0$, with two infinite sheets at $z = \pm L$ representing the ionosphere of both hemispheres of Saturn. The magnetic field is $B = B_z$. FG explain "Defined in this way, the strip resembles a strip of metal, in which the dust grains are analogous to the ion lattice and the neutralising ions are like the electrons which balance the charge on this lattice."

In this model the plasma contains a net positive charge (plasma plus negatively charged dust are overall charged neutral). Evaluating the dynamics of their coupled system "plasma + dust," FG arrive at the result that the mechanism proposed by GM—plasma cloud/particle interaction driven spoke formation—cannot work.

3. The GM model revisited

In the GM model the scale height of the plasma cloud is much greater than the scale height of the levitated dust particles. Hence the plasma cloud can be divided into two regimes (Fig. 1). The upper regime is dust-free and charge neutral (bulk plasma cloud), the lower regime is (by comparison) a thin sheet which is overall charge neutral and contains negatively charged dust particles (dusty plasma sheet). Since the Debye length in the plasma cloud is also small, typically of the order 1 m, this "dusty plasma sheet" is of very small vertical extent compared to the overall plasma cloud.

The two plasma regimes are separated by a sheath-like double layer, such as has been observed recently in space experiments on the ISS (Fig. 2). The dust cloud in these ISS experiments presents a "solid" surface of only $\sim 10^{-4}$ of the overall interface—nevertheless the plasma still reacts in many ways as if it was a continuous surface of floating potential, except that the recombination flux has a much deeper penetration (Goree et al., 1999; Annaratone et al., 2002). The interface with the B-ring also contains a sheath, of course, since the plasma cloud has to supply the electron/ion fluxes to replenish the recombination there, too. These details were not considered in the original GM paper, but they do provide additional constraints.

The "dusty plasma sheet" provides the engine (or the battery) for the subsequent evolution in the system: the dust particles undergo quasi-Keplerian motion and may leave the plasma, which is tied to the field lines. When the dust particles no longer have contact to the bulk plasma reservoir, they become positively charged by solar UV light, giving up their net negative charge as free electrons. This is the same net negative charge "missing" on the other side of the dusty plasma cloud—having become attached to the dust particles during the charging process and then transported away azimuthally.

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Of course, the same process also operates for the main B-ring. The B-ring particles (we may consider them to form a continuous sheet since the optical depth $\tau \geqslant 1$) also get charged up negatively when in contact with the plasma cloud, they also move with Keplerian velocity (different from the corotating plasma cloud) and also carry charges from the cloud out into the sunlight. However, as we will see later, the charge transport due to the dust dominates.

Both sources of electrons—ring particles and elevated dust (we omit a description why and how the dust may be elevated and refer the reader to GM)—drive an electron current, which closes through the ionosphere of Saturn and replenishes the electrons missing on the other side of the "dusty plasma sheet" and the ring. The current-driven azimuthal electric field in the GM model is then responsible for the subsequent dynamical evolution of the plasma cloud and the spoke formation. Ultimately, the energy source is gravity (Fig. 3).

4. New data

New observations published recently by McGhee et al. (2005) have yielded the following main results:

- The effective spoke particle size is 0.57 ± 0.05 μm, the size distribution is narrow.

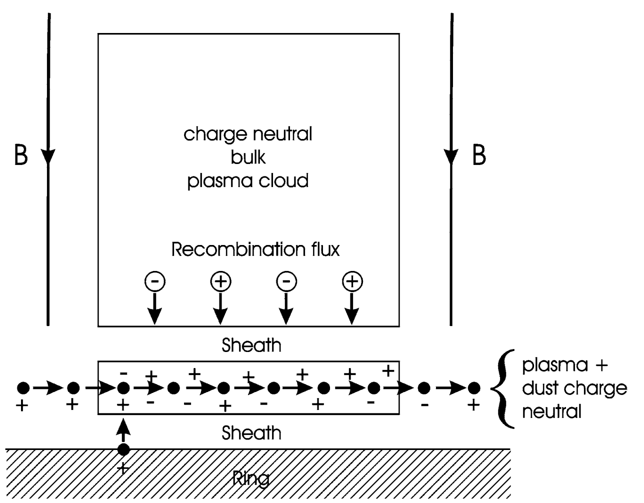

Fig. 1. Structure of the plasma cloud. The lower region (thickness ∼100 km) is the "dusty plasma sheet," where a significant fraction of the negative charge is attached to the dust particles. The upper region (thickness ∼500 km) is the "bulk plasma cloud," which consists of ions and electrons in charge equilibrium. This large reservoir of plasma supplies the "dusty plasma sheet" with fresh charges lost by surface recombination. As a consequence, a sheath-like double-layer forms between the two regimes.

- The photometric contrast (and visibility) of the spokes strongly depends on the effective ring opening angle, visibility being best when this angle is smallest.
- Multiple scattering MC calculations suggest that the spoke particle cloud occupies an extended layer thicker than the B-ring or lies exclusively above the B-ring.
- The perpendicular optical depth of the spoke particles is 0.01–0.05.

There is another significant finding that has received comparatively little attention so far, but is important for our later discussion (Grün et al., 1983).

- 95% of the spokes observed in the morning ansa (local time 5.00 to 9.00 h) originated at local time earlier than 6.00 h (estimated by Kepler shearing backwards until the leading edge is radial).

5. Evolution of the "structured" plasma cloud

Let us now discuss the *evolution of the "structured" plasma cloud* (Fig. 1) under the influence of the externally driven currents and fields (Fig. 3), making use of the new experimental information about dust–plasma interfaces (Fig. 2 and references). The plasma cloud may be considered as consisting of two parts, as mentioned before—the "bulk cloud" and the "dusty plasma sheet." There is no reason why these two parts of the plasma cloud should always stay together—in fact, given appropriate forces they will slide apart. Note also, that there is a significant physical difference between charged dust particles drifting out of the "dusty plasma sheet" and the bulk plasma cloud sliding away from the "dusty plasma sheet." In the former case negative charges are removed from the system and liberated outside it by UV light. In the latter, recombination sets in and returns the dust particles to their former charge state (the UV flux is

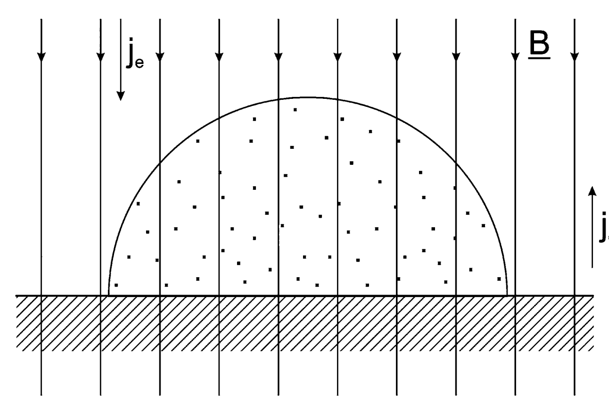

Fig. 3. Illustration of the current system produced by the dust charge transport.

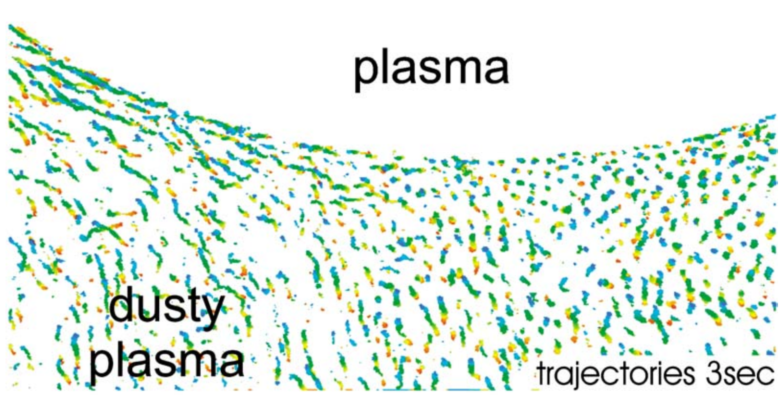

Fig. 2. Complex (dusty plasma) interface with a normal electron–ion plasma, as observed in experiments with the PKE-Nefedov laboratory on the ISS. Although the particulate surface (the microparticles are overexposed and appear much bigger than they are) only constitutes 0.01% of the interface, there is nevertheless a sheath-like boundary layer separating the two regimes, causing the sharp interface. Particle trajectories are shown, colour coded from red ($t = 0$) to blue ($t = 3$ s).