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DENSITY DEPLETION IN A CORONAL FLUX TUBE ASSOCIATED WITH SOLAR RADIO EMISSION

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Abstract. A discussion, which is motivated by recent study of solar radio emission, is presented to address the issue under what conditions the depletion of plasma density in a flux tube in the corona may take place. Two particular situations are of interest: One is that density is depleted due to the presence of beams of energetic particles, and the other is attributed to magnetic compression. The scenario discussed appears to be consistent with the occurrence type III solar radio bursts.

1. Introduction

1.1. FOREWORD

Optical observations show fibrous density structures exist commonly in the corona. These structures imply that the plasma density in the corona is in general highly inhomogeneous and there are underdense and overdense flux tubes. It is reasonable to suppose that these flux tubes may occur in the corona under different solar conditions and situations. Many of them exist intrinsically in the corona. A commonly accepted argument is that the inhomogeneity is due to the fact that the coronal plasma has a low beta value (the ratio of thermal pressure to the magnetic pressure). In a low-beta plasma a small perturbation of the ambient magnetic field in a flux tube can result in considerable density change due to pressure balance (see discussions in Dulk, 1985; Benz, 1993). However, two points should be remarked. First, the beta value at high altitudes is not always very low. Second, one may also expect that depletion of the ambient plasma density may be attributed to special circumstances.

We suggest that density depletion may also take place under conditions peculiar to active regions where solar flares occur and energetic particles are generated.

To be more specific we consider that energetic particles are generated at a site above the chromosphere (magnetic-field reconnection in the low corona may be one of the possibilities). The newly created energetic electrons and protons are supposed to propagate away from the generating site in both upward and downward directions. It is usually assumed that the downward electrons and protons would lead to the emission of X-ray (and gamma rays, if they are sufficiently energetic) while these particles "collide" with the chromosphere while the upward electrons and protons propagate directly into the interplanetary space and be eventually observed in interplanetary space or near the earth. It is well known that these energetic electrons are responsible for the type III solar radio bursts, which attracts a great deal of theoretical interest over the past several decades.

The purpose of this paper is to address a basic issue. That is, whether the energetic particles could result in density depletion in a flux tube where these particles are created and propagating. Before going further we must first explain what motivates us to carry out the present study so that the readers may attain a better understanding of the physical background and the relevant picture.

1.2. BACKGROUND AND MOTIVATION

To explain the background we mention briefly two well known phenomena: one is the solar type III radio bursts (Wild and McCready, 1950) and the other is earth's auroral kilometric radiation (AKR; *e.g.* Gurnett, 1974). Let us begin with the former.

Observations of the type III radio bursts are extensively discussed since early 1950s (Kundu, 1965). It is well known that type III solar radio emission occasionally has two components, namely the F (fundamental) and H (harmonic) waves. The former has typical frequencies close to the plasma frequency in the source region while the latter has frequencies close to twice the plasma frequency, according to conventional plasma emission hypothesis based on which a theory is proposed by Ginzburg and Zheleznyakov (1958) to explain the source mechanism due to a beam of energetic electrons. However, a series of subsequent publications (Smerd, Wild, and Sheridan, 1962; Bougeret *et al.*, 1970; McLean, 1971; Stewart, 1972, 1974a,b; Dulk and Suzuki, 1980) based on observations with better resolution raise several fundamental issues. The most intriguing one is that in general F waves and H waves with equal frequencies have coincidental apparent source regions, a conclusion in contradiction with customary expectation. The only scenario that may explain the observation is as follows. The radio waves are emitted and then confined in a flux tube which has an interior plasma density much lower than the exterior density. Consequently the true source of emission is not observable. However this wave may escape from the tube at a higher altitude where the outside plasma cutoff frequency becomes slightly lower than the wave frequency. This exit point appears as the apparent source. Based on this thinking one may easily see that an F wave emitted at a low altitude may escape with an H wave of same frequency emitted at a higher altitude at the same exit point. As a result, observers would see that the two waves have same emission source. This scenario is suggested in Duncan (1979), Wu *et al.* (2002; 2005), Yoon, Wu and Wang (2002). In conclusion, the foregoing observational results suggest indirectly that the observed radiation is generated in flux tubes where the plasma density is significantly depleted. The implication is that in the low corona under-dense flux tubes associated with type III bursts are evidently in existence. The ultimate question is whether such a density-depleted flux tube is self-consistently produced by the energetic particles or just intrinsic.

On the other hand, it is well known that the earth's auroral kilometric radiation, like solar type III bursts, is also attributed to energetic electrons. A very important point is that in situ observations show that AKR is generally produced in regions with significant density depletion, as shown in Figure 1. This is first reported by Benson, Calvert and Klumpar (1980), who studied ISIS-1 data, and confirmed later by many subsequent articles (*e.g.*, Benson, 1985; Roux *et al.*, 1993; Strangeway *et al.*, 1998; Janhunen, Olsson and Laakso, 2002). In these publications observations with ISIS-1, *Viking*, FAST, and *Polar* satellites are discussed. These observations indicate compellingly that energetic particles may induce density depletion. The question of interest is by what process the energetic particles can efficiently reduce the ambient plasma density. Evidently a theory along this line is not only of interest in its own right but also is relevant to the study of type III solar radio bursts. It is this issue that has motivated the present study.

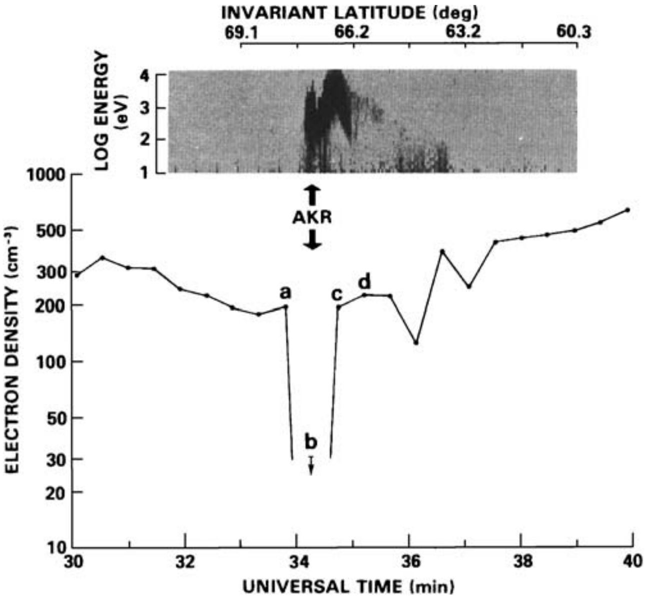

Figure 1. Electron density along the satellite track is shown. The AKR source region eencouter is indicated by the arrow (from Benson, Calvert and Klumpar, 1980).

Since the proposed scenario to be discussed later is based on some basic and relevant plasma processes, we find that it may be useful to review them at the outset. Section 2 is written for this purpose. The essential part of the theory is presented in Section 3. Then we present discussion and conclusions in Section 4.

2. Basic Relevant Processes

Let us consider a magnetic flux tube with a finite radius. Inside this tube there are four components of particles: the background electrons and protons, and tenuous beams of fast electrons and protons. We suppose that initially the electron and proton beams have equal beam speeds that are much higher than the local Alfvén speed. To show that this assumption is consistent with the situation in the corona a discussion is in order. Admittedly there is no standard magnetic field model available for solar active regions. In the following we shall adopt the same density and magnetic field models used in Wu *et al.* (2005). With these models we can calculate the ratio of $\Omega_i/\omega_{pi} = v_A/c$, where Ω_i and ω_{pi} are the gyro-frequency and plasma frequency of the ambient protons, v_A and c are the Alfvén speed and the speed of light in vacuum, respectively. The results are displayed in Figure 2 from which we see that if the energetic particles are generated at a site anywhere in the low corona and if the beam speed is about $v_b \approx 0.1 \sim 0.2c$, the condition $v_b \gg v_A$ is in general satisfied. Here the beam speed is conjectured based on that suggested by type III bursts observations (Dulk, 2000). However, it is necessary to note that Figure 2 is just for demonstrating that the beam speed is generally much higher than the Alfvén speed in the corona. The variation tendency of Alfvén speed with altitude may be

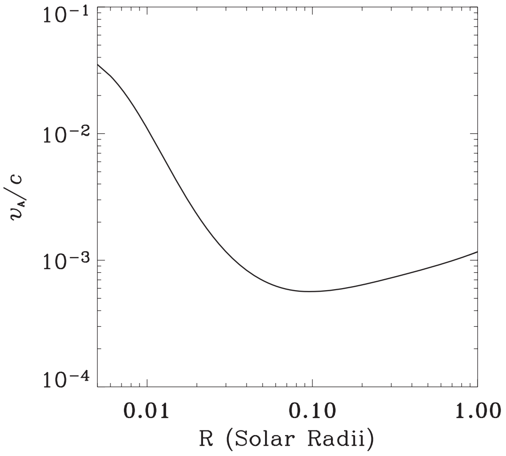

Figure 2. Variation of the ratio $\Omega_i/\omega_{pi} = v_A/c$ as a function of the altitude is displayed.

different from Figure 2 in the high corona. It is generally believed that Alfvén speed decreases with altitude in the high corona.

To proceed with the discussion we assume that outside the tube there are no energetic particles. To make our discussion self-contained we now review briefly several basic and relevant plasma processes, which are crucial for the scenario to be described in Section 3.

2.1. EXCITATION OF ALFVÉN WAVES BY THE PROTON BEAM

It is known that a fast ion beam can excite ultra-low frequency (ULF) waves (for example, see review article by Brinca, 1991). In space physics this process is verified and discussed with *in situ* observations in interplanetary space (Tsurutani and Smith, 1986a,b; Neugebauer *et al.*, 1986; Sagdeev *et al.*, 1986 and many other papers). Linear theories predict that in general ULF waves propagating in the parallel direction are most important and in fact both left-hand and right-hand polarized waves may be excited. However, numerical studies reported in the literature find that the right-hand mode generally prevails. These waves propagate in the same direction of the proton beam. Since these waves satisfy the dispersion relation $\omega = kv_{\mathrm{A}}$, where ω and k are respectively the wave frequency and the wave number, hereafter for convenience they are simply named as Alfvén waves.

Let us consider a simple model for the enhanced Alfvén waves. Hereafter we denote the wave-magnetic field by $\delta\mathbf{B}$ that is perpendicular to the ambient field. Let us adopt a coordinate system in which the ambient magnetic field is parallel to the z-axis so that the wave magnetic field in the laboratory frame of reference may be expressed as

$$\delta\mathbf{B} = \sum_k B_k(z)[\cos(\omega t - kz + \phi_k)\mathbf{i}_x \tag{1}$$

$$+ \sin(\omega t - kz + \phi_k)\mathbf{i}_y], \tag{2}$$

where $\mathbf{i}_x$ and $\mathbf{i}_y$ are unit directional vectors; and ϕ_k is a phase. In general the amplitudes $B_k(z)$ may be slowly varying in z. Thus, the total magnetic field may be written as

$$B_{\mathrm{total}}^2 = B_t^2 + \delta\mathbf{B}\cdot\delta\mathbf{B}, \tag{3}$$

where B_t denotes the background field, which is uniform, inside the tube. Hereafter for practical reasons, we shall only consider its ensemble-averaged value of (3). For this purpose we impose the random phase approximation (Davidson 1972; Ichimaru 1991) so that we obtain

$$\langle\delta\mathbf{B}\cdot\delta\mathbf{B}\rangle = \sum_k B_k^2(z), \tag{4}$$

which may be calculated if a spectrum is known or assumed. It is in this sense that we may write (3) as

$$B_{\text{total}}^2 = B_t^2 + \sum_k B_k^2(z) \equiv B^2. \tag{5}$$

We will make use of (5) later.

2.2. 'HEATING' OF BEAM PROTONS

The enhanced Alfvén waves can in turn affect the beam protons via pitch-angle scattering. This process is extensively discussed in the literature of ion pickup process (*e.g.*, early works are cited in articles written by Yoon and Wu, 1991; Li *et al.*, 1997; Wang and Lin, 2003). An important consequence of this process is that a major portion of the kinetic energy associated with the beam is transformed into random motion in the wave frame. As a result, the original beam distribution function evolves into a spherical shell (partial or complete) distribution in velocity space with a center approximately situated near the Alfvén speed.

This implies that the mean proton beam speed is significantly reduced while the beam protons are 'heated', as the scattered ions possess a high kinetic temperature. In the present discussion this process plays an essential role, as will be shown later. To demonstrate this process we present Figure 3 in which the results based on a hybrid simulation are displayed. In this simulation the following parameters are used. The density ratio $n_{\text{b}}/n_0 = 0.01$ and $v_{\text{b}} = 20v_A$ are assumed arbitrarily (where n_b and n_0 are the beam-proton density and the density of the ambient proton, respectively; v_{b} is the proton beam speed, and $\beta_i = v_i^2/v_{\text{A}}^2 = 0.01$, v_i is the thermal speed of the ambient protons). In space physics this process is evidenced with

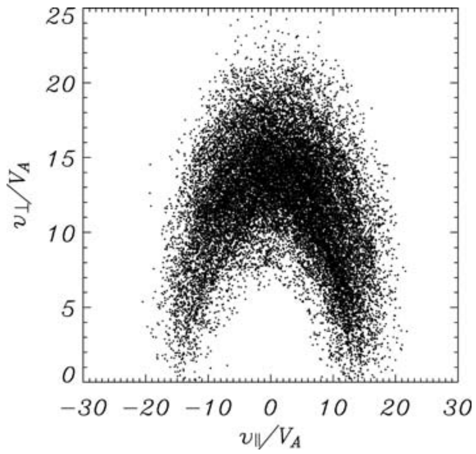

Figure 3. It is shown the velocity distribution of the original beam-protons at 180 ion gyro periods based on a hybrid simulation.

in-situ observations near cometary exospheres where newborn ions interact with thet solar wind (Mukai *et al.*, 1986; Neugebauer *et al.*, 1989).

Indeed while the proton beam is affected by the Alfvén waves, the electron beam is not because the electrons do not interact with Alfvén waves effectively (although eventually nonlinear interactions may take place at a much later stage, *e.g.* Lu and Wang, 2004). The reduction of proton beam speed means that there exists a relative velocity between the electron beam and the proton beam. This implies that a current exists along the ambient magnetic field. This current can quickly result in an induced electric field that would drive a return current to neutralize the beam current. The return current is mainly associated with the ambient electrons. Since the ambient electron density is much higher than that of the beam electrons, the velocity of the background electrons needed to form this return current is very small.

Two important points deserve attention: First, our simulation finds that the typical time scale of the formation of a shell distribution is less than 100 ion gyro periods. It means that in the solar corona where the proton gyro frequency is high, the process is almost instantaneous. Second, the beam protons with a shell distribution possess a very high kinetic temperature. For instance, if initially the beam speed is αv_{A}, then afterward the radius of the shell is roughly $(\alpha - 1)v_{\mathrm{A}}$. Therefore, the corresponding kinetic temperature is roughly

$$T_{\mathrm{eff}} = \frac{1}{2} m_i (\alpha - 1)^2 v_{\mathrm{A}}^2. \tag{6}$$

If T_i denotes the temperature of the ambient protons, then we may write (6) in terms of this temperature. That is

$$T_{\mathrm{eff}} = \frac{(\alpha - 1)^2}{\beta_i} T_i. \tag{7}$$

This means that in case of a low-beta plasma, this kinetic temperature is much higher than the temperature of the ambient protons. Clearly if the condition

$$\frac{(\alpha - 1)^2}{\beta_i} \frac{n_{\mathrm{b}}}{n_0} \gg 1 \tag{8}$$

is satisfied, the kinetic pressure associated with the beam protons is much higher than that of the ambient protons.

3. Pressure Balance Across the Boundary of the Flux Tube

3.1. BASIC CONSIDERATIONS

The essence of our model may be described as follows. We consider that energetic ions are generated in a flux tube at a source point and then flowing away. For simplicity, it is assumed that the generation process is on a time scale much longer than the thermalization time of the beam ions. This assumption is easily satisfied because according to numerical simulations the thermalization time is of the order of 100 ion gyro periods. Let us consider that magnetic reconnection gives rise to these ions and beam ions are flowing in the reconnection layer. One can see that even near the neutral sheet where the magnetic field is weakest the foregoing time scale is only a small fraction of a second. As described in the foregoing section, in our model the speed of the beam ions is much higher than the Alfvén speed in the tube and these ions would excite Alfvén waves. The ensuing waves will in turn pitch-angle scatter the ions, and result in a high kinetic temperature of these ions. The enhancement of the thermal pressure of these "hot" ions tends to deplete a significant fraction of the background plasma out of the tube. One may think that the hot ion cloud is like as a "porous" piston driving along the tube such that some of the ambient particles are able to stay but many of them are squeezed away. In summary, the hot beam protons inside the flux tube tend to push the ambient protons out of the region. These depleted protons are supposed to move ahead of the hot beam protons, and eventually precipitate to the chromosphere and the interplanetary space.

A self-consistent analysis concerning the time-dependent depletion process is difficult. One of the difficulties is that in principle the 'hot' beam protons cannot be appropriately described by a fluid theory. Another point is that protons close to the leading edge of the beam can only contribute to the excitation of the Alfvén waves but are not "thermalized". This implies that there exists a spatial gradient of the kinetic temperature T_{eff} or kinetic pressure. Obviously to discuss this transition region we need to consider kinetic processes that involve both wave excitation and pitch-angle scattering.

The residual density of the ambient plasma may be approximately estimated from a pressure balance in the direction transverse to axis of the tube. To simplify the discussion we consider that the flux tube has a constant cross section with a dimension sufficiently small so that the plasma density and temperature inside have uniform profiles. In a frame of reference co-moving with the hot ion cloud the pressure balance relation (in Gaussian units) may be written as

$$n_0 T_0 + \frac{B_0^2}{8\pi} = n_i T_i + n_b T_{\text{eff}} + \frac{B_t^2}{8\pi} + \frac{1}{8\pi} \sum_k B_k^2, \tag{9}$$

where B_0 and B_i denote the ambient field outside and inside the tube, respectively; n_0 and T_0 are the exterior density and temperature of the protons; n_i and T_i are the interior density and temperature of the ambient protons; n_b and T_{eff} are the density and kinetic temperature of the beam protons. From (9) we obtain

$$\left(1 - \frac{1}{\beta_i}\left[\frac{B_t^2}{B_0^2} - 1\right] - \frac{1}{\beta_i B_t^2} \sum_k B_k^2 - \frac{n_b(\alpha - 1)^2}{n_0 \beta_i}\right) \frac{T_0}{T_i} = \frac{n_i}{n_0}, \tag{10}$$

where we have considered that in general the temperatures of the ambient protons inside and outside the tube, T_i and T_0, respectively, may be different due to turbulent heating, and we have also defined

$$\beta_i \equiv \frac{8\pi n_0 T_0}{B_0^2}.$$

From (10) we see that density depletion can take place due to several effects. In the following we discuss them separately.

3.2. MAGNETIC COMPRESSION

Let us first consider the special case in which no proton beam is present but only the electron beam occurs. In this case it is implicitly assumed that a return current occurs so that current neutrality is satisfied. Since there is no proton beam, we expect that the Alfvén waves are not excited. It is seen that density depletion can take place if a flux tube is magnetically compressed with adjacent flux tubes: For instance, it is pinched by an expanding loop in the neighborhood. As a result of the pinch, the magnetic field inside the tube is increased from its original value B_0. Let us denote the new magnetic field by B_t such that $B_t^2 > B_0^2$. When the difference is small one may write

$$\frac{B_t^2}{B_0^2} - 1 \approx \frac{2\delta B}{B_0}.$$

where $\delta B = B_t - B_0$. Thus expression (8) reduces to

$$\left(1 - \frac{2\delta B}{\beta_i B_0}\right) = \frac{n_i}{n_0}. \tag{11}$$

Apparently this effect is important only when the plasma beta is low.

3.3. PRESENCE OF A PROTON BEAM BUT NO COMPRESSION

In the present case we assume that there is no magnetic compression and $B_t^2 = B_0^2$. In the present case the Alfvénic turbulence and the kinetic pressure of the beam protons play dominant roles. Here we remark two points. First, in general we expect that

$$B_0^2 \gg \sum_k B_k^2.$$

For example, in our simulation it is found

$$\sum_k B_k^2/B_0^2 \sim 10^{-2}.$$

This means the term associated with wave magnetic field is important when the beta value is sufficiently low, say $\beta_i \approx 10^{-2}$. Since the plasma beta increases with altitudes, the importance of this effect decreases accordingly. Second, as we have defined earlier that the beam speed is equal to αv_{A}. Since Alfvén speed decreases with altitude, for a given beam speed we expect that the parameter α increases with altitude in general. Thus, at high altitudes where plasma beta may approach unity, the kinetic pressure term in (10) is expected to prevail. The condition is

$$\frac{n_b}{n_0}\frac{(\alpha-1)^2}{\beta_i} \sim 1.$$

4. Discussion and Conclusions

In summary we suggest that the presence of the hot beam protons can drastically reduce the ambient plasma density in the tube. In the pressure balance relation we assume that the density of the beam protons remains unaffected because the beam protons are created and injected continuously into the region over a finite time interval. However, we point out that enhanced Alfvénic turbulence and 'hot' beam protons occur only during the transient phase of the depletion process. Once the depletion starts taking place the high kinetic temperature of the beam protons is expected to subside progressively in time. The reason is that the Alfvén speed inside the tube would increase gradually due to the decrease of density so that the Alfvén wave excitation subsides accordingly. During this course the interior magnetic field may adjust spontaneously to a higher value by contraction in order to maintain the pressure balance.

The same process takes place for both downward and upward proton beams. The downward beam depletes ambient protons into the chromosphere whereas the upward beam drives the ambient protons into interplanetary space. It is supposed that, in the absence of other strong driving forces, the depleted protons do not return to the flux tube where they belonged. Thus, afterward the density of the ambient protons would not return to their normal level. Indeed some of the downwardly moving hot beam protons, which have large pitch angles, may be mirror-reflected at altitudes above the chromosphere. It is assumed that the density of these reflected protons is small in comparison with that of the residue ambient protons. Once the depletion process is completed the energetic beam ions would no longer play any significant role, because by that time we expect that the outside pressure would contract the tube such that the interior magnetic field is adjusted to a higher value and consequently the pressure balance equation becomes

$$n_0T_0 + \frac{B_0^2}{8\pi} = n_iT_i + \frac{B_f^2}{8\pi},$$

where $B_f(> B_t)$ denotes the new interior field.

Indeed the particles outside the tube may eventually diffuse into the tube. To discuss this point let us consider the situation in the solar corona, and pay particular attention to high altitudes and active regions. In these regions the plasma has very low beta values and it is basically collisionless. In the absence of major plasma instabilities at the boundary the cross-field diffusion would depend on Coulomb collisions. Thus we expect that the density-depleted flux tube is expected to hold over a time scale much longer than the typical time scale of type III bursts.

It is difficult to give a quantitative estimate of the total energy required for the density depletion process because it depends upon not only the size and length of the duct but also the duration over which the energetic particle beams are generated. Moreover, the distribution of the ambient plasma density is non-uniform along a flux tube of interest. It is also necessary to note that this density depletion process doesn't need an especially energetic proton beam. If we assume that the proton beam speed is about $v_b \approx 0.1 \sim 0.2c$, which is suggested by type III bursts observations (Dulk, 2000), one can argue that Equation (7) can be generally satisfied in the corona. That is to say that the beam protons have energy density much higher than that of the ambient protons, so they have enough energy to "squeeze" the ambient protons out of the region.

Concerning the study of solar radio emission we also want to remark that in the low corona density depletion due to magnetic compression may be relatively more important than heating of energetic ions. Magnetic compression may play key roles at least in two cases. One is in front of an ejected mass from an active region in the low corona, and the other is in the interacting region of adjacent expanding loops. The former case may be relevant to the type II radio bursts while the latter may be germane to the phenomenon of the so called J bursts or U bursts in solar radiophysics.

Finally let us reiterate that, as mentioned in the introduction, the present study is primarily motivated by observations relevant to the type III solar radio bursts and the earth's auroral kilometric radiation. It is found that in both cases density depletion seems to play an important role. The proposed depletion mechanism is mainly for this purpose. In other words our interest is mainly in the low corona region. It is not our intention to claim that all under-dense flux tubes may be created by the process discussed in this paper. At this point we ought to cite the work by Buttighoffer *et al.* (1995) and Buttighoffer (1998) which are based on observations made with *Ulysses* spacecraft. In these articles it is reported that an exceedingly long under-dense channel emanates from the sun and extends to 5 AU. This finding has attracted a great deal of interest. One of the intriguing questions is how the channel is formed. To understand the formation of this low density channel is a challenging issue. It is not clear whether the model proposed in this paper is able to provide an answer. On this topic we have had considerable discussion with the referee. We appreciate that he called our attention to this outstanding problem.

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References

Benson, R.F.: 1985, *J. Gephys. Res.* **90**, 2753.

Benson, R.F., Calvert, W., and Klumpar, D.M.: 1980, *Geophys. Res. Lett.* **7**, 479.

Benz, A.O.: 1993, *Plasma Astrophysics*, Chap. 11, Kluwer, Dordrecht, The Netherlands.

Bougeret, J.L., Caroubalos, C., Mercier, C., and Pick, M.: 1970, *Astron. Astrophys.* **6**, 406.

Brinca: 1991, in A.D. Johnstone (eds.), *Cometary Plasma Processes*, American Geophysical Union, Washington, DC, p. 211.

Buttighoffer, A.: 1998, *Astron. Astrophys.* **335**, 295.

Buttighoffer, A., Pick, M., Roelof, E.C., Hoang, S., Mangeney, A., Lanzerotti, L.J., *et al.*: 1995, *J. Geophys. Res.* **100**, 3369.

Davidson, R.C.: 1972, *Methods in Nonlinear Plasma Theory*, Academic, New York, p. 135.

Dulk, G.A.: 1985, in D.J. McLean and N.R. Labrum (eds.), *Solar Radiophysics*, Chap. 2, Cambridge University Press, New York, p. 19.

Dulk, G.A.: 2000, in R.G. Stone *et al.* (eds.), *Radio Astronomy at Long Wavelengths*, American Geophysical Union, Washington, DC, p. 115.

Dulk, G.A. and Suzuki, S.: 1980, *Astron. Astrophys.* **88**, 203.

Duncan, R.A.: 1979, *Solar Phys.* **63**, 389.

Ginzburg, E.G. and Zheleznyakov, V.V.: 1958, *Astron. Zh.*, **35**, 694; transl. *Sov. Astron.-AJ* **2**, 653.

Gurnett, D.A.: 1974, *J. Geophys. Res.* **79**, 4227.

Ichimaru, S.: 1991, *Statistical Plasma Physics*, Addison-Wesley, New York, p. 239.

Janhunen, P., Olsson, A., and Laakso, H.: 2002, *Ann. Geophys.* **20**, 1743.

Kundu, M.R.: 1965, *Solar Radio Astronomy*, Interscience, New York, 660 pp.

Li, Y., Yoon, P.H., Wu, C.S., Weatherwax, A.T., Chao, J.K., and Wu, B.H.: 1997, *Phys. Plasma* **4**, 4103.

Lu, Q.M. and Wang, S.: 2004, *Phys. Plasmas* **11**, 80.

McLean, D.J.: 1971, *Aust. J. Phys.* **24**, 201.

Mukai, T., Miyake, W., Terasawa, T., Kitayima, M., and Hirrao K.: 1986, *Nature* **321**, 299.

Neugebauer, M., Lazarus, A.J., Balsiger, H., Faselier, S. A., Neubauer, F.M., and Rosenbauer, H.: 1986, *Nature* **321**, 352.

Neugebauer, M., Lazarus, A.J., Balsiger, H., Fuselier, S. A., Neubauer, F.M., and Rosenbauer, H.: 1989, *J. Geophys. Res.* **94**, 5227.

Roux, A., Hilgers, A., de Feraudy, H., Le Queau, D., Louarn, P., Perraut, S. *et al.*: 1993, *J. Geophys. Res.* **98**, 11657.

Sagdeev, R.Z., Shapiro, V.D., Shevchenko, V.I., and Szego, K.: 1986, *Geophys. Res. Lett.* **13**, 85.

Smerd, S.F., Wild, J.P., and Sheridan, K.V.: 1962, *Aust. J. Phys.*, **15**, 180.

Stewart, R.T.: 1972, *Proc. Astron. Soc. Aust.* **2**, 100.

Stewart, R.T.: 1974a, in G.A. Newkirk (ed.), IAU Symposium 57, Coronal Disturbances, Reidel, Dordrecht, The Netherlands, p. 161.

Stewart, R.T.: 1974b, *Sol. Phys.* **39**, 451.

Strangeway, R.J., Kepko, L., Elphic, R.C., Carlson, C.W., Ergun, R.E., McFadden, J.P. *et al.*: 1998, *Geophys. Res. Lett.* **25**, 2065.

Tsurutani, B.T. and Smith, E.J.: 1986a, *Geophys. Res. Lett.* **13**, 259.

Tsurutani, B.T. and Smith, E.J.: 1986b, *Geophys. Res. Lett.* **13**, 263.

Wang, X.Y. and Lin, Y.: 2003, *Phys. Plasma* **10**, 3528.

Wild, J.P. and McCready, L.L.: 1950, *Aust. J. Sci. Res., Ser. A* **3**, 387.

Wu, C.S. and Davidson, R.C.: 1972, *J. Geophys. Res.* **77**, 5399.

Wu, C.S., Wang, C.B., Yoon, P.H., Zheng, H., and Wang, S.: 2002, *Astrophys. J.* **575**, 1094.

Wu, C.S., Wang, C.B., Zhou, G.C., Wang, S., and Yoon, P.H.: 2005, *Astrophys. J.* **621**, 1129.

Yoon, P.H. and Wu, C.S.: 1991, in A. D. Johnstone (ed.), *Cometary Plasma Processes*, American Geophysical Union, Washington, DC, p. 241.

Yoon, P.H., Wu, C.S., and Wang, C.B.: 2002, *Astrophys. J.* **576**, 552.