Astron. Astrophys. 329, 765–768 (1998)

ASTRONOMY AND ASTROPHYSICS

On the diamagnetic effect associated with the ion pile-up region in the coma of comet Halley

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Received 28 March 1997 / Accepted 24 July 1997

Abstract. The ion pile-up region in the comet Halley ionosphere observed on the inbound leg of the Giotto trajectory is accompanied by a decrease of the magnetic field strength. This magnetic field dip is explained by means of a diamagnetic effect of the plasma density increase in the pile-up region. Maximum of the plasma pressure seems to coincide with the maximum of the ion density. We arrived at the conclusion that the electron temperature profile should also possess a maximum in this region. This fact corroborates the results by Eberhardt and Krankowsky (1995). No magnetic effect of the enhanced plasma density was observed near the anticipated position of the ion pile-up region for the outbound leg of the trajectory. Thus, we conclude that the ion pile-up in the inner cometary coma (as it was observed on the inbound leg of the Giotto trajectory) is a transient (spatially and/or temporarily) phenomenon rather than a permanent feature.

Key words: solar system: comets – magnetic fields – plasmas

1. Introduction

Sharp ion density maximum was observed at the distance of $\approx$ 12,000 km from the nucleus in the inner coma of comet Halley during the inbound pass of the Giotto spacecraft (Balsiger et al. 1986). This region is conventionally referred to as the ion pile-up region. At the closer distances to the nucleus, the ion density profile may be rather well approximated by r^{-1}-dependence as expected for photochemical equilibrium if the electron temperature, T_e, is constant. It is commonly believed that an increase of the ion density is due to higher electron temperature in the ion pile-up region, and, as a result, lower recombination rate (Ip et al. 1987). The electron temperature in the inner coma may be low because of collisional cooling with water molecules (Marconi & Mendis 1983; Mendis et al. 1985). Unfortunately, direct experimental data on the electron temperature are absent, since the electron population of the inner coma of comet Halley was beyond the energetic ranges of instruments onboard the Giotto and Vega spacecrafts. However, electron temperature profiles calculated by several authors (e.g. Ip 1986; Körösmezey et al. 1987; Marconi & Mendis 1988; Gan & Cravens 1990; Huebner et al. 1991) reveal the rapid increase of the electron temperature accompanied by the ion density enhancement. Häberli et al. (1995) managed to reproduce measured profiles of different ion components in the coma of comet Halley by using the temperature profile calculated by Ip (1986) for a spherically symmetric model of the inner coma. Eberhardt & Krankowsky (1995) derived the electron temperature profile from the ratio of densities of different ion species. Their calculations indeed demonstrated the T_e increase up to 25,000 K in the ion pile-up region,but with a sharp peak, whereas theoretical models do not predict a decrease of the electron temperature beyond the ion pile-up region. Eberhardt & Krankowsky (1995) argue that the T_e- maximum may be associated with the magnetic field discontinuity.

However, it is still unclear whether the ion pile-up region is a permanent, intrinsic feature of the cometary ionosphere or it is a transient, time-dependent phenomenon. It is even unknown whether or not this feature existed during the whole Giotto flyby near comet Halley, since the ion mass spectrometer was damaged near the closest approach, and there were no ion data for the outbound leg of the trajectory.

In this note we will compare the ion density profile with the magnetic field measurements along the trajectory. We will show that the enhancement of the plasma density is accompanied by a drop of the magnetic field strength associated with the diamagnetic effect. There was no such a magnetic field drop at the anticipated location of the ion pile-up region on the outbound leg, whence one may conclude that there was no corresponding ion pile-up on the outbound leg, and hence this penomenon may not be a permanent feature.

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2. Diamagnetic effect of the plasma density enhancement in the inner coma

Figure 1 shows the measured ion density, inferred electron temperature (Eberhardt & Krankowsky 1995) and measured ion temperature (Altwegg et al. 1993) profiles, along with the radial dependence of the magnetic field strength, for the inbound pass. The magnetic field profile for the inbound leg (bottom panel) exhibits rather narrow dip at the distance of $\approx 12,000$ km. The depth of this magnetic field decrease is $\approx$ 7 nT. Location of the magnetic field minimum coincides with the ion density maximum (middle panel). This is not unexpected, since the plasma is a diamagnetic medium: an increase of the plasma density results in the magnetic field decrease due to the magnetic effect of electric currents associated with Larmor gyration of plasma particles.

The maximum magnetic field decrease ΔB due to the diamagnetic effect can be estimated by means of magnetic moments μ_k of various species k (e.g. Alfvén & Fälthammar 1963):

$$\Delta B = -4\pi\Sigma\Delta n_k\mu_k = -4\pi\frac{\Delta(n_ikT_i) + \Delta(n_ekT_e)}{B}$$

where $\Delta(n_{i,e}kT_{i,e})$ is the variation of the ion (electron) pressure across the pile-up region. Outside the ion pile-up region $n_i \approx 1,000\,\mathrm{cm}^{-3}, T_e \approx 9,000\mathrm{K}, T_i \approx 4,500\mathrm{K}$, inside the pile-up region $n_i \approx 1,800$ cm^{-3}, $T_e \approx 26,000$K, $T_i \approx 5,500$K, (Eberhardt & Krankowsky 1995; Altwegg et al. 1993) whence one obtains $\Delta B \approx 15$ nT. Obviously, the electron heating dominates over the ion density increase in creation of an increase of the gasdynamic pressure. Here we neglected an increase of the ion-neutral friction force due to an increase of the ion density, since it is negligible as compared to the gas kinetic pressure gradient. Indeed, $\Delta P/\Delta x \approx 5.9 \times 10^{-9}$ dn·cm^{-2}/7×10^7 cm = 8.4×10^{-17} dn·cm^{-3}, whereas the friction force increase is $\Delta f = M_ik_{in}\Delta N_iN_nv_n = 2.1 \times 10^{-18}$ dn·cm^{-3}. Thus, the calculated ΔB-value fairly well corresponds to the observed effect. Moreover, the shape of the dip shows that a sharp maximum of the plasma pressure accompanies the ion density maximum. Hence, the electron temperature profile should have a maximum in the ion pile up region rather than exhibit just an increase of the temperature. Thus, we arrive at the conclusion that the observed diamagnetic effect corroborates the results by Eberhardt & Krankowsky (1995).

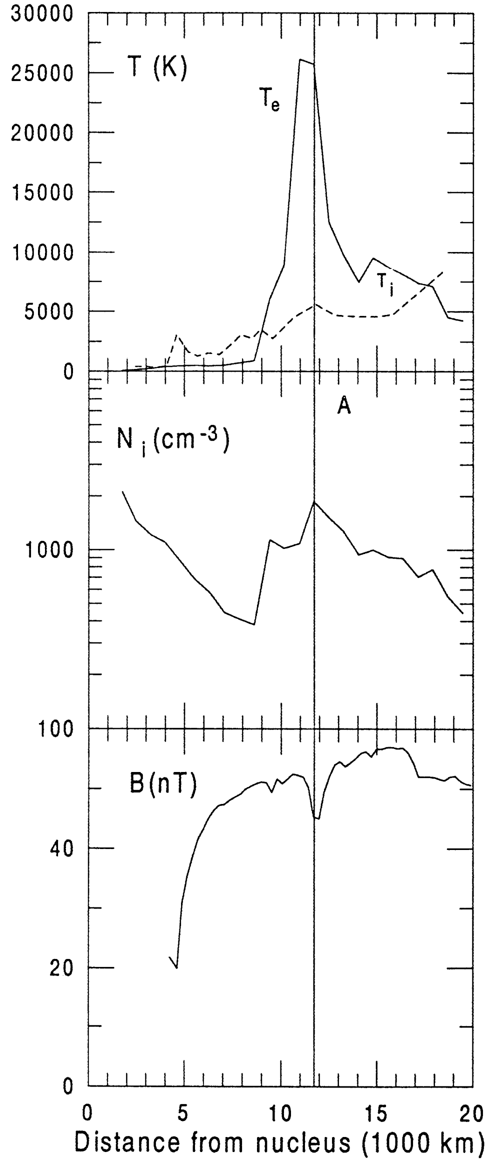

Fig. 1. Radial profiles of (top) the inferred electron temperature (solid line, (Eberhardt and Krankowsky 1995)) and the measured ion temperature (dashed line, (Altwegg et al. 1993)); (middle) the ion number density for ions with masses 19 a.m.u (Eberhardt and Krankowsky 1995)); and (bottom) the magnetic field strength along the inbound leg of the Giotto trajectory.

Let us look for a possible magnetic signature of the ion pile-up region on the outbound leg. Fig. 2 shows the magnetic field profiles along both the inbound and outbound legs (solid and dashed lines, respectively). One can see that the magnetic field dip on the inbound leg (denoted by solid vertical line A) coincides with a reversal of the B_x-component of the magnetic field. Change in the B_x-sign indicates a crossing of the current sheet created by a rapid rotation of the interplanetary magnetic field. Several current sheets, similar to this one, have been observed in the Halley ionosphere (Raeder et al. 1987). Raeder et al. (1987) have shown that there was one-to-one correspondence between the current sheet crossings on the inbound and outbound legs: each current sheet was crossed twice since current sheets drape the cometary head in a manner similar to magnetic field lines draping. Because of time delay between the inbound and outbound crossings of the same current sheet, location of the outbound crossing was displaced tailward as compared with the inbound position. This is indicative of the fact that the current sheet moves with the cometary plasma velocity, and this fact was used in order to restore the plasma velocity (Israelevich et al. 1995). The outbound counterpartner for the current sheet A is denoted by the vertical dashed line A' in Figure 2. (Note, that the signs of B_x are opposite on the inbound and outbound legs). The outbound crossing of the current sheet happened to be at the distance of 9,500 km from the nucleus. One can see,

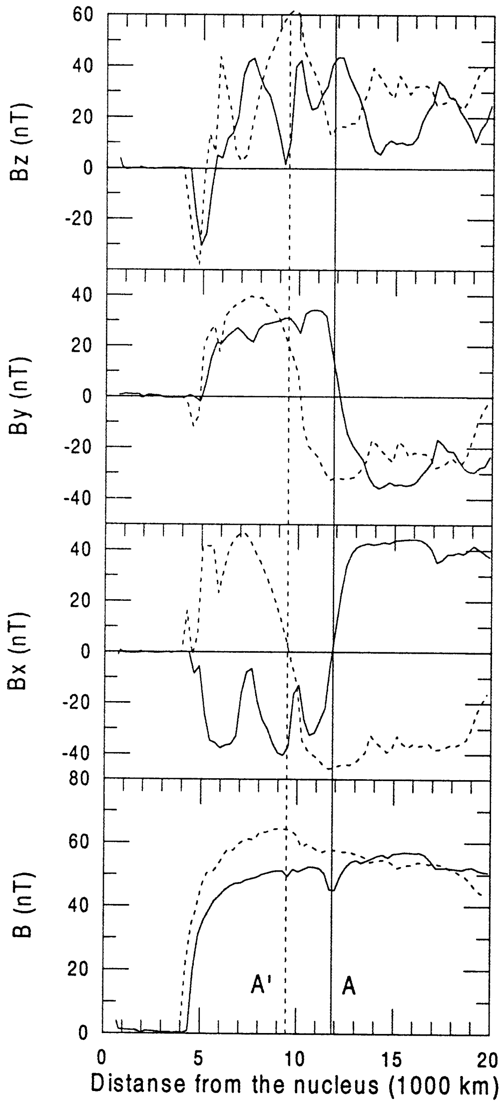

Fig. 2. Magnetic field profiles along the inbound (solid lines) and outbound (dashed lines) legs of the Giotto trajectory. Vertical lines *A* and *A'* correspond to B_x-component reversals on the inbound and outbound legs, respectively. Event *A* coincides with the magnetic dip, whereas the outbound crossing *A'* of the same current sheet is not accompanied by a diamagnetic effect.

that the behavior of the magnetic field strength was quite different at the outbound. No magnetic dip accompanied by the B_x-component reversal has been observed. Instead, at a larger distance of 10,000 km a decrease of the magnetic field strength, without recovering to initial value, has been registered. Thus, the magnetic field dip at the inbound is not associated with the magnetic field reversal, and is, indeed, due to the diamagnetic effect.

One can expect that on the outbound leg the pile-up region should be crossed at the distance interval 9,500 – 12,000 km. Indeed, it should be closer to the nucleus than on the inbound crossing (12,000 km), since the Giotto trajectory was not exactly perpendicular to the tail axis: the inbound (outbound) crossing occurred at the nightside (dayside) of the comet. The lower limit (9,500 km) is given by the position of the outbound current sheet crossing. If the outbound pile-up region were located at 9,500 km, it would be convected with the plasma drift velocity (and hence it would not be a permanent structure). One can see from Figure 2, that there is no significant magnetic dip in the region expected for the outbound ion pile-up crossing. Instead, there is a decrease of the magnetic field strength at 10,000 km, whose possible relation to the ion pile-up will be discussed below.

Several possibilities exist. First, the ion pile-up region is absent on the outbound leg. Obviously, this means that the ion pile-up is not a permanent structure.

Second, it is possible, that the T_e profile, with a sharp maximum, on the inbound leg was associated with the effect of the current sheet (Eberhardt & Krankowsky 1995), whereas the electron temperature profile on the outbound leg is more reminiscent of theoretical predictions (Ip 1986; Körösmezey et al. 1987; Marconi & Mendis 1988; Gan & Cravens 1990; Huebner et al. 1991), i.e. T_e rapidly increases in the ion pile-up region and does not decrease with distance. In this case, one may expect that diamagnetic currents would result in a decrease of the magnetic field, without recovery, rather than in a magnetic dip. A similar feature, namely, a decrease of the magnetic field at the distance of 10,000 km from the nucleus, was indeed observed on the outbound leg. Anyway, the ion-pile up region observed on the inbound leg seemed not to be a permanent steady state structure.

The existence of the magnetic dip associated with an increase of the plasma density is not unexpected. Similar dips, associated with the ion density increases upstream from the ion pile-up region, were observed by Vega 1, 2 (Galeev et al. 1986; Vaisberg et al. 1987; Yeroshenko et al. 1987). Relation between plasma density and magnetic field fluctuations has been studied by Vaisberg et al. (1989). They arrived at the conclusion that the pressure balance indeed holds in the magnetic dips observed by Vega 1, 2 (as it should be for the diamagnetic effect due to the plasma density enhancement). Detailed comparison of the Vega plasma and magnetic data will allow further clarification, whether or not the ion pile up region is a permanent feature of the cometary coma accompanied by a diamagnetic effect.

3. Conclusion

We compared the ion density and the magnetic field radial profiles along the inbound leg of the Giotto trajectory in the inner coma of comet Halley. The diamagnetic effect of the plasma density enhancement in the ion pile-up region was revealed. The diamagnetic effect is associated with the maximum of the plasma pressure. Hence, the electron temperature exhibits a maximum (rather than just a sudden increase at this location) which coincides with the ion density maximum. No clear magnetic effect of the enhanced plasma density was observed near the anticipated position of the ion pile-up region for the outbound leg of the trajectory. Thus, we arrive at the conclusion that the ion pile-up in the inner cometary coma observed on the inbound leg of the Giotto trajectory, seems to be a variable (spatially and/or temporarily) feature rather than a permanent steady state structure.

Acknowledgements. This work was supported by a grant from the German-Israeli Foundation for Scientific Research and Development.

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