Results from Gas Injection Experiment in SEPAC

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Neutral gas-plasma interaction in space was studied in the SEPAC experiment on the Space Shuttle, STS-9 mission. Nitrogen gas of 10^{23} molecules and argon gas of 10^{21} molecules were repeatedly released from the orbiter at the height of 245 km into the ionosphere. During the gas release, an enhancement of ambient plasma density and a fluctuation of orbital potential were detected. When the gas was injected together with a high speed plasma, a CVI-like phenomenon was observed. This paper summarizes the results of the gas-plasma interaction observed in the SEPAC experiment and gives a possible explanation of the observation.

1. Introduction

The interaction of neutral gas with space medium (plasma, neutral gas) is a fundamental area of research in space plasma physics. The interest in this area exists also from the applicative point of view. The behavior of neutral gas in space has been studied in the large-scale chemical release experiments, usually from ground observations. On the other hand, since the Space Shuttle came into operation, the small-scale modification of space plasma by the shuttle-generated gas has been studied by in-situ measurements. Although the modification is localized around the spacecraft, the in-situ measurements by the spacecraft have revealed many physical processes involved in the gas-plasma interaction. The generation of plasma and modification of electromagnetic environments during orbiter thruster firings (PICKETT *et al.*, 1985) are the examples of significant findings in the research.

The Space Experiment with Particle Accelerators (SEPAC) was carried out by Spacelab-1 mission in 1983 (OBAYASHI *et al.*, 1984). It was intended to perform active experiments using a high power electron beam and a magneto-plasma-dynamic arcjet (MPD-AJ). In the experiment, nitrogen and argon gas were injected into space. The well-defined gas species and the injection in a controlled manner enabled us to study the gas-plasma interaction more systematically than the previous works for the thruster gas. The interaction was observed by an on-board diagnostic package consisting of a vacuum gauge, Langmuir probe, floating probes, wave receivers, energetic electron energy analyzers, and a photometer.

2. Gas Injection Experiment

Four types of gas release were studied in the SEPAC experiment; nitrogen gas injection, argon gas injection with a high speed plasma, argon gas release, and orbiter thruster firings. Figure 1 shows the location of these gas sources on the orbiter. The nitrogen and argon gas were injected from the SEPAC instruments on the pallet and the thruster gas mainly composed of H_2O , N_2 , CO and H_2 was released from the orbiter reaction control system. Figure 2 shows the configuration of SEPAC instrumentation on the SL-1 pallet. Nitrogen gas was injected straight upward from a gas injector which was assembled in the MPD-AJ system. About 10^{23} molecules were released during 100 msec. Argon gas of 10^{21} molecules was released upward together with a high speed argon plasma from the discharge head of MPD-AJ. Argon gas of 10^{22} molecules was released also from the MPD casing intermittently. The modification of the plasma environment by the gas injection was studied by a diagnostic package (DGP) just close to the MPD-AJ system.

3. Results

3.1 Nitrogen gas injection experiment

The pressure measured before the gas injection was usually $(1.0\text{--}1.2)\times 10^{-6}$ Torr at the diagnostic package on the pallet. When the nitrogen gas was injected, the pressure increased to $(2\text{--}3)\times 10^{-6}$ Torr. As is shown in Fig. 3, the current of the Langmuir probe at the diagnostic package was greatly enhanced by the gas injection. The enhancement was observed only when the gas was injected into ram or near ram. At the initial phase of data analysis, this effect was believed to be related to a kind of gas ionization due to a gas-plasma interaction (SASAKI *et al.*, 1984). However, later analysis showed that this effect could be explained by the gas-plasma collisional interaction near the orbiter (SASAKI *et al.*, 1985). The ambient plasma drifting with respect to the orbiter at the orbital speed (7.5 km/sec) was scattered by the gas molecules and reached the probe which was located in the local wake. There are three possible processes for the collisional interaction, viz., elastic collision, ion-atom interchange and charge exchange. The cross sectional area for the collisional interaction estimated from the plasma density at the probe is around 2×10^{-21} m², which is much larger than that for the charge exchange process but is comparable to that for the other two processes. The collisional interaction produces a plasma plume moving with the orbiter. As is shown in Fig. 4, VLF waves generally accompany the enhancement of the plasma density. The generation of the waves cannot be directly explained by the gas-plasma collisional interaction but suggests that a wave-particle interaction was also involved in this process. The mechanism for the wave generation has not been identified yet, but an electric field induced in the plasma plume moving with the orbiter in the geomagnetic field is a possible energy source for the wave generation (PICKETT *et al.*, 1985).

Fig. 1. Location of gas sources on the Spacelab-1 orbiter.

Fig. 2. Configuration of Spacelab-1 pallet instruments. SEPAC system is composed of an electron beam accelerator (EBA), a magneto-plasma-dynamic arcjet (MPD-AJ), a diagnostic package (DGP), a monitor TV camera (MTV), and power subsystems (PWR, HVC).

3.2 Argon gas injection experiment with a high speed plasma

Figure 5 illustrates the operation of the magneto-plasma dynamic arcjet. First, 10^{21} molecules of argon gas are released in coaxial electrodes inside the discharge head. At 1 msec later, a high voltage (500 V) is applied between the electrodes, generating a discharge. The produced plasma accelerated by the electromagnetic force up to 20 km/sec goes out into space through the pre-ejected neutral gas plume. The discharge is terminated within 1 msec and about 10^{19} pairs of ion and electron are produced. In the MPD-AJ operation in space, long-duration effects much longer than the discharge time were unexpectedly observed by the wave, particle and optical detectors. Figure 6 shows a typical example, in which an enhancement of the plasma density, a generation of VLF waves, a fluctuation of orbiter potential and an excitation of light emission were detected for several tens of milliseconds after the termination of the MPD-AJ discharge. The observation suggests that a discharge near the orbiter was ignited for a while triggered by the plasma injection. Figure 7 shows a wave spectrum in the VLF range. The frequency of the waves is peaked near the lower hybrid frequencies of possible surrounding ions. The solid black circles in Fig. 8 show the parameter region (orbital velocity perpendicular to the magnetic field and density of ambient plasma) where the long-duration effect was observed. This effect was observed when the orbital velocity perpendicular to the magnetic

Fig. 3. Enhancement of Langmuir probe current during the nitrogen gas injection. Probe voltage is fixed at +9 V. (a) FO-4, (b) FO-9A-I.

field was relatively large and the ambient plasma density was relatively high, although these were not sufficient conditions for the effect. These features suggest that this effect is related to the concept of critical velocity ionization for the gas drifting with the orbiter (SASAKI *et al.*, 1986). The orbital velocity (7.5 km/sec) was smaller than the usual critical ionization velocity (12.7 km/sec for argon, 10.6 km/sec for nitrogen and 15.6 km/sec for oxygen) calculated based on the quasi-linear theory. However, PAPADOPOULOS (1984) has proposed that specular reflection of space plasma by the orbiter surface causes counterstreaming with respect to

Fig. 4. Enhancement of Langmuir probe current during the nitrogen gas injection. Probe voltage is swept from -9 V to $+9$ V in 84 msec. The wave intensity integrated up to 10 kHz is also enhanced by the gas injection.

the incoming space plasma, resulting in a relative velocity at twice the orbital velocity. He has argued in relation to the origin of the shuttle glow that the counterstreaming plasma exceeding the critical velocity will excite lower hybrid waves which cause electron heating and rapid ionization just as in the usual CVI phenomena.

3.3 Argon gas release

10^{22} molecules of argon gas were released very slowly from the MPD casing. This was not an intentional experiment but was performed to evacuate the gas reservoir every 2.5 min during the MPD-AJ operation. Figure 9 shows the signal of floating probes on the DGP deck. There were three floating probes (top, middle and bottom). During the gas release, fluctuations of the floating potential to a positive side were detected by the top probe (note the high level pulses beyond 10 V were caused by electron beam emission and are not related to the present effect). This effect indicates that there generated an electric field between the probe and orbiter. The same effect was also observed in the argon gas injection experiment together with a high speed plasma (Fig. 6), which is possibly related to the polarization effect of the plasma moving with the orbiter (KATZ *et al.*, 1984).

3.4 Thruster firings

The orbiter reaction control system consists of 38 primary thrusters and 6

Fig. 5. Operation of MPD-AJ. Argon plasma is ejected into space through a pre-ejected argon gas plume.

Fig. 6. Long-duration effect of diagnostic signals triggered by the MPD-AJ operation.

Fig. 7. Spectrum of VLF wave emission excited by the argon gas injection with a high speed plasma. The lower hybrid frequencies for oxygen, nitrogen and argon are also shown.

Fig. 8. Parameter region where the CVI-like phenomena are observed. Long-duration gas ionization is observed at the parameters depicted by solid black circles.

Fig. 9. Fluctuation of orbital potential during argon gas release (provided by Dr. Jill A. Marshall).

vernier thrusters. They are located in the front and rear of the orbiter. The total number of neutrals ejected is typically 1.3×10^{25} (based on 2 firings ejecting 163 g over 2 s) for the vernier thruster and 9.2×10^{24} (based on 1 firing ejecting 114 g over 80 ms) for the primary thruster (PICKETT *et al.*, 1985). Figure 10 shows a typical example of the diagnostic signals during the thruster firing. When the thruster was fired, a light emission and a VLF wave emission were observed. These indicate that the electromagnetic environment surrounding the orbiter is strongly modified by the thruster firing. In this particular case in which the payload bay directed toward ram, the ambient plasma density decreased during the thruster firing in contrast with the nitrogen gas injection experiment (Fig. 3). The high-density gas cloud generated by the thruster firing prevented the ambient plasma from entering the pallet. The density gradient of the plasma behind the gas cloud may be a cause for the VLF wave generation (STONE and SAMIR, 1986). In a case in which the payload bay was in wake, the density of the ambient plasma was enhanced during the thruster firing and no remarkable wave emission was detected (KAWASHIMA *et al.*, 1985).

4. Summary

The SEPAC experiment provided an opportunity to study various kinds of gas-plasma interaction in space. Figure 11 illustrates a summary of possible physical

Fig. 10. Change of diagnostic signals during the thruster firing.

Fig. 11. Summary of possible physical processes in the gas-plasma interaction in space.

processes involved in the gas-plasma interaction. There are three major processes after the collisional interaction. Collisional interaction with a high-density gas cloud causes a depletion of plasma behind the gas cloud, generating the plasma instabilities by the density gradient. The depletion of the ambient plasma and associated wave emission were observed during the thruster firing. On the other hand, the collisional interaction produces a plasma plume moving with the orbiter, producing an $\mathbf{E} \times \mathbf{B}$ electric field in the plume, resulting in a wave particle interaction. This process was observed in nitrogen gas injection experiment under a special orbiter configuration. The collisional interaction could produce an ion beam, generating the lower hybrid instability and results in the ionization. This process is believed to be observed in the argon gas injection experiment triggered by a high speed plasma

injection. In the SEPAC experiment, the phenomena induced by the gas release were measured at a single point on the pallet, that was insufficient to understand the total processes involved in the gas-plasma interaction in space. In order to understand the physical mechanism more definitely, multi-point measurements surrounding the spacecraft are required in the future research.

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