

Effects of Gradient Magnetic Fields on CO₂ Sublimation in Dry Ice

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Abstract. A process of CO₂ sublimation in a fragment of dry ice was observed under static gradient magnetic fields of up to 7 Tesla. Results indicated that Tesla order magnetic fields enhanced the release of CO₂ gas from solid matter containing carbon dioxide. Paramagnetic oxygen molecules transported the sublimated particles containing carbon dioxide to a higher magnetic field.

1. Introduction

Magnetic fields in the range of micro-Tesla to milli-Tesla are unique properties of our planet and civilization. Mars has no magnetic fields and does have an abundant supply of dry ice at both of its poles. In contrast, as a gaseous planet, Jupiter, which has strong internal magnetic moments, has magnetic fields about ten times greater than those of Earth. Recently, our planet has begun to experience an increase in the volume of atmospheric CO₂ gases, which is thought to be life-threatening if it continues. Many reasons for the increased generation of CO₂ gases have been investigated and discussed with the aim of preventing or even reversing their release.

On the other hand, many studies on magnetic separation technique were reported concerning gaseous, liquid, and solid-state materials in gradient magnetic fields [1-7]. Most of them focused on the importance of the difference in magnetic susceptibilities of molecules which were involved in an experimental system.

In the present study, we observe the sublimation of dry ice into the atmosphere in the presence and absence of a strong static magnetic field, which is generated by a superconducting magnet. The results show that magnetic fields on the order of a Tesla can possibly enhance the release of CO₂ gas from dry ice. A hypothesis concerning the passive transportation of CO₂ by magnetic force acting on oxygen is proposed and discussed based on a qualitative experiment.

2. Methods

2.1. Magnetic field generators

We utilized superconducting magnets with a room temperature bore as magnetic field generators. The utilized 5-T vertical superconducting magnet (Oxford Inst., Microstat BT) generated a maximum field

at the center and provided gradient fields of 4T with 50T/m at 20 mm from the center. In case with a horizontal superconducting magnet of maximum 8 Tesla (Oxford Inst.), a gradient field of 7T with 40T/m was utilized.

2.2. Macroscopic observation of CO₂ sublimation and gas flow control

CO₂ sublimation in a fragment of dry ice, which was set in the bore of magnet, was monitored both by a CCD video camera and directly by eyes. A commercial dry ice was used for the experiments. Dry ice fragment with an edge about 20 mm in length was chosen for the experiments. In the experiment in 5-T vertical bore of the superconducting magnet, a gas flow condition of the atmosphere near the dry ice was roughly controlled by a tubing outlet which provided a gas from either a gas bottle of He, O₂, and CO₂.

In the experiment to measure a magnetic field dependence of sublimation rate in dry ice, the initial weight of dry ice fragments were set to 6.7 to 6.9 g, and the weight of fragment was measured after 8-min of magnetic field exposure at 25°C.

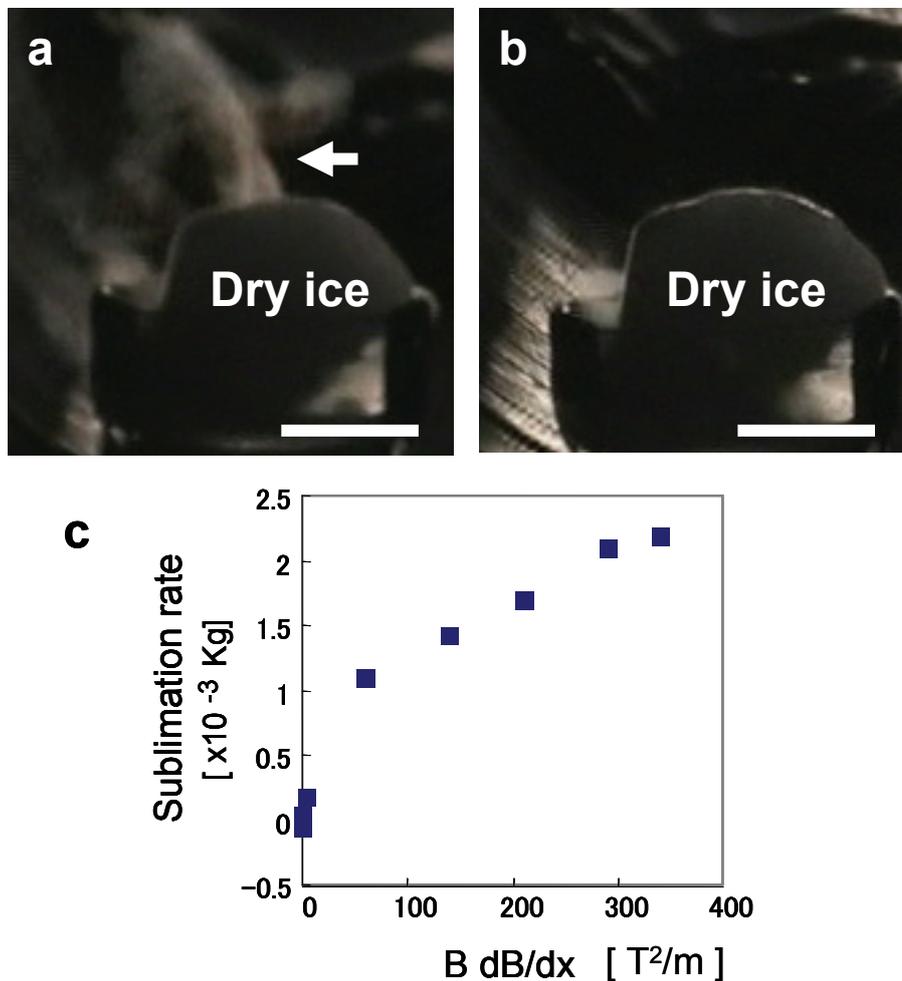


Figure 1. Effects of magnetic forces on sublimation of dry ice. Bars, 20 mm. a, a clot of dry ice set in 7 Tesla gradient magnetic fields. b, the dry ice set in 5 x 10⁻³ Tesla magnetic fields. c, sublimation of dry ice with an initial weight of 6.7 to 6.9 g at 25°C per 8 min. B dB/dx is the product of magnetic fields and gradients.

The obtained sublimation rate was plotted versus the product of magnetic fields and gradients ($B \text{ dB/dx}$), which was proportional to the magnetic force acting on materials in the fields. The temperature inside bore was controlled by a water jacket with a thermally controlled water circulation.

3. Results and Discussion

Figure 1 shows photos dry ice with and without magnetic field exposure in a horizontal bore of 8 T superconducting magnet. In general, sublimation of dry ice produces streams of CO_2 aerosols directed downward because the density of the low-temperature CO_2 gas is heavier than that of air. A magnetic field of 7 Tesla, which had a spatial gradient of 40 T/m, remarkably enhanced the sublimation of dry ice (Fig. 1a) compared with dry ice in the magnet bore at 5 mT without superconducting currents (Fig. 1b). The magnetic field of 7 T caused the CO_2 aerosols to move upward (Fig. 1a) and the CO_2 aerosol flowed toward the higher magnetic fields of 8 Tesla. In case with the exposure, the aerosol formed a white and broad stream, which is marked by a white arrow (Fig. 1a). Dry ice in a 7 T gradient field exhibited the most rapid decrease in weight (Fig. 1c).

Next, the same kind of experiment was carried out in a vertical bore of 5 T magnet. In the observation of dry ice sublimating to CO_2 gas, gaseous stream was visualized by white aerosol containing water, oxygen, and nitrogen as well as the sublimated carbon dioxide, as shown in Figure 2 and 3. The surface of dry ice set in a room temperature atmosphere was partly covered by white powders. The white powder was mainly consisted of CO_2 because they increased in volume when additional CO_2 gas was flowed into the magnet's bore.

It was remarkable that the dry-ice-powder accumulated in the side faced toward higher fields (Fig. 2). Also the CO_2 aerosol stream directed to a higher magnetic field which was similar to the observation in a horizontal bore at 7 T (Fig. 1). The vertical type of magnet's bore generated two maximum gradient magnetic fields (GMF) along the axis of bore; the upper part and the lower part produced diamagnetic force in the upward and downward direction, respectively. The observed phenomena are paradoxical because CO_2 molecules have diamagnetism.

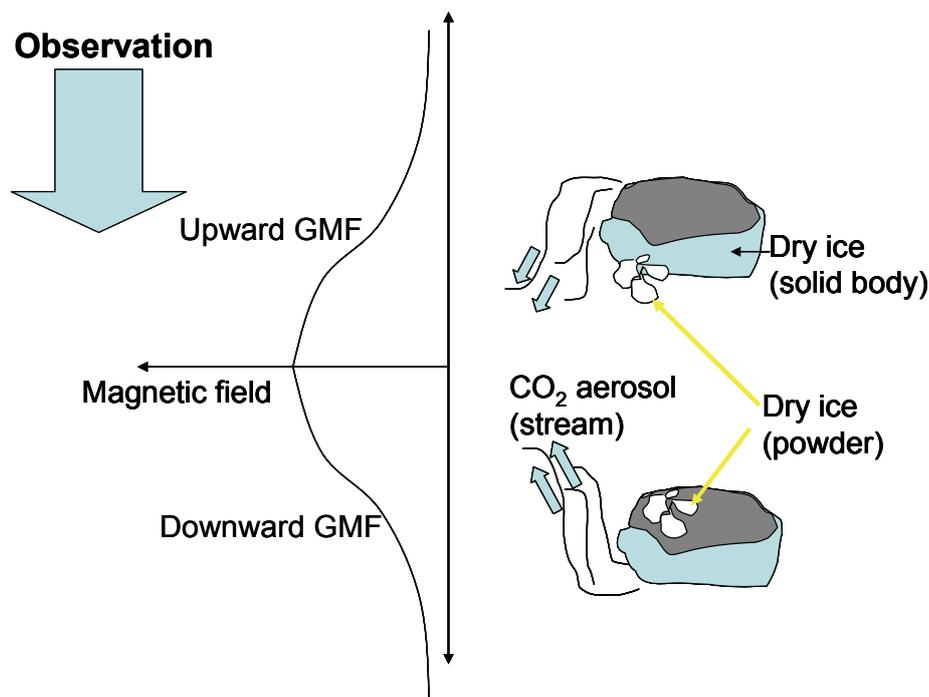


Figure 2. Behaviors of CO_2 aerosol and powder under gradient magnetic fields

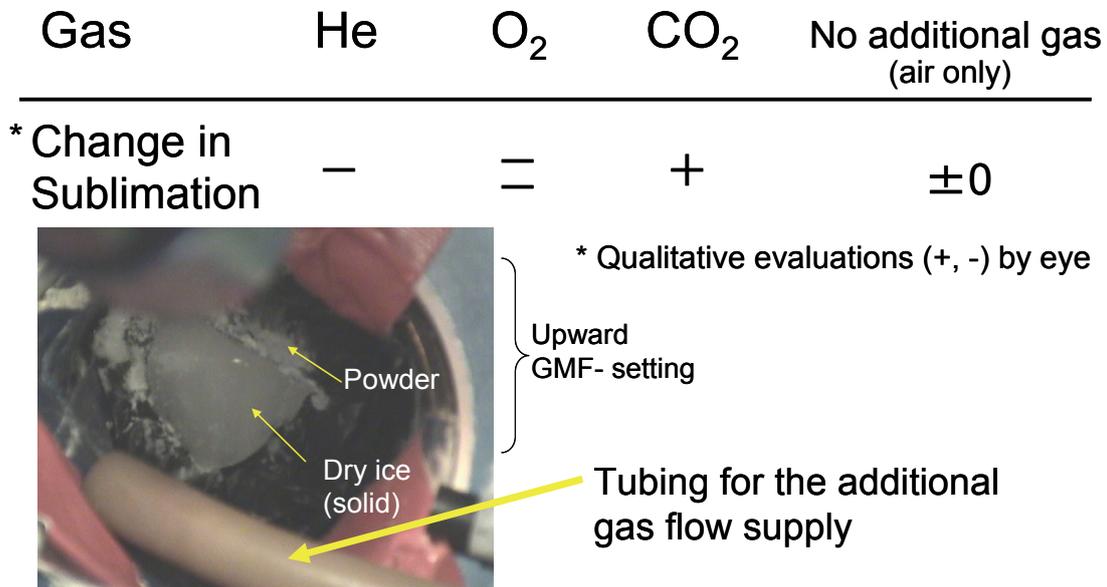


Figure 3. Effects of additional gas flow (He, O₂, and CO₂) under 4–5T gradient magnetic fields. The top panel (table) shows a qualitative evaluation for a relative change in dry ice sublimation by providing additional gas flows.

The magnetism of CO₂ is diamagnetism and a magnetic force directs CO₂ gas towards lower magnetic fields. However, oxygen gas, which is paramagnetic, has a magnetic force that is more than two 160 times greater than that of CO₂. Therefore, it is speculated that the oxygen gas carries the CO₂ aerosols towards the higher magnetic fields. In addition, the temperature gradient between the atmosphere surrounding the dry ice and areas at room temperature away from the dry ice provided a gradient in the magnetic susceptibility of the oxygen gases. The combination of magnetic field gradients and the susceptibility gradient enhance gas flow convection.

To investigate the possible effect of magnetic susceptibility of atmosphere surrounding the dry ice, behaviors of dry-ice-powder at the surface of fragment was observed when an additional gas, such as He, O₂, and CO₂, was supplied by tubing in a flow rate of ~2 ml/min shown in Fig. 3. The top panel (table) in Fig. 3 shows a relative change in dry ice sublimation rate during the additional gas supply. The frequency and amount of white aerosol stream flowing from the dry ice were evaluated by the experimenter’s eyes qualitatively. The results showed the additional CO₂ supply enhanced the sublimation in dry ice; however, O₂ supply decelerated the sublimation. It was notable that no white powder appeared on the surface of dry ice during the additional O₂ supply. We can hypothesize that much of O₂ supply increased the magnetic susceptibility of atmosphere to a moderate condition where the oxygen transport in atmosphere became out of rate limiting.

In the future study, we need control the concentration of gases more precisely and clarify the mechanism for above mentioned difference between the additional gas supplies of CO₂ and O₂.

We can expect the mechanism may provide a new application of magnetic fields to the control of environmental CO₂ concentration by means of CO₂ collection by oxygen at the temperature of dry ice.

4. Conclusion

Enhancements of CO₂ sublimation in a fragment of dry ice, which was set in the bore of magnet, were observed. The data of sublimation rate suggest that the rate of dry ice sublimation depends on the magnetic field gradients. The sublimation enhancements were distinctly observed when the product of a magnetic field and its gradient, BdB/dx , was above 70 T²/m.

Changing the gas concentration near the dry ice affected the magnetic field effect, and particularly supplying an additional gas of CO₂ and O₂ accelerated and decelerated the sublimation, respectively.

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