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Wet Hail and Thunderstorm Electrification

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ABSTRACT: Hailstones in wet growth are commonly found in thunderclouds. While the ice-ice relative growth rate mechanism is generally accepted as the most likely cause of thunderstorm electrification, it is uncertain if this mechanism will operate under wet growth conditions because ice crystals are more likely to stick to the wet surface of a hailstone rather than bounce off it. Experiments were carried out in the laboratory to investigate if there was any charge separated when vapor-grown ice crystals bounced off a wet hailstone. A cloud of supercooled droplets, with and without ice crystals, was drawn past a simulated hailstone. In the dry growth regime, the hailstone charged strongly positive when droplets and crystals co-existed in the cloud. With only droplets in the cloud, there was no charging in the dry growth regime. However, as the hailstone attained wet growth, positive charging currents of about 0.5 and 3.5 pA were observed at 12 and 20 m s^{-1}, respectively. We hypothesize that this observed charging was due to the evaporation of melt water. This so called Dinger-Gunn Effect is due to the ejection of negatively charged minute droplets produced by air bubbles bursting at the surface of the melt water. However the charge separated in wet growth was an order of magnitude smaller than that in dry growth and, therefore, we conclude that it is unlikely to play an important role in the electrification of thunderstorms.

INTRODUCTION

Hailstones grow by the accretion of supercooled water droplets, a process that is also known as riming. The freezing water transfers latent heat to the hailstone so that if the accretion rate and/or air temperature are/is high enough, its surface temperature may rise to 0ºC when it is said to be in wet growth. Hailstones in wet growth are commonly found in thunderclouds, especially in the lower regions where the air temperature exceeds -10ºC [Pruppacher and Klett, 2010]. In the dry growth regime, the riming particles are known as soft hail or graupel.

It is now generally accepted that the dominant mechanism of thunderstorm electrification is the so-called relative growth rate mechanism, where, when two ice particles impact and separate, the particle with the higher surface diffusional growth rate acquires the positive charge [Baker et al., 1987; Saunders, 2008]. Laboratory experiments have shown that substantial amounts of charge are separated when graupel pellets interact with vapor-grown ice crystals [Reynolds et al, 1957; Takahashi, 1978; Jayaratne et al, 1983; Keith and Saunders, 1990]. The relative growth rate, and therefore the sign of charge acquired, depend on the temperature and cloud water content [Baker et al, 1987]. Generally, throughout most of a

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cloud, graupel acquires a negative charge and the ice crystals an equivalent positive charge. Falling graupel pellets carry the negative charge downwards, while the ice crystals are swept up in the strong updrafts to the top of the cloud, giving rise to a thundercloud dipolar charge structure with the positive above the negative [Simpson and Scrase, 1937]. Takahashi [1978] and Jayaratne et al. [1983] showed that at temperatures higher than a critical value called the 'reversal temperature' the graupel will acquire a positive charge, with the ice crystals becoming negative. The reversal temperature was dependent on the cloud water content, being colder at higher water contents. They used these observations to explain the existence of the lower positive charge center giving rise to the commonly-observed tripole charge structure in thunderstorms [Krehbiel, 1986; Williams, 1989]. Although much effort has been devoted to the study of the relative growth mechanism of thunderstorm electrification, its precise physical mechanism has eluded scientists to-date. One of the controversial observations over the years has been the observation of strong positive charging at relatively high cloud water contents observed by Takahashi [1978]. Calculations have shown that, at the temperatures, cloud water contents and speeds of interaction corresponding to this charging regime the surface of the hailstone was in wet growth [Jayaratne, 1993]. Saunders et al [1991] suggested that under such conditions impacting ice crystals would stick to the hail pellet rather than bounce off thereby preventing any charge transfer. This was later confirmed by Saunders and Brooks [1992] who found negligible charging under wet growth conditions. However, Williams et al [1991] suggested that crystals can bounce off a hailstone in wet growth, charging it positively. Saunders and Brooks [1992] showed that, in a cloud water content vs temperature diagram, the transition from negative to positive charging of rime did not coincide with the boundary between dry growth and wet growth. The present study was carried out to experimentally resolve the question of whether charge is separated during ice crystal – hail interactions under controlled conditions of wet growth.

METHODS

The experiments were carried out in a large chest freezer in the laboratory. A cloud of supercooled droplets was produced by injecting steam from a boiler placed outside the freezer. The cloud was seeded by popping a small plastic packing bubble in a syringe. The rapid expansion and cooling gave rise to ice crystals that grew vigorously at the expense of the droplets to a size of about 50 μm, after which they fell out of the cloud. Crystal size and concentration were determined by collecting them on formvar-coated glass slides and analysing the replica under a microscope as described in Griggs and Jayaratne [1986].

Fig 1 shows a schematic diagram of the experimental arrangement. The hailstone was simulated by a stainless steel rod (R) of length 32 mm and diameter 4 mm, fixed horizontally in a vertical tube of internal diameter 36 mm. The cloud was drawn past the rod at a controlled speed by means of an air pump located outside the freezer. The supercooled droplets impacting on the rod formed a layer of soft rime on its surface. Once the cloud was seeded, the ice crystals interacted with the riming rod simulating particle interactions in a thundercloud. The rod was electrically connected through a current-to-voltage converting amplifier (A) to a sensitive electrometer (E) that continuously measured the current due to any charge acquired. The charge acquired flowed through the electrometer to ground with a time constant of 1 s. A small plastic cup (C) prevented a rime bridge forming between the rod and earth that would cause the

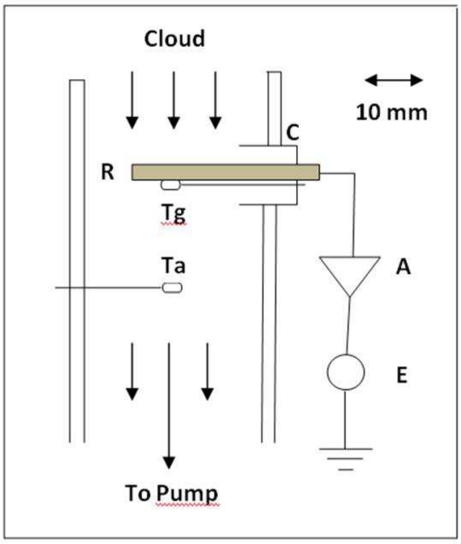

Fig 1: Schematic diagram of the experimental arrangement.

current to leak to earth by-passing the electrometer. An input current of 100 pA gave an output voltage of 1V. The minimum detectable voltage was 1 mV which corresponded to a charging current of 0.1 pA.

The temperature of the cloud (Tc) was measured by a bead thermocouple mounted within the freezer. The temperature of the rime or graupel (Tg) was measured by a thermocouple mounted on the underside of the rod. Another thermocouple (Ta) was mounted just below the rod. Supercooled droplets impacting and freezing on this thermocouple raised its temperature above Tc. The temperature elevation was related to the cloud water content, Tc and the air flow rate in the tube. The cloud water content was measured by capturing cloud droplets on a thin wire moved through the cloud. A series of calibration experiments were carried out at a range of conditions and this enabled an estimate of the cloud water content to be derived during the experiments in relation to the observed value of Ta.

RESULTS AND DISCUSSION

In each experiment, the freezer was cooled to a pre-determined temperature and steam injected to produce a stable cloud of supercooled droplets at a required cloud water content. Where required, the cloud was seeded at this stage. The cloud was then drawn through the tube at a fixed flow speed.

Such a stable cloud was obtained at Tc = -10ºC at a water content of about 3.0 g m^{-3} and drawn through the tube at a steady speed of 12 m s^{-1}. The graupel temperature, Tg, increased steadily and the rime on the rod attained wet growth within about 2 min. No charging was observed until Tg reached -2ºC when a small positive charging current of about 0.5 pA was observed (Fig 1a). Next, the experiment was repeated with a mixed cloud of supercooled water droplets and ice crystals. In the dry growth regime, the rod charged strongly positive when droplets and crystals co-existed in the cloud. The charging current was of the order of a few tens of pA and gradually increased as the temperature of the rime increased from

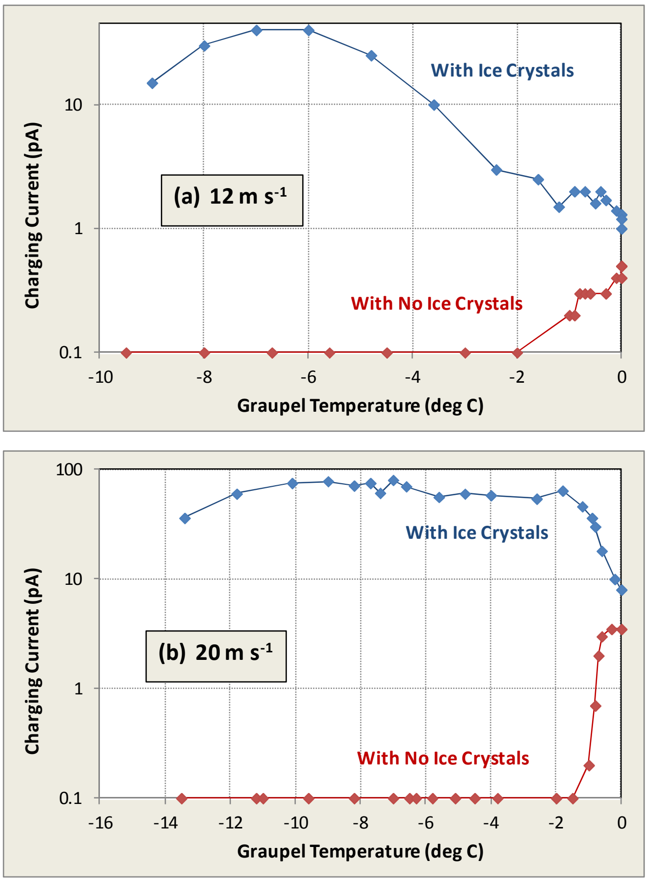

Fig 2: Charging current vs graupel temperature at two different flow speeds, with and without ice crystals in the cloud of supercooled droplets.

-10ºC to -5ºC and then steadily decreased with further increase of temperature to 0ºC when wet growth was achieved. At this stage, the charging current remained at about 1.0 pA. The experiment was repeated several times and yielded similar results.

Next, we repeated the experiment at a flow speed of 20 m s^{-1}. The initial cloud temperature was reduced to -14ºC while the cloud water content remained at 3.0 g m^{-3}. Once again, with only supercooled droplets present, there was no charging until Tg had exceeded -2ºC. At wet growth, a positive charging current of about 3.5 pA was observed (Fig 1b). With a mixed cloud, a higher charging current was observed at all temperatures, remaining at 50-90 pA all the way up to -2ºC, beyond which it fell sharply to attain a steady value of about 8 pA at 0ºC.

Fig 3 summarises these results in a graphical form. The observations with mixed clouds, when ice crystals co-existed with supercooled droplets at a cloud water content of 3.0 g m^{-3} were broadly in agreement with the results of Takahashi (1978) and Jayaratne et al (1983) who also found positive charging under these conditions. As the rime surface temperature reached 0ºC, the charging fell by an order of magnitude. This was probably because the crystals were sticking on to the wet rime. The finite charging current that was observed may indicate that a small fraction of the crystals were still able to rebound off the wet surface. However, this charging current was at least an order of magnitude lower than during dry growth. Inspection of the rod under the microscope showed many ice crystals stuck on the surface of the glazed rime.

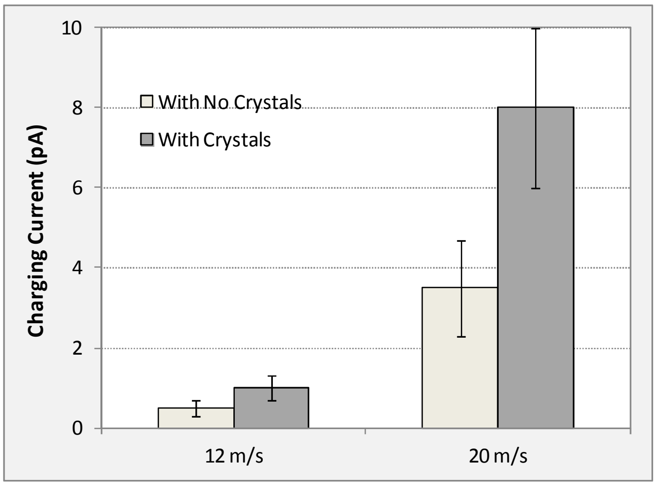

Fig 3: Mean values of the charging current at 0ºC with and without ice crystals in the cloud.

Also, in agreement with the two previous studies above, with a droplet-only cloud, there was no charging in the dry growth regime. The more interesting observation is that, when the rime attained wet growth at 0ºC with a droplet-only cloud, a significant charge separation was taking place. In fact, looking at Fig 3, we see that a substantial amount of charging observed with a mixed cloud at 0ºC, approximately 50% at 12 m s^{-1} and 44% at 20 m s^{-1}, was due to the charging that occurred with water droplets alone.

We hypothesize that the observed charging in wet growth was due to the evaporation of melt water. This so called Dinger-Gunn Effect was first reported in 1946 (Dinger and Gunn, 1946). Subsequent studies have attributed the charge separation to the bursting of air bubbles during the melting of ice (Dinger, 1964; MacCready and Proudfit, 1965; Drake, 1967). Latham and Stow (1965) suggested that the electrification was due to the evaporation of the meltwater under a temperature gradient. A common observation in all these experiments was that the ice acquired a net positive charge.

CONCLUSIONS

Thus, we conclude that the ‘hailstone’ in our experiments charged positively during wet growth due to electrical effects associated with the melting and evaporation of ice, otherwise known as the Dinger-Gunn Effect. The charge separation in the presence of ice crystals was due to the relative growth rate mechanism. The charge separated in wet growth was an order of magnitude smaller than that due to the relative growth rate mechanism in dry growth. This observation contradicts Takahashi (1978) who did not find such a large difference in the magnitude of charging between the dry and wet growth regimes. Following our findings, we conclude that the charging in the wet growth regime is unlikely to play an important role in the electrification of thunderstorms.

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