Temperature Dependence of Static Charging in Ice Growing by Riming

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ABSTRACT

Charge transfer between colliding ice particles is measured using a wind tunnel inside a cold room. A cylinder growing by riming in a wind tunnel was used as a target for collisions between 5 and 6 m s^{-1} with ice spheres of 100-μm diameter. The target temperature was adjusted to simulate different liquid water concentrations. As the target temperature increased, for air temperatures below −18°C, initial positive target charging reversed sign to negative; with a further temperature increase the charging reversed sign again. These measurements, which are relevant to thunderstorm electrification, were carried out with and without riming and results are compared with other works. A novel approach is presented here suggesting a new pair of variables describing the charging.

1. Introduction

There is now extensive field evidence (Gaskell et al. 1978; Krehbiel et al. 1979, 1983) showing that the development of electric fields within thunderstorms is largely the result of charge separation during collisions between ice particles (Latham 1981; Illingworth 1985; Saunders 1993).

Laboratory experiments of graupel growing by riming (Reynolds et al. 1957; Takahashi 1978; Gaskell and Illingworth 1980; Jayaratne et al. 1983; Baker et al. 1987; Keith and Saunders 1989; Saunders et al. 1991) showed that the sign and magnitude of the charge transferred depends on temperature (T), liquid water concentrations (LWC), impact velocity, and size of the interacting particles. In most cases the charge separated per collision has been inferred from the accumulated charge caused by large fluxes of particles.

Several mechanisms have been proposed for the ice–ice collision charging process. Buser and Aufdermaur (1977) and Caranti and Illingworth (1980) suggested that it depends on the contact potential difference between the two surfaces of the interacting particles; Avila et al. (1988) proposed the crystal fracture from one of the particles, Baker and Dash (1989) the surface liquid-like layer, and Keith and Saunders (1989) the presence of charged dislocations on the surface. Each mechanism seems to explain part of the observations.

Takahashi (1978) and Jayaratne et al. (1983) rotated a rimed rod through an environment of supercooled water droplets and ice crystals and measured the charging of the target. They found that no measurable charge was transferred in an environment of supercooled water alone and that the rod charged slightly negatively when it collided with ice crystals alone. They observed that T and LWC were the principal independent variables and that the sign of the charge acquired by the simulated graupel depended on them. However, their results were different. There were attempts to explain their discrepancies by recalling that the speeds used were very different, but it is apparent that speed alone could not be the only cause.

Baker et al. (1987), working on multiple collisions, extended the measurements of Jayaratne et al. (1983) to a wider range of temperatures and obtained results consistent with the latter work. They suggested that the sign would depend on the relative rate of growth of the interacting particles; the fastest-growing particle would charge positively. Keith and Saunders (1990) also measured multiple collisions and they suggested that charged dislocations on the surface of the interacting particles would be responsible for the observed transfers.

Avila et al. (1988), Caranti et al. (1991), and Avila and Caranti (1994) measured charge transfer in single collisions. Their results showed that when the simulated graupel growth from deposition or by riming, events of both signs were present within the same experimental conditions and normally one kind of them prevailed. They found that the collisions break off frost or rime structures from the surface of their target. The broken structures carry net charge away. These authors use a mechanism driven by temperature gradient to explain the positive charge left on the target when the protuberances grow from vapor. The same mechanism would explain the negative charging when the protuberances are sublimating. An independent confirmation

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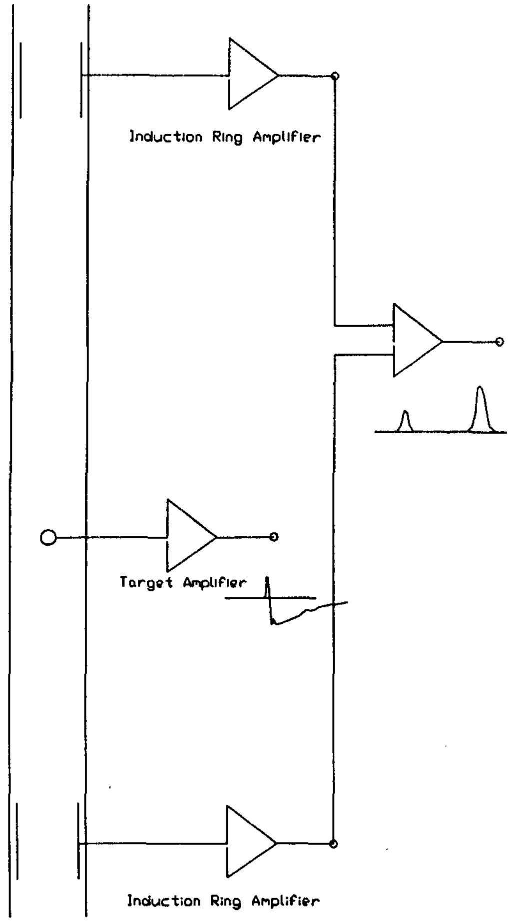

FIG. 1. Measuring section of the wind tunnel. The airstream from the top carries with it the colliding particle whose charge is sensed by the top ring. After the collision with the 4-mm diameter target, the bottom ring detects the charge of all passing particles.

of this mechanism comes from the work of Saunders et al. (1993), who also measured charge separation during fragmentation, but this time an air jet was used to remove frost or pieces of rime from ice surfaces instead of ice–ice collisions.

Saunders et al. (1991) measured currents to a target growing by riming while it was subjected to collisions against ice crystals in a series of experiments under controlled conditions. The liquid water concentration was varied, while the size of the crystals and the velocity were kept constant. This work extended previous measurements by Jayaratne et al. (1983) and modified the charging diagram (T–LWC). They also proposed that the charging mechanism, whatever it may be, involve the movement of charge across the point of contact between the interacting particles and that it could be due to contact potentials or charged dislocations.

Williams et al. (1991) suggested that the polarity of the charge transfer in ice particle collisions is determined by the state of growth of the ice surface either by sublimation or deposition. Their calculations specify conditions on temperature and LWC for sublimation and for deposition during riming in the dry growth regime. Comparisons with the laboratory observations of Takahashi (1978) suggest that riming graupel particles that are sublimating charge negatively and graupel undergoing vapor deposition charge positively.

The previous discussion not only shows the great importance that the temperature and LWC have in the charge exchanged among interacting ice particles but, also, it suggests that the target heating produced by LWC affects the charge transfer.

In the present work we introduce new measurements about charge transfer in individual collisions between small spheres of ice and an ice target that is warmed with respect to the ambient temperature and we examine the dependence of the charging with ambient and target temperatures while the target in being rimed.

By heating the target, it is possible to achieve any temperature that natural latent heat release during riming would produce. We compared the charging obtained when the target is being heated with the results obtained by other authors when they changed the LWC.

On the other hand, a variation in target temperature could be used to study the effect of heat losses in standard charging experiments. In fact, it should be acknowledged that in many laboratory experiments in which a target either moving or stationary is undergoing rime the temperature it acquires is far from the one corresponding to free-fall accretion. There are several reasons for this, but perhaps the most important is the presence of a support or target holder that dissipates heat from the metallic target. Generally, the shape of the target is cylindrical, and this also contributes to a trend in temperature that does not agree with that of graupel of the same diameter.

We discuss some of the proposed mechanisms in relation to the results here obtained.

There are some research works on the matter (Jayaratne et al. 1983; Baker et al. 1987; Jayaratne 1993). We present a systematic study of the temperature dependence in another range than previously done.

2. Experimental apparatus

The experiments were carried out using a wind tunnel placed inside a cold room. Uniform size drops produced at the top of the tunnel have charge and size selected a priori. Each drop is frozen as it falls though a section of the tunnel cooled by liquid air. This section is short enough so as to only begin the freezing. After beginning to freeze, the particle has a free fall of more than 50 cm at cold-room temperature allowing the completion of the freezing and subsequent thermalization. There is an acceleration zone where cold-room air enters the tunnel and drags the particle with it, leading to a particle–target collision at the desired speed. In this work the velocity was kept at about 6 m s^{-1}.

The working section of the wind tunnel (Fig. 1) has a diameter of 2 cm. The target is a copper cylinder 4 mm in diameter. An electrically insulated Peltier element is attached to one end of the target, which allows the target temperature to be adjusted to several degrees above or below the ambient temperature. To measure the target temperature as accurately as possible, an electrically insulated thermistor is located inside the target in the middle of the impact zone. It should be noticed that the Peltier element is thermally connected to an efficient heat sink. This ensures that the target temperature is completely controlled by the Peltier element. In absence of current through the Peltier, the heat sink keeps the target at ambient temperature except for very high effective liquid water concentrations (EWs). The target is connected to a sensitive charge amplifier with a detection limit of 2 fC.

There are induction rings sensing the initial charge on the frozen drops and the products of the collisions. The rings were connected together to a charge amplifier with the same detection limit as the target amplifier (Avila and Caranti 1994). Figure 2 shows a set of pulses involving a nonfracture and a fracture events. The upper oscilloscope trace is the charge on the incident particle together with the charges after the interaction. The lower trace shows the charge transferred to the target. In Fig. 2a the charge transfer is negative in spite of the positive sign of the incoming particle. After the collision there is only one particle with a larger positive charge. In Fig. 2b there is another negative transfer, but this time there are two particles after the collision. Their sizes must surely be quite different, as it can be seen from their time of passage through the lower ring. The smaller particle acquires the airspeed sooner. This is the particle considered the fragment. From the several time delays involved in both collisions it is clear that case a is a glancing collision and case b is a frontal one. In both cases the sum of the charges before and after the collision are consistent with the conservation of charge.

The cloud was generated outside the cold room by boiling water. The water vapor was conducted to the wind tunnel by several tubes ensuring thermalization. The liquid water concentration was adjusted by the power given to the boiler. Although the cloud so formed was not totally neutral, this charge was considered part of the background noise.

The EW is determined by weighting the mass of water collected by the target during a given time. The calculation takes into account the time interval, the cross sectional area of the target, and the air velocity (Avila and Caranti 1994).

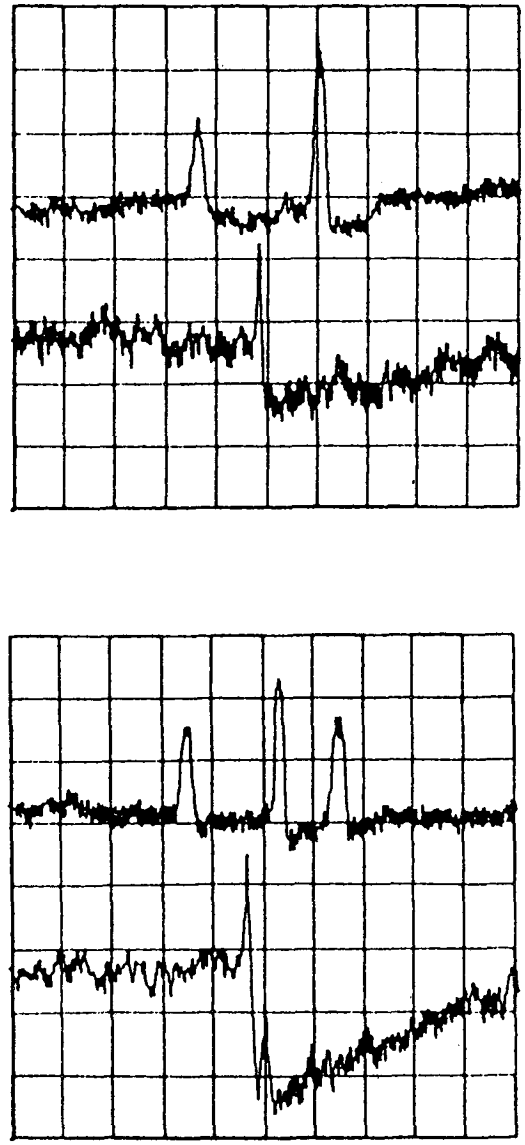

FIG. 2. Typical charge transfer pulses: upper trace is the rings signal; lower trace is the target signal. Horizontal axis 20 ms division^{-1} vertical axis 10 fC division^{-1}. (a) A positive particle colliding at 5 m s^{-1} transfers net negative charge to the target, and afterward its passage is detected by the lower ring. (b) A positive particle impacts at 5 m s^{-1}, and after rebounding (see the wavy target signal) its passage together with a fragment is sensed by the bottom ring. The time of passage differences are associated with the respective sizes.

3. Results

Each experiment consisted of consecutive runs with and without riming. The charge transferred in collisions between ice particles and the ice-covered target are measured, while the target is forced to a certain chosen temperature. In particular, since it is of interest to simulate the temperature that the target would acquire if it was freely growing by riming instead of being fixed to a holder, the temperature was raised with the Peltier element. The target temperature was the same in both consecutive runs, and the duration was about 5 min in each.

Ice particles between 80 and 100 μm in diameter and repetition rates of 1 s^{-1} were used.

a. Measurements with riming

The measurements with riming were carried out for three ambient temperatures, T_a, (−15.7°, −18°, and −20°C), and target temperatures, T_b, up to 7°C warmer than T_a. In all cases the ambient relative humidity with respect to ice was lower than saturation and within the range of 60%–80% over ice according to the cold-room cycle, although inside the tunnel, during the riming runs, the cloud ensured saturation.

Effective water concentration values were purposely kept at about 0.3 g m^{-3}. A higher quantity of water clogs the inlets too soon. So, by limiting the water content, typical run times with riming are extended to about 5 min.

Figure 3 shows the behavior of the average charge transferred to the target calculated for different ambient and target temperatures including fracturing and nonfracturing events. The target was growing by riming, and the impact velocity was 6 m s^{-1}. Abscissas represent the temperature difference of the target with respect to the ambient and is defined as $\Delta T = T_b - T_a$.

The fracture efficiency is defined as the proportion of events with fragmentation over the total number of events. Figure 4 shows this efficiency for each pair of temperatures, T_a and T_b, when the charges are measured with riming. It is interesting to note that the highest efficiencies are obtained when the ambient temperature decreases, and at the beginning of riming we observed that higher efficiencies are obtained with longer target accretion times.

When the air was at $T_a = -15.7$°C, the magnitudes of the individual charge transfers were in the [−30, 40] fC range, but when $T_a = -18$°C, the charges were in the [−60, 50] fC range, while for $T_a = -20$°C they were in the range of [−40, 30] fC. For all ambient temperatures the largest magnitudes corresponded to events with fracture, irrespective of sign. Collisions with and without fracture are observed to transfer charge of either sign. Moreover, the average charge associated with fragmentation events is slightly more negative than the average charge associated with nonfracturing events.

b. Measurements without riming

The measurements without the cloud of supercooled droplets were carried out for T_a (−15.4° and −19°C) and T_b up to 7°C warmer than T_a. The size of spheres and the impact velocity were the same as in the previous measurements. The target surface was still covered with ice formed by riming during the previous run, and the collisions showed a proportion of fracture events.

Figure 5 shows the behavior of the average charge transferred for the above-mentioned ambient temperatures as a function of ΔT. Here, we can see that the variation of average charges with ΔT is similar to the variation measured with supercooled cloud droplets. However, the charges for both T_a's are more negative than in the riming case. In these measurements we also find a mixture of signs of the individual charge transfers, irrespective of the production of fragments.

For $T_a = -15.4$°C the magnitudes of charge transfer were in the range [−40, 30] fC, and for $T_a = -19$°C they were in the range [−50, 20] fC. We found no correlation between the largest magnitudes with any particular kind of event.

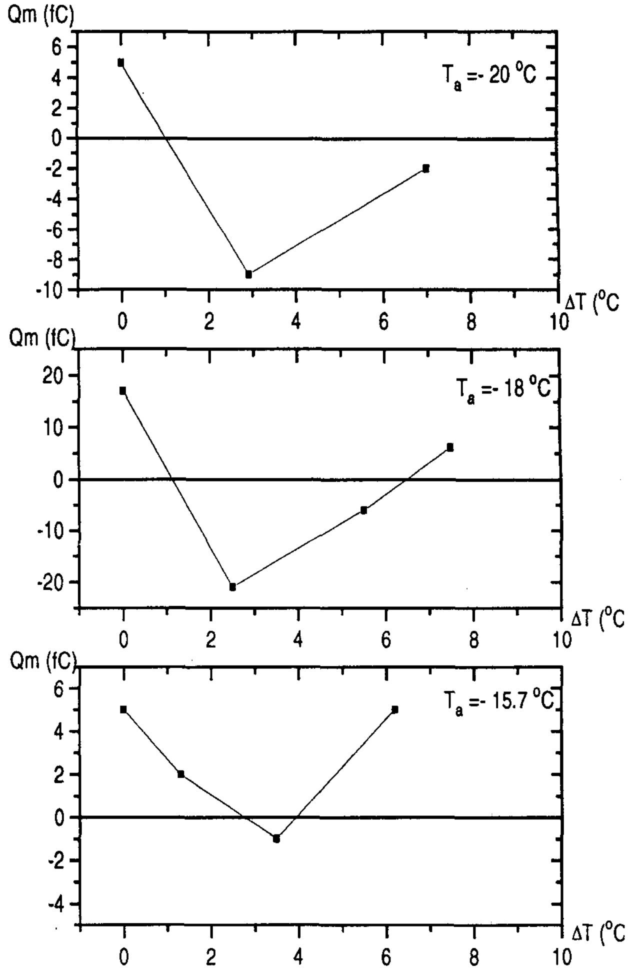

FIG. 3. Mean charge transfer in collisions between a target under riming and ice particles of 100-μm diameter. The effective liquid water concentration EW is 0.3 g m^{-3}. Each square represents the average of all pulses acquired during a 5-min run.

4. Discussion

a. Case with riming

The magnitudes of charges observed in our experiments are in a similar range to those observed by Gas-

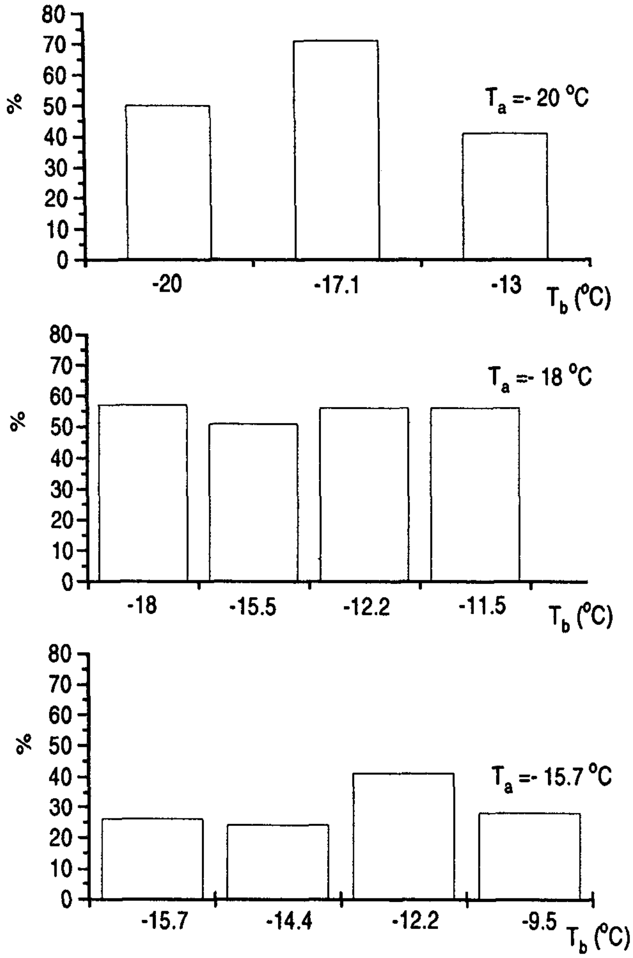

FIG. 4. Fracture efficiency as a function of the target temperature (T_b); air temperature is denoted by T_a. (See text for description.)

kell and Illingworth (1980), who also found mixed signs in the charge transfer, with the target growing by riming.

Using the results shown in Fig. 3, we can see that as the ΔT is increased the average charge transfer tends to negative values at first and then increases giving a V-like graph.

Takahashi found, for a temperature range between $-10°$ and $-30°C$, which increased the LWC from almost zero to beyond the wet growth limit, that the sign of charges transferred to the rimer alternated positive–negative–positive (see Fig. 8 in Takahaski 1978). For temperatures warmer than $-10°C$ Takahashi found only positive charging. Saunders et al. described a similar behavior for temperatures lower than $-20°C$ (see Fig. 7 in Saunders et al. 1991). Baker et al. also found a V-type charging of a target (see Fig. 4 in Baker et al. 1987) but as a function of rime accretion rate (RAR) at a fixed $-24°C$ ambient temperature.

The similarities found by these authors using different techniques when they increased the cloud concentration and our results for an artificially heated target in the presence of supercooled drops are striking.

Incrementing the cloud droplets concentration (CDC) is not the same as raising the target temperature. In fact, the rime structure is a function of the both the CDC and the temperature as well as other variables such as cloud droplet sizes and impact speeds. Nevertheless, to increment the CDC results in an increment of the target temperature, therefore, we propose that the effect on the charging of heating the target is similar to that obtained by increasing the CDC.

Of course, a comparison between the present work and those of Takahashi (1978), Saunders et al. (1991), and Baker et al. (1987) would be impossible because they did not measure the target or rimer temperatures.

The average charge transfer behavior as a V shape is not completely in accord with the results obtained by Jayaratne et al. (1983). In fact, they found at $T_a = -14.9°C$ and ΔT between 0 and 6°C that the charging was positive and increased until $\Delta T = 2.5°C$ and then decreased. Moreover, they observed that it was possible to reverse the negative charging of the rime at $T_a < -20°C$ to positive by warming the rime by a few degrees. They concluded that both sign and magnitude of the charge transfer depended more on the target temperature than on the ambient temperature or ΔT. Furthermore, they suggested that the sign of the charge transfer did not depend on whether the rime surface was growing or evaporating. In our measurements at $T_a = -15.7°C$ the average charge transfer is positive for almost the complete range of measured ΔT (0° to 7°C). It decreases until $\Delta T = 3.5°C$ then increases. Furthermore, at $T_a = -18°$ and $-20°C$ we reverse signs from positive to negative charging by warming the target a few degrees. This tendency is observed in both fracturing and nonfracturing events.

As seen in Fig. 5, the V shape is also obtained without cloud, indicating that ΔT is an important parameter controlling the charging and suggesting that the temperature is more of a dominant factor than the rime structure. The rime structure would enter in this context as determining variations in surface temperature (Avila and Caranti 1994), leading to the observed variability in charge transfers (in the absence of cloud) and to the variability and larger mixture of charge signs (with cloud).

Caranti et al. (1991) worked on charge transfer with ice-covered targets in which the ice could only exchange mass with the environmental water vapor. They found that after a collision one or more fragments could be ejected with a charge dependent on the various temperatures involved. These temperatures were the target temperature, controlled by the latent heat release and heat of conduction, and the air temperature. The sign observed for fracture charging was positive (to the target) when the target was growing and negative when it was evaporating. They propose that the temperature gradient, along breakable protuberances, was respon-

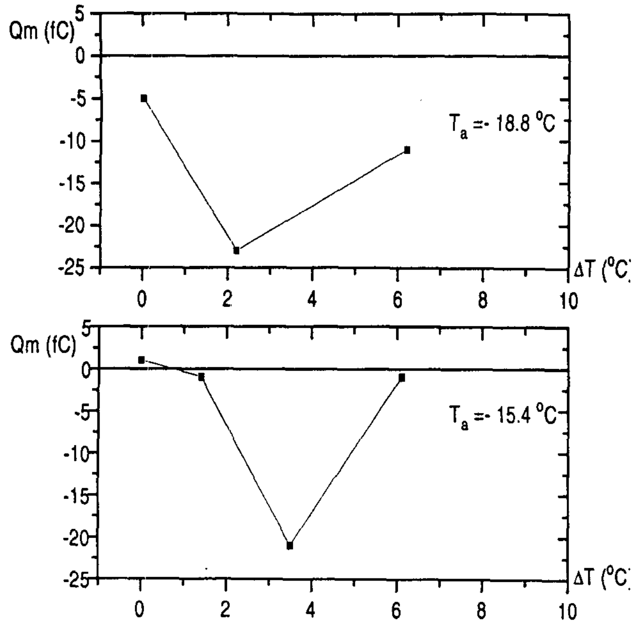

FIG. 5. Charge transfer during collisions between a rimed target and ice particles of 100-μm diameter.

sible for the charging. Avila and Caranti (1994) propose that a similar fracture mechanism operates when the target grows by riming. In this case the temperature gradient is controlled by the release of latent heat of freezing, evaporation, and sublimation—and to the some degree to the heat conduction to the environment. They suggested that the degree of positive charging is related to the fraction of surface covered by water vapor supplied by freezing droplets. Therefore, when the target is heated up, it is expected that the negative transfers, for charging associated with fragmentation, would be favored.

The results illustrated in Fig. 3 are in part consistent with the above description. In fact, initially, the charging tends to be negative as ΔT increases. However, the other branch of the V needs a different explanation. Since the change in slope occurs at larger temperature differences between colliding particles, it may be caused by differences in surface properties such as adhesion, surface potential, etc. or it could involve the mechanics of the collision, probably through the effect of multiple interactions. The mechanics depends on the temperature through, for instance, changes in elastic properties. At this moment the data suggests that the incoming particle is able to exchange charge with the fragment and with the target in any order. There is a clear indication of this in the pulse shapes; in fact, the incident particle is very well distinguished from the fragments, and the charges on them are measured separately, and, as it can be seen in Fig. 2, there is no unique way of sharing the charge.

Applying all of the above to natural free-falling graupel or hail, it can easily be shown that small temperature changes would produce substantial variations in the charging. Fluctuations in LWC could result in flipping the predominant sign acquired by the precipitation particle. This effect could be related to the positive charge pocket in the bottom of the clouds.

The fact that the falling particle temperature is one of the main variables suggests that the charge acquired by a falling ice particle inside a cloud would not be related to LWC only, and therefore a single pair of variables is not able to describe the charging. In particular during this work, keeping EW constant and heating the target from ambient temperature, the charge varied enough to reverse sign.

b. *Case without riming*

In measurements without supercooled cloud droplets we found a mixture of signs. This does not agree with Gaskell and Illingworth's (1980) results. They found only one sign of charge transfer when their target was sublimating. The main difference between these experiments is that the targets were produced in different ways. Our target was rimed for a time interval before taking measurements, while Gaskell and Illingworth's target had a smooth surface. On the other hand, in our experiments (Fig. 5) there is a preference for a negative charge transfer to the target on average, which is in accord with the sign obtained by other authors when their targets were sublimating (Gaskell and Illingworth 1980; Jayaratne et al. 1983; Baker et al. 1987; Jayaratne 1993).

The average charge transfers in the absence of riming show a dependency on ΔT similar to our measurements with riming. The V-shape function is reproduced but with a shift toward negative charges. Baker et al. (1987) obtained a similar dependency but for the charging current in a multiple collisions experiment. They measured the current collected by a stationary target of 5-mm diameter. Only ice crystals were drawn past the target at a constant speed of 15 m s^{-1}. The target could be temperature adjusted by means of a thermoelectric element. The environmental temperature used was -10°C. The concentration and mean size of the ice crystals were about 600 cm^{-3} and 25 μm, respectively. They reported that the current variation with ΔT has a minimum, but this variation is less marked than in the present work as far as charge transfer is concerned. This behavior also agrees with the results of Jayaratne (1993). He found that by warming the target by 1°C the negative charging increased. Their results corresponded to $T_a = -10$°C, with a flow speed of 15 m s^{-1}.

Previous temperature excursions by Jayaratne et al. (1983) using stationary ice targets impacted with what was believed to be ice crystals alone showed a negative mean charge transfer and did not vary significantly in the temperature range 0° to −25°C. When the target was heated by a few degrees above the environment, the charging was more negative. The negative charging was also increased when the crystal cloud was warmed up. However, when the air was saturated, the target became positively charged. The same thing happened when the target was cooled with respect to the cloud. The charge transfers calculated by these authors were too small in comparison to the charging obtained during accretion of supercooled cloud droplets. For a flow speed of 9.8 m s^{-1} and crystal size of 30 μm, the mean charge calculated was around −0.25 fC. In the same work they suggested that the parameter controlling the sign of the charge transferred is the surface state of the target. The target would charge negatively when sublimating and positively when growing. Undoubtedly, we also think that the state of the surfaces is a major controlling parameter; nevertheless, it does so in a complicated manner. In fact, our results show that when the target surface increases its evaporation monotonically with ΔT, the charging, although remaining negative, goes through a minimum.

Recently, Jayaratne (1993) measured the electric charge acquired by a stationary rimed target while it interacted with a crystals cloud. The temperature of the rime was varied by means of a Peltier cell. As in Jayaratne et al. (1983) and Baker et al. (1987), he found that warming the rime resulted in a negative current, while cooling the rime reversed the sign to positive. The cloud temperature was close to −14°C, the flow speed was maintained at 8 m s^{-1}, and the target temperature was varied by about 2°C. The magnitude of charges separated and calculated by Jayaratne were in the order of 50 aC for crystal in the size range 20–50 μm. These values are five times less than the values calculated by Jayaratne et al. (1983) for similar crystal sizes and flow speed: a difference that shows the uncertainties in the determination of the average charge transfer using the technique of multiple collisions. The behavior of the charging as a function of ΔT presented by Jayaratne et al. is similar to our result for low values of ΔT, although his charges are smaller by about one order of magnitude. Surely, that is a consequence of different sizes of impacting particles used in both experiments.

On the other hand, Jayaratne (1993) suggests that in his experiments there is no fractures of frost fibers or rime protuberances as a consequence of collisions with ice crystals, because, according to him, in his measurements there were small vapor-grown ice crystals, which apparently would be unable to produce fracture. However, the kinetic energy calculated for crystals of 30 μm, using the mass estimated by Nakaya and Terada (1935), and velocity of 8 m s^{-1} is 1.09×10^{-10} J. This energy is enough to break 2.73×10^{9} hydrogen bonds, corresponding to an area of 182 μm^2. Therefore, it seems likely that some ice crystals would be able to break protuberances. A similar argument can be applied to the experiments carried out by Baker et al. (1987), Jayaratne et al. (1983), and Takahashi (1978). The latter actually observed particles that could be considered as fragments.

In all runs we obtained charge transfers of the same order of magnitude as in the measurements with riming. This is in accord with Gaskell and Illingworth (1980), but it does not necessarily agree with interpretations made on the outcome of experiments with multiple collisions. In fact, Jayaratne et al. (1983) and Jayaratne (1993) found that the charging current drops about one order of magnitude when the steam supply of supercooled water droplets was cut off. However, in order to deplete the cloud droplets, it is necessary to wait several minutes. In this time the crystal concentration diminishes, and obviously the charging current decreases. Even so, it is difficult to assure that there were not cloud droplets present during their experiments.

It is interesting to observe in our measurements that the fracture efficiency is similar to that of the measurements during riming. Furthermore, we observed that the charging associated with fragmentation does not stop after the riming ceased; it only diminishes slowly along the 5-min run. However, Avila and Caranti (1994) observed that the events with fractures stop about 1 min after the steam was cut off. We may remember from previous work that the target was growing by riming for a shorter period than the present case and that here the rime is being heated, making some protuberances more fragile. We find again that the mean charging associated with fragmentation is slightly more negative than the mean charging associated with nonfracturing events.

5. Conclusions

In this work we measured the charge transfer in ice–ice collisions with a focus on the influence of the target temperature. Comparisons are made between rime and nonrime runs but otherwise with similar temperatures. As expected from the arguments given in the introduction, the target temperature is an important parameter. Our data show the charging has a relatively high sensitivity with this temperature, which in turn suggests that in experiments where no provisions were made to compensate for different heat dissipations that the results would not correspond to what occurs in a real cloud. The charging is so sensitive that a few degrees warming can even change the sign.

One of the main findings in this work is the V-shaped dependency of the average charging with the ice target temperature. This shows that given the proper latent heat warming of the target it is possible for the present mechanism to produce negative charging right in the air temperature range of interest for cloud electrification.

On the other hand, the water concentration enters rather indirectly, and the important pair of variables is now the ambient temperature and the temperature of the larger particle, instead of LWC. In this way, other effects such as temperature lags due to fast falling could also enter into play.

Of course, the process is very complicated, and there is still the need for providing a mechanism that would explain every possible detail of the observed charge separation. We are presently working in that direction.

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