Response to Prof. Lorin S. Matthews

RC2: 'Comment on egusphere-2026-2931', Lorin S. Matthews, 28 Jul 2026
Citation: https://doi.org/10.5194/egusphere-2026-2931-RC2

This study considers the effect of charging on the aggregation of ice and several types of metal oxides in the mesosphere/lower thermosphere region of Earth's atmosphere. The oxides are chosen to be the primary oxides expected to be injected into Earth's atmosphere from debris from orbiting satellites re-entering the atmosphere. The study focuses on the probability of collisions of two spherical particles leading to sticking, based on the polarization induced as a charged particle approaches a neutral particle, or when two like-charged particles approach each other. The authors find that the type of oxide has a small effect on the collision results (due to the variation in the dielectric constants of the materials), but there is a significant size selection effect. These results are interesting and serve as the basis for further analysis of the effects of the increased injection of anthropogenic meteoric particles in the atmosphere. The manuscript's utility could be improved by considering additional charging cases and suggesting possible implications for the size selectivity.

The authors sincerely thank Prof. Lorin S. Matthews for her careful evaluation of our manuscript and for highlighting our results as interesting and important for future studies in this domain. We have considered and addressed all the concerns. The point-wise responses to the reviewer's comments are as follows. To facilitate the referee, the major changes are highlighted in blue in the revised version of the manuscript.

A few considerations for improvement are detailed below.

Scientific questions

1. "For the case of fixed singly negative charge ice and oxides with (rH2O = 1 nm, rOxide = 1 nm) and (rH2O =5 nm, rOxide =5 nm), we observed that ECoul ≈E0 for all the metal oxides. For these cases, the polarization effect is not strong enough to create the attractive energy well. Aggregation is not possible in these cases." Polarization can't create an attractive energy well, but might there be another mechanism for creating the binding energy if the collision energy is sufficient to overcome the coulomb repulsion barrier? When do van der Waals forces start to kick in? Some of this is taken into account by the coefficient of restitution. Can you elaborate on this further? What about contact electrification resulting from the collision, even if it doesn't result in a bound aggregate?

Response

The van der Waals force is generally comparable to the electrostatic interaction at short separation distances of 0.1 nm to a few nanometers *[Israelachvili, Jacob N. Intermolecular and surface forces, Academic Press, 2011, Filippov JETP 134(5) 2022, 590-599],* leading to stronger binding near the point of contact, which may increase u_{max}. The Van der Waals interaction may reduce the E_{Coul}. However, the reduced value of u_{min} will remain significantly higher than u_{th}. As a result, the aggregation probability may not vary significantly, because most of the velocity regime of the Maxwellian distribution is not able to overcome the E_{Coul}. However, the Van der Waals Interactions may affect the aggregation scenario.

Furthermore, the contact electrification resulting from the collision may also contribute to the formation of a bound aggregate. Laboratory experiments suggested a typical charge transfer of the order of $10^{-5}\, C\, m^{-2}$ *[Shen et al. Journal of Electrostatics, 82, 2016]*. With a typical collisional area $A \sim \pi r_{Oxide}^{2}$, $|Q| \sim 0.005e$ and $0.123e$ for rOxide = 1 nm and 5 nm, respectively. So for nanometer-sized particles, the charge transfer due to contact electrification is marginal in the MLT region.

As this study focuses on quantifying the effect of electrostatic interactions on particle collisions and aggregation, small perturbations that could bring particles close together, such as van der Waals forces and contact electrification, are not considered.

We added these discussions to the revised manuscript. Please see: Lines 172-173; Lines 209-227; Lines 235-237.

2. This study only considers collisions between two spheres. In this case, the aggregates formed are dimers –further growth of the aggregate particles is not examined. Even considering the dimers as new spherical particles, is there a way to estimate the continued growth or maximum size of aggregate particles? Of course, the polarization of an aggregate dimer will be more difficult to calculate, and the aggregation resulting in a trimer will be direction-dependent.

Response

We appreciate the reviewer for bringing this to our attention. The primary objective of this study is to identify the velocity ranges that facilitate aggregation after collisions between two spheres. Further growth process depends on the initial size, charge, and velocity distributions of the monomers. Each collisional aggregation event will create a dimer. When considering the dimer as a new spherical particle with a larger radius, just after the collision, the charge of this new spherical particle will be the sum of the charges of the two monomers. However, as the new particle is embedded in the weakly ionized plasma, its charge state will be modified within the charging time scale. Hence, the growth process not only depends on the collision probabilities, but also on the charging currents to the particle. Therefore, even if we consider the dimers as new spherical particles, estimating the maximum size of aggregate particles would require further computation, because at each time step, one has to track collisional events, size increment, charge modification due to collision, and charge modification due to plasma medium before the next collisional event. But the present study will play a crucial role in such computation, which will be taken up in the future study.

3. How does the growth of anthropogenic space debris particles compare with the growth of MSPs? Does the incorporation of a metal oxide in the aggregate increase the likelihood of further growth of the ice particle?

Response

The present analysis highlights that ASPs show aggregation behavior similar to that seen in the ice-MSP aggregation regime. Specifically, metal oxide with a larger dielectric constant has a higher probability of aggregation. Furthermore, if the number density of a particular metal oxide is higher, then its aggregation is also going to be significant. Both cases enhance the likelihood of the continued growth of ice particles. As the number of space debris-originated metal oxides increases, the growth of larger ice particles is likely favored by ASPs, leading to a greater occurrence of noctilucent clouds (NLCs) caused by anthropogenic activity.

4. Given the aggregation probability reported, how will this affect processes in the mesosphere/lower thermosphere region? How will it affect charge balance, transport and growth, and ice particle formation, compared with current conditions associated with MSPs? What is the significance for preferentially large particles being aggregated (in the case of like charged particles) or for preferentially small particles aggregating (in the case of a charged particle and a neutral particle)?

Response

As the charges are not generated and annihilated during the aggregation processes, the overall quasineutrality of the region is maintained. During the aggregation event, the number density of individual particles decreases as larger aggregates form. Furthermore, the collisional event will affect the overall charge distribution among the particles, affecting subsequent collisions and growth. However, the simultaneous and comparable presence of ASPs alongside MSPs will increase ice particle growth over time in both larger (like-charged) and smaller (charge-neutral) particle aggregations. As a result, the formation of larger particles will be faster. These large particles can rapidly accrete ions and free electrons with the plasma medium, thereby potentially affecting their population densities within the MLT region.

5. The results were presented for a charge on the ice particles of 1e-. Since the charging is a stochastic process, there is a significant probably for either particle to have a charge of 2e-. or e+. How will this change the results?

Response

We understand the reviewer's concern. For a like-charged case, increasing the charge from $-1e$ to $-2e$ increases the Coulomb barrier E_{Coul} and reduces the magnitude of E_0. As a result, it reduces the effective regime of (u_{min}, u_{max}), thereby reducing the probability of aggregation. For like-charged rH2O = 100 nm, rOxide = 1 nm, changing qH2O = -1e from -2e, reduces the aggregation probability from 77% to 46%. For the oppositely charged case, $E_{Coul} = 0$, and due to polarization effect, $|E_0|$ is significantly stronger than the Coulomb attraction, which increases u_{max}, leading to an enhancement of aggregation probability. As particle size increases with a fixed charge, surface charge density decreases. This reduction lowers the binding energy and the probability of aggregation. However, in the parametric regime used in the present analysis, the aggregation probability exceeds 99.5%.

We added these discussions to the revised manuscript. Please see: Lines 238-245.

Technical comments:

1. ***"The framework presented in Bichoutskaia et al. (2010) has been utilized to derive the electrostatic interaction energy between charged ice and various oxides. The basic equations to derive ECoul and E0 have been solved using the method explained in Brazil Lindgren (2017)." Can you give a one-sentence description of the method? I was unfamiliar with these works and had to read the articles to figure out what was being done.***

   Response

   We have provided a brief discussion of the method in Appendix A. Please see: Lines 145-146; Lines 290-306.

2. ***Figure 2 – authors note that FeO has lowest values of u_min and u_max while SiO2 has highest values of u_min and u_max. It is very difficult to distinguish the differences on the five panels in Figure 2 – is there another way to show the variation in the data? Perhaps show the data for for FeO or SiO2, then in a separate panel show the data for the other oxides normalized by u_min and u_max for FeO or SiO2. This scheme could also be used for Figs. 3 – 5 and would better illustrate the differences between the data presented in the tables in the Appendices. (It would be helpful to give the dielectric constant on each subplot (along with the name of the oxide) and to arrange the subplots and the data in Table I in ascending or descending order in the dielectric constant.)***

   Response

   We understand the reviewer's concern. We have modified Figures 2-5.

This study brought to mind other papers I read on size-segregation and increased collision probability due to triboelectric charging. These papers might be applicable to this study:

Aerodynamic generation of electric fields in turbulence laden with charged inertial particles, Nature communication, vol 9, 1676 (2018)

D.R. Johnson, A. Bocanski, E.M. Diorio, J. Chen, & H. Meng, Amplification of particle collision through contact electrification in isotropic turbulence, Proc. Natl. Acad. Sci. U.S.A. 122 (38) e2507580122, https://doi.org/10.1073/pnas.2507580122 (2025).

Response

Thank you for suggesting these papers. We have incorporated the following discussion in the revised manuscript.

"Furthermore, the contact electrification resulting from the collision may also contribute to the formation of a bound aggregate. Laboratory experiments suggested a typical charge transfer of the order of $10^{-5}\,C\,m^{-2}$ *[Shen et al. Journal of Electrostatics, 82, 2016]*. With a typical collisional area $A \sim \pi r_{Oxide}^{2}$, $|Q| \sim 0.005e$ and $0.123e$ for rOxide = 1 nm and 5 nm, respectively. So for nanometer-sized particles, the charge transfer due to contact electrification is marginal in the MLT region. However, the contact electrification or triboelectric charging may become significant in the environment with significant collision frequency, where dust/particle density is large, such as Earth's lower atmospheric clouds and dusty atmospheres of Mars (Di Renzo and Urzay, 2018; Johnson et al., 2025)." Please see: Lines 217-224.