Measurement of electric charges on foraging bumblebees 
(*Bombus terrestris*)

C Montgomery, K Koh and D Robert

School of Biological Sciences, University of Bristol, Bristol, UK

clara.montgomery@bristol.ac.uk

**Abstract.** Bumblebees carry electric charge. Almost always positive, this charge facilitates pollen transfer between bumblebee and flower during pollination and is likely to play a role in the detection of electric fields. Models of the Coulomb forces acting on pollen grains during pollination are predominantly based upon laboratory measurements of bumblebee charge. Using a novel method, the charges on bumblebees are measured outdoors for the first time. Outdoor bumblebees are found to carry similar positive charges to those previously measured in the laboratory. Bee charge is affected by local weather conditions, with the most positive charges being found on bees flying in warm, dry conditions. Results show that bee charges used in previous models of pollen transfer are representative of wild foraging bumblebees, and that pollen transfer between bee and flower is likely to be affected by local weather conditions.

1. **Introduction**

Electrostatics has been shown to facilitate pollen transfer between plant and pollinator during pollination [1]. Measurements of charge on flying pollinators, typically honeybees (*Apis mellifera*) and bumblebees (*Bombus terrestris*), have found that flying insects tend to accumulate a positive charge during flight [2-4]. When a flying insect approaches a flower, the difference in charge between the insect and flower creates an electric field, the shape and strength of which is dependent on the morphology and charge of both flower and insect [1, 4]. The electric field strength is strongest around protruding floral structures, including the edges of petals and around the stigma and anthers. When a pollen-bearing insect approaches a flower, Coulomb forces propel pollen grains through the air and attract them towards the floral reproductive structures [1]. The effect of the Coulomb forces is thus deemed to enhance pollination.

Current experimental and theoretical understanding of pollen transfer relies on values of insect charge obtained from laboratory measurements. The quantification of insect charges has thus far either been achieved using triboelectric charging [5, 6] or measured from insects flying in constrained laboratory conditions [2, 4]. Field measurements of honeybee charges exist [3] and are similar in polarity and magnitude to laboratory measurements [2, 3]. Recent models of pollen transfer were developed based on laboratory data, as no data currently exist on the electric charge of bumblebees foraging in the field. In this paper, we address this gap by measuring the electric charges carried by foraging bumblebees at a field site, using a novel non-contact induction ring technique. Charges are measured on bees under different meteorological conditions to test whether charge is affected by local weather conditions, and whether existing models of pollen transfer need adapting when pertaining to free-flying bees gathering charge in natural field conditions.
2. Methods
A bumblebee colony (Bombus terrestris audax, (Koppert UK, Suffolk, UK)) was set up in a laboratory at the University’s School of Veterinary Sciences in Langford, North Somerset, UK. Bees could enter and exit the colony via a polycarbonate tube (inner diameter: 14 mm) that led to the outside via a hole in the wall. At the tube’s exit was the ring charge sensor (RCS) that consisted of two concentric copper rings (inner diameter 90mm, outer diameter 92mm, width 28mm) separated by an insulating polypropylene surface. To access the colony, bees had to fly through the inner ring and land on the tube entrance.

The RCS outer ring was connected to ground and acted as an electrical shield. The current in the RCS inner ring was measured using a custom-made picoammeter and analysed in MATLAB (2016b) via a data acquisition board (CompactDAQ Chassis, National Instruments, Austin, Texas). A charged object passing through the ring, such as a bee, induces a current in the inner ring that is proportional to the passing charge. This current can then be time-integrated to establish the actual charge on all bees flying into and out of the colony.

The RCS was calibrated using a Faraday pail (JCI 141, Chilworth Global, Southampton, UK) by dropping cubes of charged polyurethane foam through the RCS into the pail. Using this method, the ring was calibrated 4 times in different weather conditions (excluding rain) to account for possible differences in sensitivity of the RCS caused by humidity. A model was developed in R to predict the charges carried by bees based on RCS current and relative humidity (1). Bee charges were compared between different weather conditions. The weather was categorised by independent observations, and the temperature and humidity during each observation was measured with a thermometer-hygrometer (RT811C, Compact Hygro-Thermometer Clock, Radiance Instruments Limited, Guangdong, China).

3. Results
Relative air humidity significantly affected the relationship between the charge measured by the Faraday pail and the charge measured by the RCS. A general additive model was developed in R to predict the bee charge from the RCS ring current accounting for humidity (figure 1). The modelled relationship was:

$$Q_{bee} = 0.26 + (5.73 - 0.022RH) \int I \, dt$$

(1)

Where $Q_{bee}$ is the predicted charge on the bee, $I$ is the current in the inner ring and $RH$ is the relative humidity.

The charges measured on bees flying into the colony were nearly always positive and were similar in magnitude to charges previously measured from bees in the laboratory using the Faraday pail [4] (figure 2). Bumblebee charges measured by Clarke et al. [4] formed the basis for subsequent models of pollen transfer [1]. As the charges measured on outdoor bees are similar to laboratory measurements or are even more positive (figure 2), these pollen transfer models are suggested here to be largely accurate. From the distribution of charges observed in the field (figure 2), models may in fact underestimate the Coulomb forces acting on pollen carried by bumblebees.

The charges carried by bees flying into the colony were significantly affected by weather (Kruskall-Wallis, P<0.0001, X=22.3, DF = 93, figure 3), with bees having significantly lower charges during rain than in any other weather (Wilcoxon pairwise comparison with corrections for multiple testing (Sunny-Cloudy P=0.005; Cloudy-Rainy P<0.001; Sunny-Rainy, P<0.001).
Figure 1. (Colour online) Charge measured with the Faraday pail and the RCS when dropping polyurethane foam cubes through RCS into pail. Predicted charges are shown for bees flying in low humidity (30%RH, red line) average humidity (61%RH, black line) and high humidity (99%RH, blue line).

Figure 2. The electric charges measured from flying bees in the field experiment (white, mean charge: 116 ± 159pC) and the electric charges on flying bees measured in the laboratory by Clarke et al. [1] (grey, mean charge: 32 ± 35pC).

Increasing humidity corresponded with a significant decrease in bee charge (figure 4). The most parsimonious model (2) shows an exponential decay of charge with increasing relative humidity (General Linear Model, P<0.0001, N = 93, F=97.63). The equation for this model is:

\[ Q_{bee} = e^{7.15 - 0.054RH} + Q_{min} - 1 \]  

Where \( Q_{bee} \) is bee charge, \( RH \) is relative humidity, and \( Q_{min} \) is the lowest bee charge measured during the experiment.

The negative relationship between relative humidity and charge accumulation is well established in the triboelectricity of powders [7, 8]. The relationship proposed here (2) supports that found by Nomura et al. and Schella et al. for the tribocharging of powders and polymer beads [7, 8]. The mechanism involved is deemed to involve water inhibiting the non-conductive build-up of local electric charges and preventing objects from accumulating large charges. Additionally, increased humidity increases the rate of charge loss from charged objects and powders. Under humid conditions, bees may be unable to charge efficiently, whilst any charge gained during flight is quickly lost to their surroundings.

The electrostatic facilitation of pollination might be enhanced on days of low humidity where the Coulomb forces acting on pollen grains are likely to be higher than previously thought, due to the elevated bee charges. Conversely on humid days the reduced (sometimes negative) charges carried by bees suggest that electrostatics plays a reduced role in pollen transfer under these conditions. For future models, the variability of bee charge in different environmental conditions should be considered when modelling pollen transfer.
Figure 3. The electric charges measured on bees before (grey) and after flight (white). Bees had significantly lower charges after flight during rain than when sunny (P<0.001) or cloudy (P<0.001) whilst the charges on bees before flight remained stable. Boxes show median and IQRs. N=95 post-flight, 90 pre-flight.

4. Conclusions
The electric charges measured on outdoor, free-flying bumblebees were found to be mostly positive and similar in magnitude to the charges measured on bees in laboratory experiments. However, outdoor bees have a much greater range of charges and this charge is largely affected by the local humidity. On warm, dry days the charges measured on outdoor bees exceed those found on indoor bees, suggesting that models of pollen transfer based on indoor bee charge measurements may underestimate the role of Coulomb forces in pollen transfer under fair weather conditions.

Acknowledgements
This work was funded by a BBSRC SWBio studentship grant to CM, a responsive mode grant from BBSRC, and the ERC to DR.

References
[1] Clarke D, Morley E and Robert D 2017 J. Comp. Physiol. A 203 737-48
[2] Gan-Mor S, Schwartz Y, Bechar A, Eisikowitch D and Manor G 1995 Can. Agr. Eng 37 189-94
[3] Colin M, Richard D and Chauzy S 1991 J. Bioelectricity 10 17-32
[4] Clarke D, Whitney H, Sutton G and Robert D 2013 Science 340 66-9
[5] McGonigle D F and Jackson C W 2002 Pest Manag. Sci. 58 374-80
[6] McGonigle D F, Jackson C W and Davidson J L 2002 J. Electrostat., 54 167-77
[7] Nomura T, Satoh T and Masuda H J P T 2003 Powder Technol 135 43-9
[8] Schella A, Herminghaus S and Schröter M 2017 Soft Matter 13 394-401