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The electrification of dust-lofting gust fronts ('haboobs') in the Sahel

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ABSTRACT

Two Doppler radars and a suite of auxiliary surface observations are used to document the electrical, aerosol and aerodynamic properties of dust-lofting gust fronts near Niamey, Niger during the AMMA (African Monsoon Multidisciplinary Analysis). Electrification with dominant negative polarity is a common behavior, consistent with earlier studies on dust devils and the Harmattan wind in dry environments.

1. Introduction

Violent dust storms ('haboobs') are commonplace (Sutton, 1925, 1931; Hamilton and Archibald, 1945; Slingo et al., 2006; Bou Karam et al., 2008; Williams, in press) in the Sahelian belt of West Africa. Their preferential occurrence there, between the dry Sahara Desert to the north and the moist tropical belt to the south is attributable to two transitional features: the ground is sufficiently dry to suppress vegetation and thereby to expose dry soil, and the boundary layer is moist enough to sustain deep convection that ultimately raises the dust. When African easterly waves are present, rainfall episodes on one day are often followed by dry periods of subsidence for 2–4 days, allowing drying of the soil between events. The mechanism for dust-lofting in the wet season is the gust front driven by the cold outflow from deep convection, produced by both isolated thunderstorms early in the wet season (June, July) and westward propagating squall lines later in the season (August, September) when the conditions over the Sahel are more baroclinic.

Interest arose in the haboobs during the AMMA because they are readily detected and tracked with the MIT Doppler radar, they produced marked signatures in many instruments at the nearby ARM (Atmospheric Radiation Measurement) facility, and because they are highly electrified as indicated by lightning-detection equipment. The haboobs are of scientific interest because of their possible role in the export of dust from Africa (Williams et al., 2006; Williams, in press) and of agricultural interest because of their role in soil erosion (Sterk, 2003), but in this study the electrical behavior is the central issue. The electrification of blowing sand and dust is hardly a new topic (Rudge, 1914; Keith, 1944; Demon et al., 1953; Latham; 1964; Harris, 1967; Kok and Renno, 2008), and the electric field of the dust devil has been widely studied (Freier, 1960; Crozier, 1964; Renno et al., 2004; Jackson and Farrell, 2006). The present study appears to be the first systematic investigation of the electrical behavior of West African haboobs.

2. Observational methods

The principal means for detecting these dust-raising gust fronts from afar was the MIT C-band Doppler radar, which

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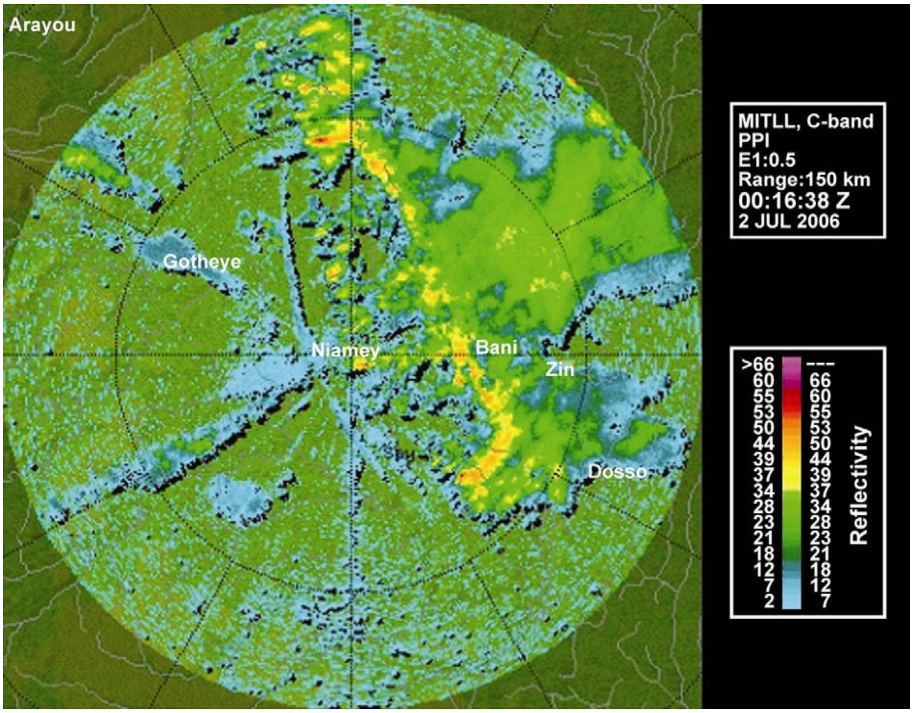

Fig. 1. Surveillance scan showing a gust front out ahead of a storm on July 02, 2006.

was operated continuously in Niamey, Niger during the African Monsoon Multidisciplinary Analysis (AMMA) project from late June to late September, 2006. The gust fronts in Africa showed similar characteristics as those in mid-latitude regions where dust is not raised, i.e., long thin lines with radar reflectivities in the range 0–15 dBZ. The dust itself is probably not the main radar target. Further evidence for this claim comes from the radar observations at mid-latitude showing that the radar targets are anisotropic—a behavior expected for insects, sticks and blades of grass, but not for dust and sand grains which are equidimensional.

An electric field mill of the inverted (goose neck) variety manufactured by Mission Instruments was used to record the electric field perturbation at ground level for these events. Its output sensitivity is one volt per 2 kV/m for a full scale range in these measurements of ±20 kV/m. This was an adequate range to bracket the values exhibited by these dusty gust fronts.

The radar and electric field measurements at the MIT radar site were supplemented by a suite of observations at the nearby ARM (Atmospheric Radiation Measurements) site approximately 1600 m south of the radar. These measurements included 1-minute samples of surface wind speed and direction, temperature, relative humidity and a visibility measurement with a Vaisala PWD 10/20 instrument. A local value for dust mass loading in micrograms per cubic meter was inferred from the visibility measurement using an empirical power law relationship from Shao et al. (2003). A vertically pointing radar operating at 95 GHz was used to obtain the vertical air motions in the gust fronts as they traversed this site.

3. Preliminary results

A radar PPI surveillance scan through the gust front on July 02 is shown in Fig. 1. The gust fronts in Africa are similar to

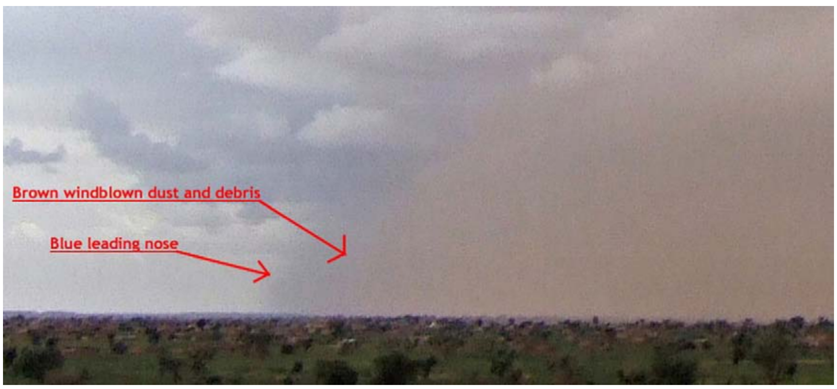

Fig. 2. Photograph of an haboob generated by a gust front ahead of a vigorous squall line on September 12, 2006.

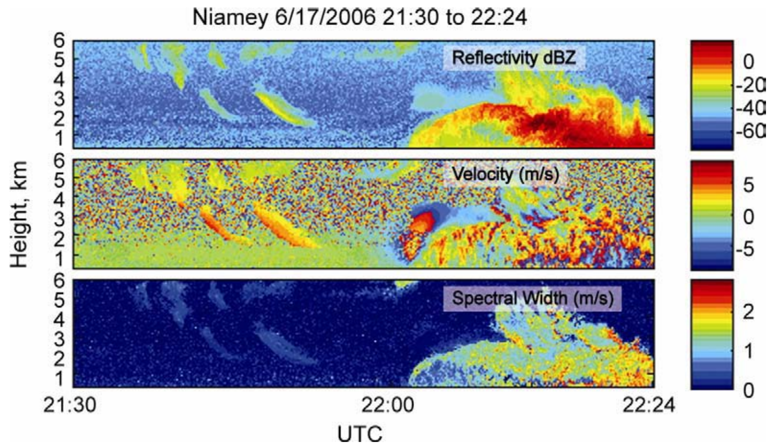

Fig. 3. Vertical profiles of radar reflectivity (top), mean Doppler velocity (middle), and Doppler spectral width (bottom), for a gust front on June 17, 2006, at an operating frequency of 95 GHz.

like events in the USA (Charba, 1974) and elsewhere, and can be tracked away from their parent storms for periods of an hour or more, owing to their substantial depth (see below). The dust is lofted quasi-continuously along the broad swaths traversed by these fronts. Fig. 2 shows a photograph of the leading edge of a typical haboob in which dust is lofted on the miniature cold front which is the gust front outflow. Major changes in visibility are noted when these deep walls of dust cross the observation site in less than a minute.

These dust clouds extend to considerable heights in the atmosphere. Heights recorded with the 95 GHz vertically pointing radar for a dozen selected cases show maximum altitudes varying from 2000 to 5000 m (AGL), with a mean of 3500 m. These heights approach the local height of the

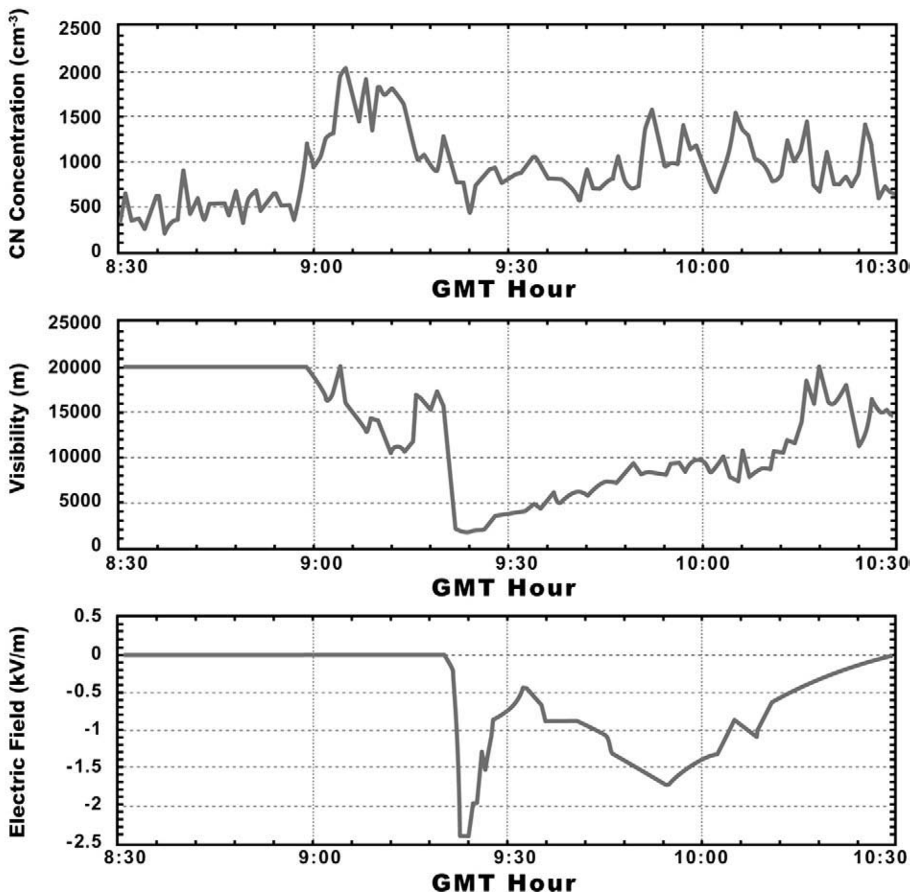

Fig. 4. The evolution of condensation nuclei, visibility and electric field for a gust front arrival with monopolar behavior on July 31, 2006.

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African easterly jet. Fig. 3 shows a continuous vertical profile of reflectivity and mean Doppler velocity during the traversal of a violent and destructive gust front on June 17, 2006. The frontal nature is clearly evident, with pronounced updraft (and a mean Doppler velocity substantially exceeding the Nyquist limit of 8 m/s) at ~2203 UT just ahead of the dust cloud and with more radar-reflective debris behind. This picture illustrates the warm air rising up over the advancing colder air within the storm outflow. The modest spectral width in the core of the updraft is consistent with the assertion that the main radar targets have a narrow range of terminal fall speed.

The magnitude of the field perturbations associated with these events are in the range 1–10 kV/m, values which are generally more than an order of magnitude larger than the Earth's fair weather electric field. The gust fronts are normally sufficiently far from the often strongly electrified parent thunderstorms so that uncontaminated signatures from the dust and sand alone are obtained. Cumulus convection is frequently induced by the gust front (often as an arcus cloud), but precipitation seldom forms (both because the convection is relatively shallow and because abundant cloud nuclei are present). Consequently, the primary source of field appears to be the electrified dust and sand.

Two distinct patterns of electric field perturbation have been documented as the dusty gust fronts approach, cross, and recede from the observation site. In all cases, the initial excursion of the electric field is indicative of dominant negative charge overhead. But in one subset of cases, the upward field is sustained and maximizes near the time of minimum visibility. This unipolar field behavior is consistent with a monopolar accumulation of electric charge. In the second category, the initial excursion of field is followed usually within 10 min or so by a reversal of field polarity, indicating positive charge overhead. The latter field maximum in these bipolar cases more closely coincides with the minimum in visibility at the surface.

Fig. 4 shows an example of records of electric field, CN (condensation nuclei) concentration and visibility for a monopolar event on July 31. Fig. 5 shows the same set of parameters for a bipolar event on July 20. Note the transition of the electric field to positive values later in the event for the bipolar case, in contrast with the monopolar event.

A frequent feature of these events, significantly more common for gust fronts ahead of squall lines than from isolated thunderstorms, is a substantial enhancement in CN concentration for a 8–12 minute period that then generally disappears on the arrival of the heavy dust and sand. The occurrence of this feature in advance of the initial excursion in electric field (frequently, but not invariably) and the pronounced drop in visibility are evidence that these nuclei are

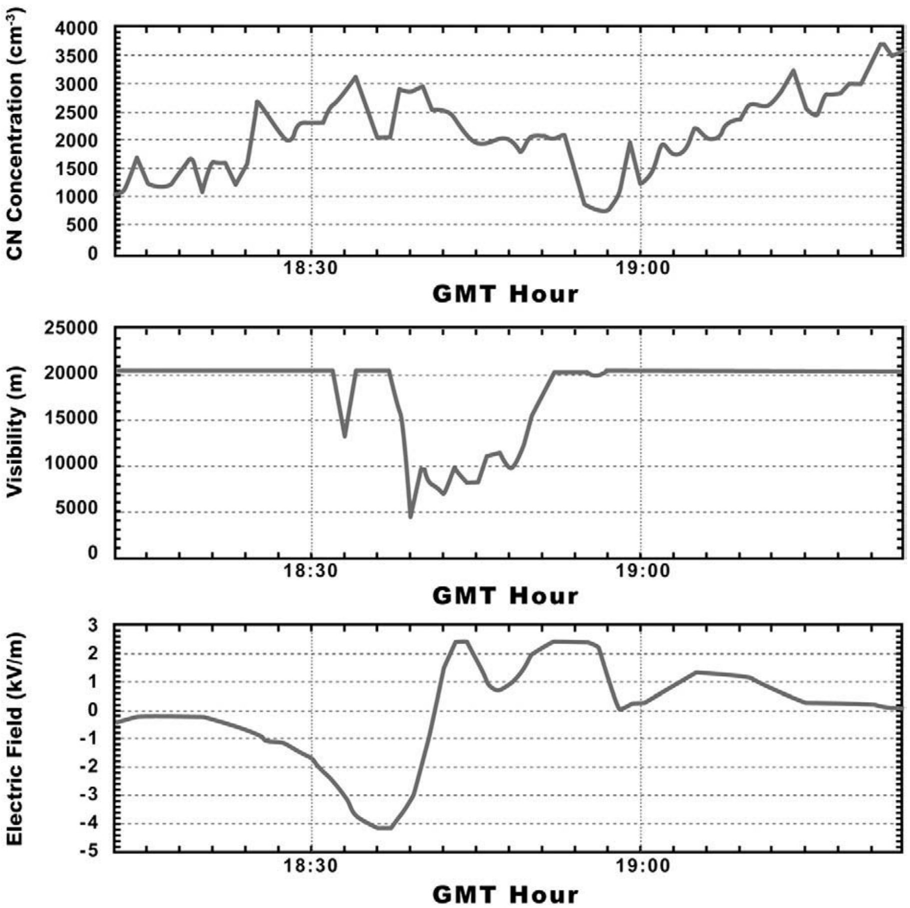

Fig. 5. The evolution of condensation nuclei, visibility and electric field for a gust front arrival with bipolar behavior on July 20, 2006.

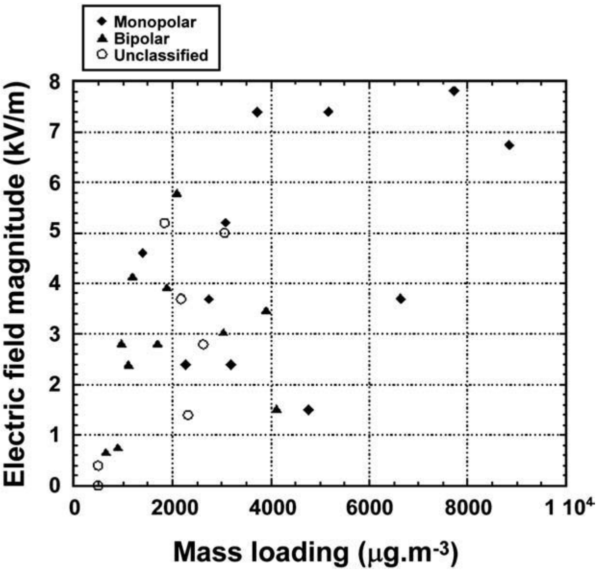

Fig. 6. Peak electric field perturbation versus peak mass loading for all gust front events. Events are classified (when possible) as monopolar and bipolar.

neither highly charged nor influential in visibility, and that the observed strong electrification requires the presence of heavy dust.

Further evidence for a primary role of the heavy dust in the production of these perturbations in electric field is shown by the plot of peak electric field versus peak mass loading (derived from the minimum visibility), for all events during 2006 in Fig. 6. Despite considerable scatter, some of which may result from the 1600 meter distance between the observation sites for electric field and visibility, positive correlation is evident. In Fig. 6, monopolar and bipolar field behavior is distinguished with symbols. The notable tendency for the monopolar events to predominate in the upper right hand corner of the figure suggests that the events with heavy dust (and likely largest particles) are most likely to exhibit monopolar behavior and the strongest electrification.

4. Discussion

The placement of these findings on haboob electrification in the context of previous work on the electrification of dust and sandstorms, as well as thunderstorms, may be helpful. The sand/dust phenomena differ from the electrification of thunderstorms in (at least) one important way. The particles that become electrically charged in haboobs all originate at the Earth's surface, rather than within a storm aloft. Three kinds of particles need to be considered. These broad categories are the fine aerosol (including the cloud condensation nuclei and ice nuclei, submicron in size), the dust (composed primarily of clay particles in the size range 1–100 μm) and the sand (primarily quartz, but also including other silicate minerals in the size range of 0.1 mm to several millimeters). These important size ranges are dictated by typical wind speeds near the Earth's surface, and the fall speeds of the particles in air under gravity (Bagnold, 2005).

The evidence that the aerosol is not the main carrier of electric charge, and so not an agent of charge separation, is the observation of a lack of strong field perturbation (Fig. 4) when the measured condensation nuclei maximize in advance of the heavy dust. The frequent reduction of CN within the heavy dust cloud is likely caused by the capture of aerosol by the larger dust and sand particles.

Saltation is the principal physical process for dispersing silicate minerals (aerosol, dust and sand) from the Earth's surface into the atmosphere (Bagnold, 2005), and is one means for particle charging by intermittent contact with that surface. If clay particles are also present, then the saltation process is also capable of transferring these dust particles from the surface into the atmosphere, where they can then travel far from the source.

In most laboratory studies that attempt to simulate saltation with sand alone (Schmidt et al., 1998; Zheng et al., 2003; Qu et al., 2004) a negative space charge accumulates in the sub-meter saltation layer, a thickness bounded by the bouncing heights of saltating sand grains. To the extent that positive charge is transferred to the Earth and negative charge to the sand grains, this process is expected to create a monopolar electric field at the Earth's surface because only one polarity of charge enters the atmosphere.

In the Sahara Desert, where the moist convection and cold downdrafts necessary for haboobs are generally not present, straight line winds are more common. In this situation, one can frequently have true sandstorms in which the sand particle concentrations in the atmosphere are confined to a shallow (<1 m) saltation layer. Careful electrical measurements in such specific conditions are unfortunately unknown to the authors to enable comparisons with the available laboratory measurements on sand (Schmidt et al., 1998; Zheng et al., 2003; Qu et al., 2004) and with model results for saltation (Kok and Renno, 2008). One electrical study of (Demon et al., 1953) sandstorms in the Sahara Desert of Algeria (otherwise undocumented) showed a tendency for downward-directed field perturbations of the same magnitude as those observed here. Positive charge in the levitated sand grains was inferred but not measured.

The situation in the Sahel of West Africa is substantially more complicated, for at least two reasons: (1) both clay particles and sand grains are present in abundance, and (2) moist convection is present to produce the haboobs. The latter provides an enhanced wind for saltation, but also provides, as the vertically pointing radar observations have shown, updrafts on the gust frontal boundaries that represent marked departures from straight line winds. The measured updraft speeds (5–10 m/s) are sufficient to levitate the entire suite of mineral particles previously considered to altitudes of kilometers, and hence orders of magnitude higher than the depth of the saltation layer.

Since the electric field measurements in this study were made at a height above the sand grain saltation layer, and a predominant upward-directed field was evident initially in nearly every case, this cannot be explained by negative space charge in the saltating layer alone, for this would produce a field at 1 m height with downward direction. The upward electric field must be caused by negative charge above the measuring instrument, but whether this negative charge resides on clay particles or on sand grains advected upward by the gust front updraft from the saltation layer is not presently known, and will require further study.

The vertical air motion in the haboobs enable a second distinct process of charge separation, given that all the mineral particles, large and small, are carried upward after leaving the surface. This second process is volume charging, involving collisions between particles of different size and fallspeed, and subsequent separation under gravity, much like the presently favored mechanism involving ice particles in thunderstorms. This mechanism is expected to produce a bipolar charge configuration and a departure from monopolar field behavior on the ground. It is possible that the later excursions to downward-directed field were caused by volume charging of sand, but further measurements are needed to verify this speculation. We lack at present an explanation for the tendency of the bipolar cases to be associated with haboobs with lesser mass loading (Fig. 6).

The importance of the collisional mechanism for volume charging has been downplayed in the case of electrification of dust in the form of powder in the laboratory (Loeb, 1958; Kamra, 1973) (with particle size distributions typical of clay particles in the natural environment), but the larger particles inferred to be present throughout haboob clouds were not involved in such studies.

The suggestion that the bipolar haboob cases documented here might be caused by the electrification of the deep convective storm parent to the haboob was examined by comparing closest distances to storm radar reflectivity for the cases in Fig. 6 with bipolar and monopolar behavior. No systematic relationship was found, thereby casting doubt on this idea. In general, the gust fronts raising the dust had moved out substantially ahead of the parent storms (by many kilometers) and so their electrostatic fields were small in comparison with those from the dust. It was quite typical for the fields at the radar site to be of fair weather magnitude and polarity when the initial gust fronts arrived. In contrast, the magnitude of the electric field perturbation by the action of mineral particles is comparable to that measured on the ground beneath, and in the immediate vicinity, of thunderclouds.

5. Conclusions

Virtually every cold outflow from moist convection in Niamey, Niger is a source of substantial dust and electric field, throughout the wet season. The physical mechanism responsible for the inferred negative charging of the smaller dust particles with long residence time in the atmosphere, though consistent with a large body of other evidence in other locales (e.g., Harris, 1967), remains unclear. Regarding the electrostatic configuration of the charged dust clouds, we can expect a monopolar cloud if all particle charge transfer takes place at the Earth's surface, and a dipolar cloud if volume charging is dominating. Evidence for both behaviors has been shown in the observations. The microphysical explanation for particle charging is poorly understood in both cases of saltation near the surface and volume charging at higher levels, and will require further study, with techniques that go beyond those employed here.

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