The Charlemagne Event: Introduction to the ~774-775 AD isotope spike in light of modern space weather understanding

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Introduction

Solar storms have become recognized as a significant natural hazard and potential threat to critical infrastructure. A well-studied solar storm in 1859 called the Carrington event, occurred at the dawn of the electric age, when there was little to be damaged by a solar storm. If it were to happen today, it is expected to cause trillions of dollars in direct and collateral damage to power systems, communications, transportation, navigation and other digital systems, resulting in widespread emergency situations without electricity during the months to years it could take to recover. Evidence exists of potentially-stronger events in the last 1300 years.

There are varying ways in which a solar eruption can affect the terrestrial environment. X-rays from a solar flare can ionize and slightly expand the upper atmosphere, disrupt radio communications, and in extreme cases, called *magnetic crochets*, flares can cause disruptions to earth's magnetic field and anomalous currents to flow in the atmosphere. Within as little as 15-20 minutes, solar energetic particles can arrive through earth's interplanetary magnetic field connection to the sun, causing aurorae, geomagnetic storms, and posing further radiation risk to astronauts and high latitude air travelers. The magnetospheric impact of a coronal mass ejection (CME) normally occurs 2-4 days after the flare, and has two primary impacts on earth. 1) The compression of the sun-facing magnetic field and Van Allen belts can trigger significant geomagnetic disruptions and force electrons into the atmosphere, which can influence the global electric circuit, and 2) solar wind plasma flows into atmosphere at the polar cusps, triggering aurorae, strengthening of the auroral and equatorial electrojets (and their induced geoelectric currents), which combine with other geomagnetic effects, leading to power grid disruptions, digital systems malfunctions, GPS errors, radar blackouts, etc.

One solar storm that may have exceeded the strength of the Carrington event occurred in ~774-775 AD; this event is commonly called "The Charlemagne Event". It appears as a global spike in ^{14}C in tree rings, and a corresponding spike in ^{10}Be and ^{36}Cl in Arctic and Antarctic Ice cores, which have also been used implicate a similar, slightly smaller event in 994 AD. (Güttler, Beer, Bleicher, 2013; Miyake, Masuda, Nakamura, 2013; Usoskin et al., 2013; Jull, Panyushkina, Lange, 2014; Mekhaldi et al., 2015).

The ~774-775 AD event has been subject to varying analyses of its strength, including those akin to solar flares larger than our star is known to be able to produce, implying a galactic gamma-ray source. (Miyake et al., 2012; Hambaryan and Neuhaeuser, 2012). One estimate of proton fluence exceeded $4x10^{10}$ protons/cm^{-2}, which is ~100,000 stronger than most recorded events in modern times. (Usoskin et al., 2013). However, other analyses indicate a more reasonable, yet still uncommonly powerful, solar eruption approximately 10-20 times stronger than the Carrington event (Melott and Thomas, 2012), and a later re-analysis determined that it may have only been 10 times stronger than the 1989 event that caused widespread electrical disruptions in Quebec (Thomas et al, 2013).

The concept of tremendous, isolated solar events is imaginatively and intellectually stimulating, but it is difficult to engage scientifically. In addition to the fact that known solar events have little to no isotope effect, including the Carrington event, (Wolff et al, 2012), we know that compounding effects of multiple solar eruptions can dwarf larger, isolated events. For example, in the most recent solar cycle, numerous X-class solar flares and geoeffective CMEs occurred, but the strongest storms occurred during consecutive impact situations, as happened in June of 2015, when small eruptions (low M-class flares and CMEs) struck in succession triggering a Level 4 (Kp8) geomagnetic storm. The number of flares, the geoeffectiveness of the CMEs (which direction in space they ejected), the solar energetic particle flux of each event, the time between impacts at earth and the polarity of the solar wind all determine the terrestrial impacts, and therefore it is difficult to analyze historic events in isolation. For example, the 1989 Quebec blackout was triggered by consecutive effects of an X15 solar flare on March 6, 1989, a second CME on March 9, 1989, and at least four more X-class solar flares that occurred before the major geomagnetic storm effects on March 13, 1989. The 1989 event had a 30 MeV proton flux that peaked excess of 10 protons/cm^{-2}, which is well-within the normal range for strong solar storms.

Three open inquiries are addressed here. 1) Are multiple major solar energetic particle events a better explanation for the ~774-775 AD isotope record than a single event from the sun or the galaxy? 2) What was the primary geoeffective nature of the ~774-775 AD event and how does it compare to the Carrington event? 3) What effects would a recurrence of the ~774-775 AD event have today?

Compounding solar storm effects

At the end of October 2003, 17 major solar flares occurred and triggered geomagnetic storms that caused major disruptions to power grids in northern Europe. While some of these flares were exceptionally powerful, the sequence began in the middle of October and lasted until early November, and it was not until the cumulative effects of the peak flares from October 28-November 1, 2003 that the damaging storms occurred.

We do not need to go far back in time to witness a similar event about which we know very little. In 1921 an auroral display produced ground currents up to 10 times stronger than the 1989 event, which matches the lower limit of generalized strength hypothesized for the ~774-775 AD event, but like the Carrington event, is not readily identifiable in isotope data (unlike the massive isotope spike in 774-775), is lacking data regarding how many solar eruptions took place/impacted earth, and the generalization requires conflating solar energetic particles and induced currents into a direct, linear relationship. We have little information about the total activity of the sun during the Carrington event, and even less about the activity in ~774-775 AD.

Using the lower limit of hypothesized strength of the ~774-775 AD event (10x stronger than the 1989 storm), we still are required to witness a solar storm that far-exceeds any ever recorded by satellite or ground-based system. Something ten times stronger than X15 is far less reasonable, for example, than four X40 events in succession, even though the former is not considered *impossible* for a sun-like star. On the other hand, ten times the proton flux of the 1989 storm is very-much still within reasonable range.

It should also be recognized that large, complex sunspots are the only features on sun-like stars capable of major flaring (prominence eruptions may produce M and even small X class ‘hyder’ flare events) and a sunspot that would be capable of a Carrington/774-775 AD event would likely be producing numerous solar flares and CMEs, and would likely have multiple geoeffective impacts in any such scenario.

One still cannot preclude a gamma-ray source from the galaxy, but modern space weather understanding offers another plausible solar-genesis explanation for the event, one that is likely to be more common than a solar flare in excess of X100.

Solar energetic particles vs CME impact

Solar energetic particles and CMEs do not necessarily have a linear relationship in terms of earth-affect. Powerful flares can eject CMEs at earth without much effect on the solar energetic particle fluence, while non-earth-directed flares and CMEs can produce particle events as the CME sails far away from our planet and never touched earth's magnetic field. Solar energetic particles coming along the interplanetary magnetic fields bypass earth's magnetosphere and stream directly into the atmosphere, while geomagnetic storms describe the disruption to that magnetic fields itself, and the induced electricity in the atmosphere and the ground.

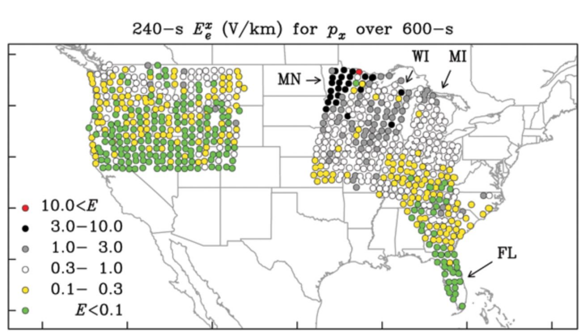
There is no means of determining the geomagnetically induced currents produced by the ~774-775 AD event, nor is there a way to determine the full extent of the strength of the currents induced by the Carrington event, or its proton fluence. While the Carrington event and many other solar storms have failed to produce readily recognizable isotope signals, other events like one in February of 1956, produced ground level enhancements of energetic particles that far exceeded powerful storms like the 1989 and 2003 events. However, the 1956 storm had fewer worldwide electrical/communications disruptions than one would expect from a linear relationship with the proton fluence. What does this mean? *Every solar storm is unique.* This raises the question: what is the best way to think of the ~774-775 AD event?

Solar flares and geomagnetic storms do not change isotope production rate, and so the primary mode of analysis for the ~774-775 AD event should be of its energetic particles- the cause of the isotope changes. For the Carrington event, it makes more sense to think in terms of solar flare magnitude and geomagnetically induced currents. When considering the reality of space weather events, one cannot rule out that the Carrington event produced very few proton storm effects, and that the ~774-775 AD event had a solar flare/CME profile far less-extreme than its particle fluence.

Effects on modern technology

While that scenario is plausible, and while the relationship not linear, *geomagnetic effects are most likely during or closely following strong particle events*, because they both require an eruption on the sun. While the 1956 storm did not have global disruptions, it did make a British submarine appear to have vanished, causing significant concern for naval operations. The 2003 storms were notable in both solar energetic particles and geomagnetically induced currents. If the ~774-775 AD event had a more linear relationship between solar energetic particles and induced currents (like the 2003 storms) we can hypothesize the extent of damage to infrastructure due to such an event.

Figure 1 - Geoelectric Hazard Map, from *Love et al., 2016.*



In Figure 1, we see the most-recent geoelectric hazard map for the United States (Love et al, 2016). The map results from analysis of a solar event on par with the Carrington Event. Given the vastly stronger isotope effects of the ~774-775 AD event than the Carrington event, a linear relationship with induced currents requires considering storm effects at least 3x those of the Carrington event, and probably more.

Nearly 100% of the studied areas increase one ‘color level’ if the geomagnetic effects are 3x larger than the Carrington event. In the median assessment of the ~774-775 AD event (10x the Carrington event), all gray and black areas become red, and white and yellow areas elevate to black and gray, respectively. It is also likely that many green areas would elevate in risk, and that transition areas between colors should be moved (expanding the coverage) to account for gap-jumps in the geology due to excess current, and effects on neighboring systems.

This first example is topical and almost without meaning; the method used to interpret the ~774-775 AD event is not rigorous and is the most basic of qualitative analyses. Furthermore, the map is extremely limited in coverage, and the study analyzed only powerful currents induced by the auroral electrojet- excluding the equatorial electrojet and GEC/Van Allen effects. Despite the model limitations, we can conservatively estimate that more than one third of the United States is at high risk of disruption from solar storms, and by extension, most of Canada, if an event similar to the ~774-775 AD event occurred today.

A simpler deduction may be made using Lloyd’s well-publicized 2013 report, **“Solar Storm Risk to the North American Electric Grid”**. That report found that major geomagnetic storm disruptions from a Carrington-like event could trigger blackouts for up to 40 million people and cause up to $2.6 Trillion in damage, with a recovery time of 5 months- just in the United States. New York, Chicago, Boston, Philadelphia and Washington DC would all be at high risk for extended blackout scenarios.

These are scary realities given that at the most-recent National Space Weather Enterprise Forum (June 27, 2017, attended by this author and others from Space Weather News) no concrete plan for extended blackouts was described beyond seven days- the threshold at which the government considers modern society unprepared to continue without power. These numbers may also be an underestimation of the potential effects.

Using similar topical analyses to modify the quantitative analyses in Lloyd’s 2013, we can conservatively estimate that a severe ~774-775 AD event in today’s world could functionally affect the entire US population, cause more than $20 Trillion in direct and indirect damage/losses, including a collapse of the insurance industry, which is predicated on disasters being both rare AND localized (compared to nationwide emergencies).

Recovery time in a ~774-775 AD event could be incalculable. The ‘5 months’ given by the Lloyd’s report is based on lead time for transformer production. In this hypothetical the need would be vast; production capabilities could be overwhelmed and backlogged for years, presuming they are even operable after the solar storm- which is by no means guaranteed in such a scenario. This level of event could require international aid, which may also not be available due to the storm, or which may be of questionable quality and timeliness. Every nation on earth would have similar risks and emergency needs.

The Lloyd’s report, while less geophysically rigorous than Love et al. 2016, uses many of the same principals, including actual grid setup and geoelectric ground potential. However, the Lloyd’s report weighs the factors differently, as you can see in Figure 2, which displays the 3rd and 5th figures from that report:

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Figure 2 - Figures 3 and 5, and captions, from *Lloyd's 2013.*

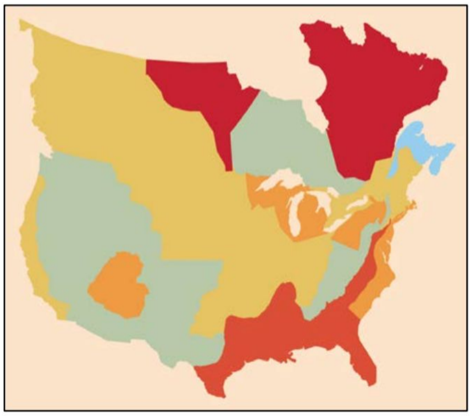


Figure 3: Relative risk from strong electric field fluctuations in the US and Canada based on ground conductivity models. Red and blue represents the highest and lowest risk regions, respectively.

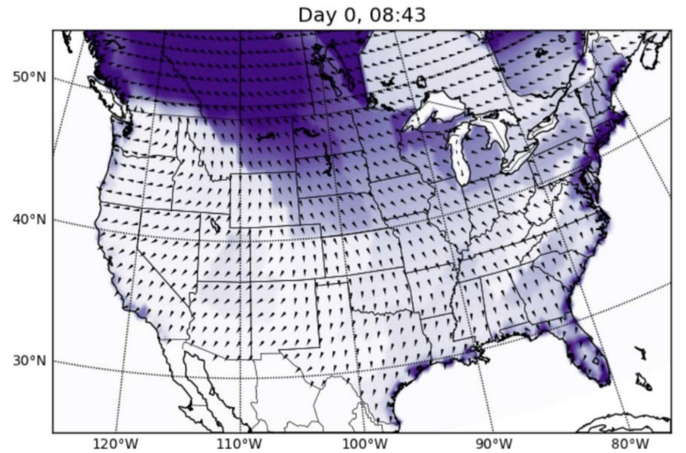
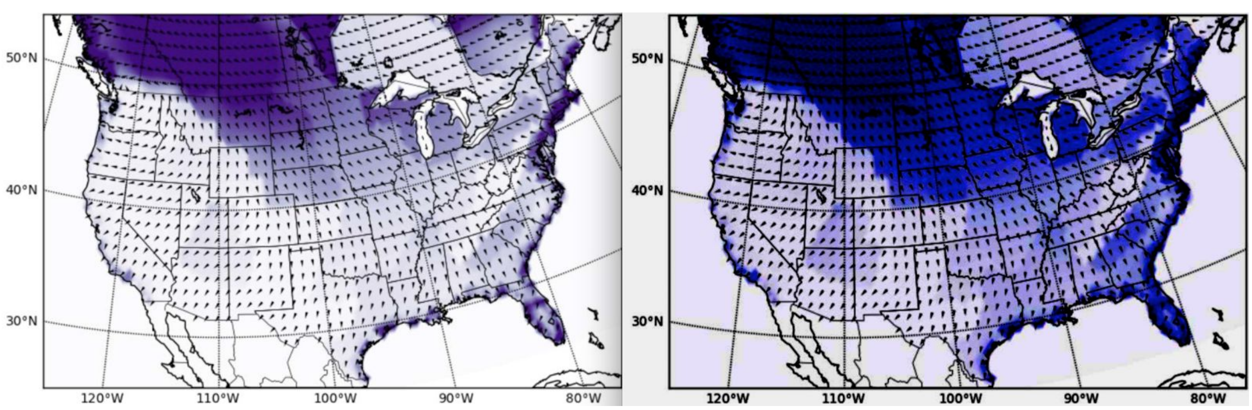


Figure 5: A snapshot of electric field amplitudes (color-scale) and direction (barbs) during a simulated Carrington-level storm. Regions shaded in dark purple are experiencing the strongest surface electric fields at that time.

The Lloyd's report did not place as high of a value on magnetic latitude in terms of storm risk, but rather amplified the risk posed due to high grid density (paths of low-resistance, existing overload risk) and those dictated by lithospheric magnetism. These factors were utilized in *Love et al., 2016* but were clearly given different weight in the model. In Figure 2 we find a much different outlook than in a mostly latitude-driven model, with both graphics showing high risk to the entire eastern US, especially the coastal regions, and to much of the midwest and south-central states. Central and Southern California also exhibit risk at the Carrington-level scenario. Lloyd's 5th figure (Figure 2 here) may be easily modified (Figure 3, right) to show how severe the electric fields could be if a ~774-775 AD event were to happen today.

Figure 3 - Lloyd's Figure 5 (left), and modified Figure showing potential electric field risk in a ~774-775 AD scenario (right).



In the figure on the right, color intensity, shading, and exposure were all modified 20%, since the coverage and pathways dictated by the grid and geology were already well-represented. In the modified chart, compared to the Lloyd's chart: Atlanta, GA is at the same level of risk as Boston or northwest

Canada, eastern Texas is at a level of risk comparable to Chicago, central Texas is the *only* major commercial region outside of high-risk area, no part of Florida is “likely to have power” (teal zone, *Lloyd’s* Figure 3), and no part of the United States or Canada is considered “very likely to have power” (blue zone, *Lloyd’s* Figure 3).

Conclusions

By restricting analyses to colossal single occurrences, science may have disserviced the likelihood of the ~774-775 AD event having a solar origin via multiple compounding effects.

The more modest estimates of energy required for such an isotope event are within the geomagnetically plausible spectrum of known space weather events, and the solar energetic particle fluence is not impossible, even for a single event. Solar genesis for The Charlemagne Event is highly plausible.

The concept of a ‘solar killshot’ to our electrified way of life has become a prominent piece of recent popular culture. A solar event on the millennial recurrence scale could dwarf the power and expected losses from a Carrington-level event, were it to occur today. It is unlikely that major power grids would remain intact, and unlikely that any part of the world would remain unaffected. It is unclear if the effects of a Carrington-level storm would be sufficient to qualify as an event that ‘sends us back to the stone-age’, but the likelihood for those types of large-scale emergencies and the following societal breakdown, in an event like the one seen in the 770s, is considerably higher than the probability of such an event actually occurring.

In other words- the chances of us seeing one is rare, but if we do, it’s not going to be a good day to be a transmission wire.

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