Evidence for a Solar Flare Cause of the Pleistocene Mass Extinction

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March 17, 2009, revised October 29, 2009

Abstract. An abrupt rise in atmospheric radiocarbon concentration evident in the Cariaco Basin varve record at 12,887±10 calendar years before 2000 (cal yrs b2k) contemporaneous with the Rancholabrean termination, may have been produced by a super-sized solar particle event (SPE) large enough to overpower the magnetopause sheath and deliver a lethal radiation dose to the Earth's surface. This event, one of several radiocarbon spurts to occur at the beginning of the Younger Dryas (YD) may have been the climactic event in the Pleistocene megafaunal extinction. The demise of mammalian genera prior to this terminal event could be due to the extended period of increased solar flare activity that may have prevailed during the Bölling-Alleröd. The 12,887 cal yrs b2k SPE is registered in the GISP2 ice core record as a large magnitude acidity spike which is associated with high NO^{-3} ion concentrations. The collapse of the magnetopause at the time of coronal mass ejection impact would have discharged the circumterrestrial dust sheath into the Earth's atmosphere. This could explain why extraterrestrial (ET) dust and magnetic spherules are present in high concentrations at the Rancholabrean termination boundary. Ammonium ion concentration peaks associated with dark bands evident in GISP2 ice beginning several years after this event are identified with a biomass combustion episode arising during a period of excessive aridity. It is noted that the termination boundary for Pleistocene megafaunal remains does not coincide with the beginning of the YD cooling as some have previously suggested, but occurs over a century later when the YD cooling trend had almost reached its maximum. The YD cooling is proposed to have been solar flare induced.

Introduction. The Late Pleistocene megafaunal extinction, which spanned a period of several millennia, ended about 12,900 years ago. One distinctive feature is its terminal nature. Extinct species were not replaced with new genera, neither through immigration nor through evolution (1). This circumstance contrasts with the rest of the Pleistocene during which there was a more or less orderly replacement of the old by new genera. Guilday compares this terminal event with the extinction of the dinosaurs at the end of the Cretaceous (2). Both events involved differential extinctions, large land animals (greater than 25 – 50 kg adult body weight) being primarily affected with the smaller vertebrates and the plant kingdom being in general relatively unaffected.

The cause of the Pleistocene mass extinction has for a long time been a mystery. Paul Martin had proposed that in North America it was caused by the arrival of aggressive paleolithic hunters immigrating via a land bridge that connected North America with Siberia during the ice age and that had become ice free during the Alleröd warming (1). However, this overkill hypothesis does not explain why the extinction took place also in Europe and Siberia. It also does not account for the simultaneous disappearance of 10 genera of birds (3) nor for the demise of many relatively young, tender mammoths in the San Pedro valley without any sign of Clovis impact (4).

Others such as Vereshchagin (5), Slaughter (6), and Guilday (2) have offered the alternative explanation that the disappearance of the megafauna could be attributed to the changes in climate that took place near the end of the ice age. However, Edwards points out that climatic change could not have accounted for these extinctions since abrupt changes have occurred in a cyclic manner throughout the Pleistocene without having any particularly pronounced effects on animal life (7). Also Mehringer points out that there were no major barriers to migration into favorable habitats that might account for the extinction (8).

More recently, Firestone et al. (9, 10) report the discovery of an approximately 5 cm thick sediment layer, termed the Younger Dryas Boundary (YDB), overlying the termination boundary for the extinct Pleistocene megafauna as well as the Clovis PaleoIndian occupational surface. Their discovery that the YDB contains high concentrations of ET indicators such as magnetic microspheres, iridium, nickel, and helium-rich fullerenes led them to suggest that this material was deposited by the impact or aerial explosion of one or more large comets (1 - 500 kilometer diameter range) which they say were also responsible for the extinction of the Pleistocene megafauna. They also report that charcoal, soot, and vesicular carbon spherules are present in this layer at certain Clovis locations and identify these with the occurrence of intense wildfires ignited at the time of cometary impact/explosion.

However, there are problems with this hypothesis (11). For example, no impact crater has yet been identified and aerial explosions normally imply that the bolide has a size <160 m in diameter. The comet theory also does not adequately explain why the relative abundance of the ET markers in the YDB layer varies substantially from one geographic location to another. Also the presence of ET indicators in high concentrations does not uniquely imply that this material originated from a cometary encounter. In addition, the proposal of a discrete catastrophic event for the megafaunal extinction conflicts with paleontological evidence indicating that the extinction transpired over several millennia (12). Furthermore the suggestion of Firestone et al. that soot from the resulting widespread wildfires and dust from the cometary impact/explosion had darkened the sky for an extended period of time triggering the YD climatic cooling is problematic. As is shown below, the YD cooling trend lasted approximately 150 years and had been in progress for approximately one century prior to the Rancholabrean termination.

It is suggested here that this unique mass extinction may instead have had a solar cause. Several studies indicate that toward the end of the ice age the Sun was far more active than it is today. To explain the vitrification of particles found in glazed areas of lunar rocks, Gold concluded that some time in the last 30,000 years the Sun's luminosity must have increased by as much as a hundred fold for a period of 10 to 100 seconds either due to radiation from a very large solar flare or to the occurrence of a nova-like outburst (13). LaViolette has suggested that the glazing of the lunar rocks could instead be explained if the Earth and Moon had been engulfed by the hot plasma of a solar coronal mass ejection (14). Also Zook et al. studied solar flare tracks etched in micrometeorite craters found in lunar rocks and concluded that around 16 kyrs b2k the average solar cosmic ray intensity was 50 times higher than it is at present, declining to 15 times higher by 12 kyrs b2k, and eventually reaching the present activity level (15). Also elevated radiocarbon concentrations found in the surfaces of lunar rocks indicate that for a period of 5000 years prior to 12,000 years b2k the Moon was being exposed to a solar cosmic ray flux averaging 30 times higher than the present flux (16).

LaViolette has proposed a Galactic cause for this elevated solar activity, attributing it to the entry into the solar system of large quantities of cosmic dust (14, 17-21). He presents astronomical and geological evidence indicating that a relatively intense volley of Galactic cosmic rays and associated electromagnetic radiation, termed a *Galactic superwav*e, had passed through the solar system from around 16 to 11 kyrs b2k, vaporizing cometary ice residing outside the solar system and propelling inward large quantities of dust, gas, and fragmentary cometary debris. Energy released from the Sun's accretion of this nebular material and the heating effects of back-radiation coming from the congested circumsolar dust cloud would have elevated the Sun's luminosity and level of flaring activity. He proposed that this elevated solar cosmic ray flux not only was a contributing cause of the abrupt climatic changes at the end of the Pleistocene but also was responsible for the extinction of the Pleistocene megafauna (14, 20, 22). New evidence presented here strengthens the proposal that the Pleistocene mass extinction had a solar cause.

Elevated Solar Activity at the Beginning of the Younger Dryas. The Cariaco Basin varved ocean sediment record located off the coast of Venezuela shows that between 13,500 and 12,800 cal yrs b2k the radiocarbon abundance excess ($\Delta^{14}C$) in these sediments underwent a 95 per mil rise relative to the ^{14}C trend line, with the majority of this increase occurring within the latter 200 years between 13,007 and 12,810 cal yrs b2k; see figure 1 (upper profile) (23). This ^{14}C excess is the largest increase to be seen in the Cariaco Basin record as far back as 15,000 cal yrs b2k and is seen as well in sedimentary records from various locations around the world. This ^{14}C rise is seen to have occurred synchronously

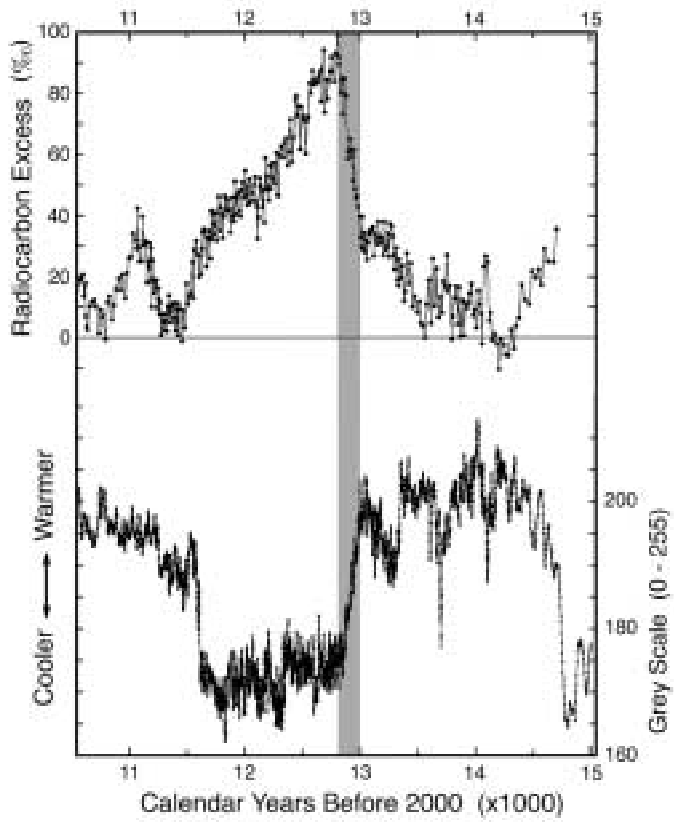

Figure 1. Radiocarbon abundance excess relative to the trend line value for the Cariaco Basin sediment core (upper profile) compared to the core's grey scale climate profile (lower profile) Higher grey scale values indicate warmer temperatures. Data is from Hughen, et al.(23).

with a 160 year-long climatic cooling 13,007 - 12,845 cal yrs b2k that initiated the YD stadial; see figure 1 (lower profile).

Stocker and Wright (24) attempted to computer simulate the YD $\Delta^{14}C$ rise on the presumption that an MOC-^{14}C correlation might exist, but were able to attribute only half of the YD $\Delta^{14}C$ rise to a reduction in thermohaline convection. Muscheler et al. (25) subsequently used beryllium-10 deposition rates determined from analysis of ice from the GISP2 Greenland ice core (26, 27) to model the atmospheric radiocarbon production rate at the end of the ice age. They concluded that the $\Delta^{14}C$ increase at the onset of the YD is partly due to the increased production of atmospheric radiocarbon and partly to a reduction in old carbon entering surface waters which they attribute to a 30% reduction in the diffusive carbon exchange in the ocean due to a reduction in North Atlantic deep water formation.

Atmospheric ^{10}Be, like radiocarbon, is currently produced primarily by the intergalactic cosmic ray proton background radiation that strikes the Earth's atmosphere. As seen in the lower profile of figure 2 (26, 27), the ^{10}Be deposition rate at Summit, Greenland was generally elevated around the latter part of the Alleröd and early YD, although there was a 200-year lull period during the onset of the YD (13,075 to 12,880 cal yrs b2k). So that the ^{10}Be data may be matched with the Cariaco Basin radiocarbon profile, the ^{10}Be sample dates from the GISP2 ice core have been adjusted to conform to the Cariaco Basin varve chronology using the climatic match points presented in Table 1. It should be noted that one ^{10}Be data point is missing for the depth range 1709.5 - 1711 meters (12,921 - 12,957 cal yrs b2k) which lies within the ^{10}Be production rate lull.

It is unlikely that these ^{10}Be and ^{14}C variations are due to changes in geomagnetic screening since the average field intensity did not change appreciably across the Alleröd/Younger Dryas transition (28). The increases could variously be attributed either to an increase in the primary cosmic ray background flux, to a decrease in solar modulation of the primary cosmic ray flux due to Maunder-minimum-like reduction in solar activity, or to a very large increase in solar flare activity capable of countering the effects of increased modulation of the primary flux. So increased solar flare activity for this critical period at the onset of the YD remains a distinct possibility. The minimum between the two ^{10}Be peaks could be attributed to enhanced solar wind screening of the cosmic ray background flux, indicating a time when the Sun was more active than normal.

A portion of the $\Delta^{14}C$ rise evident at the beginning of the YD is most probably due to a reduction in the rate of influx of old radiocarbon into ocean surface waters due to a reduction in ice sheet melting. For example, ocean radiocarbon concentration, which was substantially higher during the late glacial stage, began to rapidly drop around 16 kyrs b2k with the onset of climatic warming and glacial melting. Radiocarbon depleted meltwater was discharging into the oceans at a relatively high rate until around 13 kyrs b2k which kept ocean sediment $\Delta^{14}C$ concentrations reduced to low values throughout this period; see shaded section in figure 3, data taken from Hughen et al. (29). With the onset of cooler temperatures at the beginning of the Younger Dryas and the corresponding decline in the influx of ^{14}C depleted meltwater, ocean ^{14}C concentrations progressively rose, aided by a rise in atmospheric radiocarbon production. The decline in $\Delta^{14}C$ during the YD after 12,800 cal yrs b2k can be explained by a subsequent decline in atmospheric radiocarbon production (25).

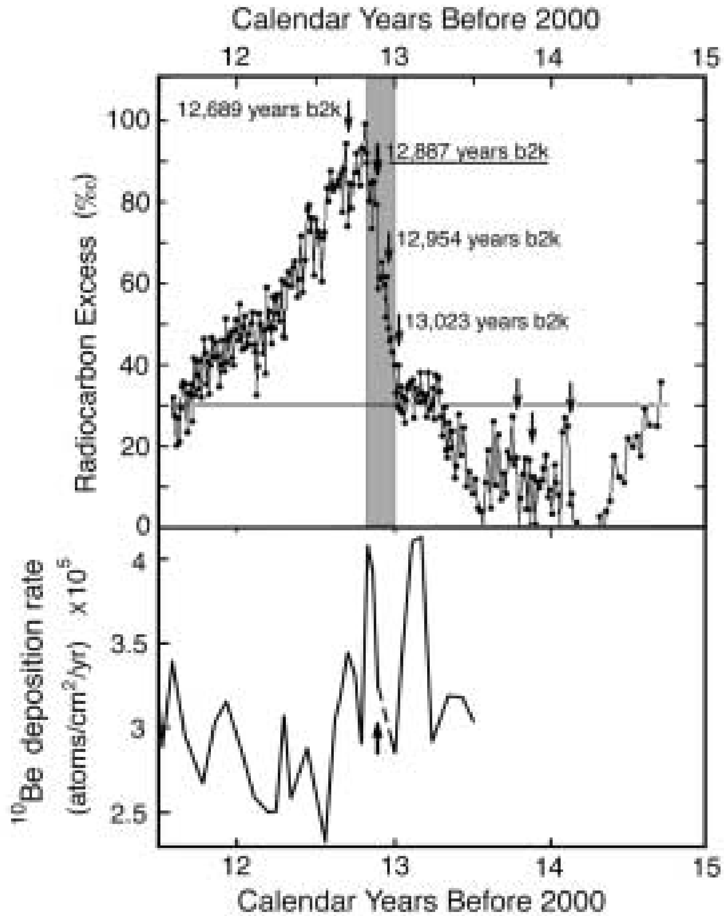

Figure 2. Upper profile: Radiocarbon abundance excess relative to trend line as seen in a Cariaco Basin sediment core. Arrows indicate times of large spurts in ^{14}C production, indicative of dates of SPEs. Data is from Hughen, et al. (23). Lower profile: beryllium-10 deposition rate based on the ^{10}Be concentration data of Finkel et al. (26) multiplied by corresponding ice accumulation rate from the data of Alley et al. (27) .

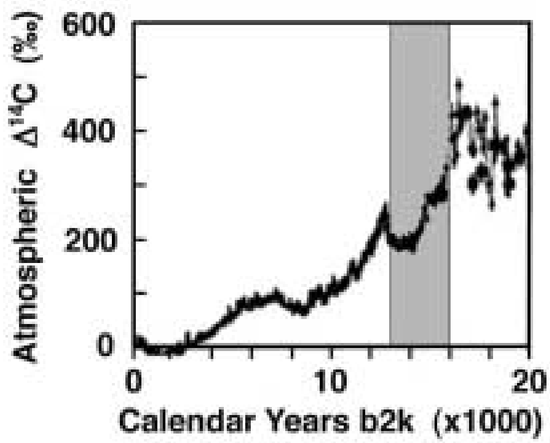

Figure 3. Radiocarbon abundance excess relative to trend line over the past 20,000 years (29).

A close examination of the Cariaco Basin ^{14}C data shows that the rise in oceanic ^{14}C concentration at the beginning of the YD was punctuated by four spurts or sudden jumps in ^{14}C concentration which most likely had a solar cosmic ray cause; see arrows in figure 2 (upper profile). In terms of the rate of ^{14}C rise per year, these four incidents were among the five largest changes in ^{14}C concentration to occur during the period from 14.5 to 11.5 kyrs b2k. They date at 13,023 ± 10, 12,954 ± 10, 12,887 ± 10, and 12,689 ± 10 cal years b2k according to the Cariaco Basin varve chronology. It is worth noting that they are spaced from one another by multiples of the Hale solar cycle period of 22.2±2 years, that is, by 69±4, 67±4, and 198±4 years, or three, three, and nine Hale cycles. The finding that the timing of these events conforms to the solar cycle period favors the interpretation that these spurts are real increases in atmospheric ^{14}C and not chance artifacts of the radiocarbon measurement process. Most probably they register SPEs that were generated by the Sun's discharge of super-sized CMEs.

The Sun's magnetic field reverses direction every 22 years. Satellite observations have shown that during times when the Sun's magnetic field is pointing north, the solar wind is able to most easily penetrate the magnetopause and charge the magnetosphere with solar wind plasma thereby increasing the probability that a coronal mass ejection will overpower the geomagnetic field. This could explain why the YD ^{14}C spurts are seen to be spaced by 22-year multiples. Their presence suggests that a portion of the increase in radiocarbon production at the onset of the YD may have been due to increased solar activity, a conclusion that also finds support in the earlier cited lunar rock evidence. Such SPEs could also have created spurts in atmospheric ^{10}Be production of less than a few weeks duration, but such peaks would not be expected to show up in the low resolution GISP2 data set which sampled the ice core using 1.6 meter sections (~30-year intervals).

The two most recent ^{14}C spurts at 12,887 cal yrs b2k and 12,689 cal yrs b2k, which register a 2 percent rise, are the largest ^{14}C spurts seen in the Cariaco Basin record. The 198-year interval between them is of particular interest because it approximates the Suess (de Vries) cycle of 205±5 years. These four spurts are seen to coincide with two major increases in excess ^{14}C seen on the INTCAL98 ^{14}C excess profile (Fig. 4) (30). The two largest spurts coincide with major rises in ^{14}C excess whose maxima at 12,824 and 12,624 cal yrs b2k are also spaced by 200 years. Wagner et al. (31) have noted the Suess cycle to be present also in ^{10}Be data from the GRIP ice core (25 - 50 kyrs BP).

The SPE that impacted during the February 1956 solar maximum, which was one of the largest in modern times, is estimated to have produced an atmospheric ^{14}C increase of only 0.2 per mille (32), or 4% of the variation produced over the course of a typical solar cycle. So, if the 12,887 or 12,689 years b2k spurt events register the occurrence of SPEs, their 2 percent rise in ^{14}C concentration suggests that either were at least 100 times more intense than the 1956 SPE event. Flares of such a large magnitude are not unusual from the astronomical perspective. For example, "superflares" ranging from 10^2 to 10^7 times the energy of the February 1956 solar flare have been observed to occur on nearby sun-like stars (33). Currently, solar cosmic rays account for less than 1 percent of the ^{14}C production (34). But a solar proton event two orders of magnitude larger than the February 1956 SPE could have produced a sufficient amount of radiocarbon to produce a net rise in atmospheric ^{14}C concentration in spite of the increased screening of the galactic cosmic ray flux that would have prevailed at that time.

The ring current generated by the 1956 SPE was able to produce a 1% decrease in the

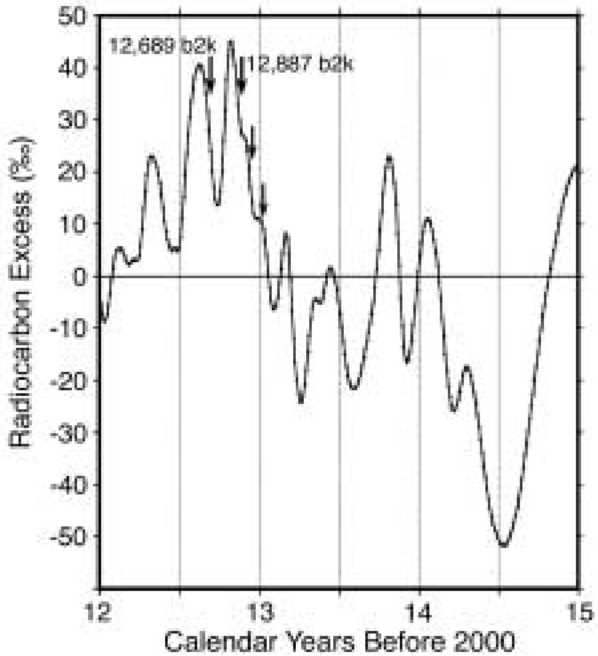

Figure 4. INTCAL98 radiocarbon calibration data charting radiocarbon excess expressed as per mil deviation (30). Data in this date range are based on marine records. Dates of ^{14}C spurts evident in the Cariaco Basin varve record are shown for comparison.

geomagnetic field during main phase decrease (35). Consequently, ice age SPEs that were over two orders of magnitude stronger than this could have entirely overpowered the Earth's field and allowed the full intensity of their cosmic ray plasma to contact the Earth's atmosphere (14, 18). Uffen (35) has proposed that geomagnetic reversals could occur at times when the Earth's field is at minimum strength and that at such times cosmic rays and solar wind particles trapped in the radiation belts could spill onto the Earth causing a major increase in the mutation rate. While he suggested that such field intensity minima arise as a result of instabilities in the Earth's liquid metal core dynamo, the alternate possibility proposed here is that these geomagnetic minima could be solar flare induced (18, 22). Magnetopause collapse caused by the arrival of a super-sized coronal mass ejection would result in Earth's exposure to a cosmic ray flux many orders of magnitude higher than Uffen was considering and hence could induce mass extinctions rather than just a rise in mutation rate. This would explain why Earth's past history shows there to be a strong correlation between geomagnetic reversals and the extinction of foraminifera and radiolaria (37-41). The geomagnetic excursion produced by the proposed super-sized SPE would be difficult to detect in the sedimentary record due to the event's brevity. Nevertheless, a study of Lake Erie sediments near Erieau, Ontario does show that geomagnetic inclination was unstable between about 13,000 to 10,500 ^{14}C years BP (15,500 to 12,600 cal yrs b2k) (42).

The 12,887 ± 10 cal years b2k ^{14}C production spurt, the largest such event to occur over the entire Alleröd-Younger Dryas period, was likely the terminal episode that ended the 1400 year-long climax phase of the mass extinction. The cosmic ray radiation from such an event would have been fatal to large animals that were not sheltered from exposure. The February 1956 SPE, which had a relatively hard spectrum, was observed to produce a ground level particle enhancement at Leeds, UK that was 45 times that of the cosmic ray background. It is estimated that a person taking a four-hour Paris-New York Concord jet flight at an altitude of 17 kilometers would have received from this SPE a radiation dose of 6.1 milli Sieverts (mSv) (43). Consequently, the 12,887 years b2k event could have delivered a ground-level dose of about 10 Sv over a two day period if the geomagnetic field had been suppressed during a solar storm main phase decrease. Radiation doses exceeding 3.5 Sv are known to be lethal to humans (44). Hence a 10 Sv dose is likely to have been lethal for most of the Pleistocene megafauna as well. Incident solar cosmic ray protons could have generated thermal neutrons within animal tissues which upon colliding with organic nitrogen could produce radiocarbon in situ in the animal remains (14). If the cosmic ray intensity had reached very high intensities in certain locations, this could explain why some megafaunal remains have anomalously young radiocarbon dates uncharacteristic of the strata age they are found in.

The Contemporaneous Mass Extinction. The three ^{14}C spurts that occurred between 13,025 and 12,885 calendar years b2k during the onset of the YD climatic cooling coincided with the climax of the Pleistocene mass extinction. Figure 5 charts the temporal distribution of dates on the remains of extinct Pleistocene megafauna taken from various North American sites with the number of remains found in each of a consecutive series of time slots. The ^{14}C data is taken from Meltzer and Mead (45, 46) and is plotted here in terms of Cariaco Basin calendar years instead of radiocarbon years. The dark bars in the histogram represent dates occurring prior to 12,960±100 cal yrs b2k (11,000±100 ^{14}C years BP), an approximate cut-off date that marks the termination boundary beyond which no surviving extinct Pleistocene mammals are found in most parts of the world. The light bars represent dates occurring more recently than this, many of those ^{14}C dates possibly being anomalously young due to contamination with young carbon or due to in situ ^{14}C production. The lower pixilated bars represent the subset that Meltzer and Mead consider to be more reliable radiocarbon dates. Haynes (47) proposes a slightly more recent date of 10,900 ± 50 ^{14}C years b2k for the Rancholabrean termination, which in the Cariaco Basin varve chronology translates to 12,915 ± 50 cal yrs b2k. This also marks the date of deposition of the ET debris-rich YDB layer described by Firestone et al., a stratum that is overlain by the black mat, a carbon-rich layer found in American southwest covering the remains of extinct megafauna. The date of this termination coincides with the 12,887 cal yrs b2k SPE to within the stated margin of error.

The data in figure 5 show that the mass extinction had been underway for about five millennia prior to this termination date. The majority of the animal remains found are seen to date from the 1400 year period preceding the termination boundary. Grayson and Meltzer (48) note that of the 35 mammal genera that disappeared in the extinction, only 15 can be shown to have lasted beyond 12,000 ^{14}C years b2k (13,900 cal yrs b2k). Hence over half of the genera became extinct one millennium prior to the Rancholabrean termination date. The progressive character of the mammalian extinction poses a problem for theories proposing a single catastrophic event as a main cause of the extinction, one example being the comet impact/explosion scenario of Firestone, et al. While a solitary event of this sort could account for the abrupt termination of the extinction, the preponderance of extinct fossil remains in preceding millennia remains unexplained. It is argued here that the terminal extinction event was more likely brought about by the impact

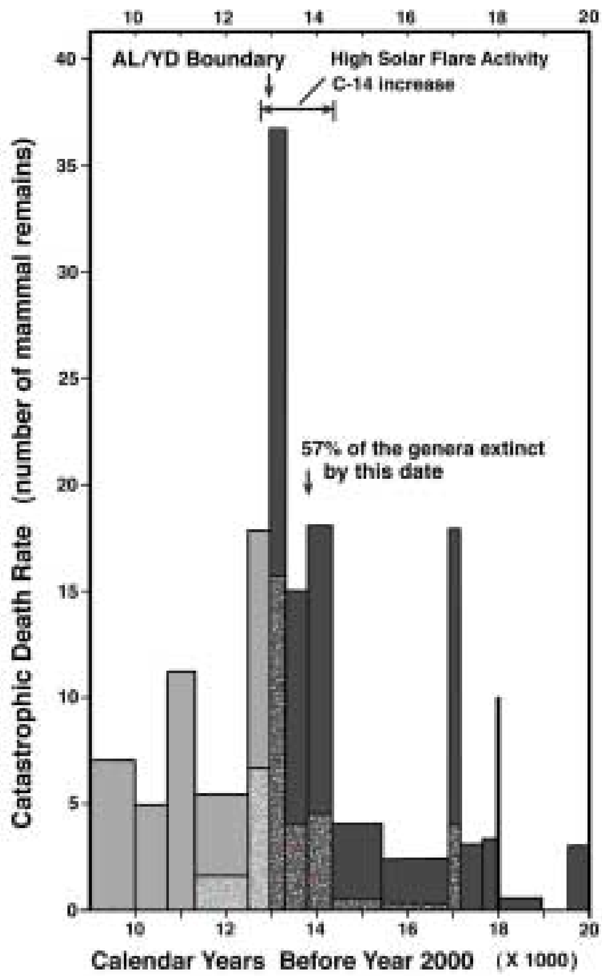

Figure 5. Chronological distribution of calendar dates on remains of extinct mammals from 163 localities in North America. Black bars indicate dates prior to 12,960 cal yrs b2k. Pixilated bars indicate the subset of more reliable dates. Based on data from Meltzer and Mead (45) and Martin (46) with ^{14}C dates being converted to calendar dates using the Cariaco Basin ^{14}C varve chronology.

of a super-sized solar coronal mass ejection and that elevated solar activity over preceding millennia was responsible for earlier disappearances. Catastrophic glacial meltwater floods issuing from the ice sheet surface during the Bölling/Alleröd climatic warming as well as during warm intervals occurring within the Younger Dryas stadial would have posed an additional hazard (14, 18). Catastrophic deposition produced by such floods would have helped to preserve megafaunal remains from decay and could have contributed to their elevated probability of discovery in sediments dating from these times.

A Solar Conflagration Possibly Recorded in Polar Ice. By transferring the Cariaco Basin chronology to the Summit, Greenland ice record, it is possible to locate the specific ice core depth correlative with these ^{14}C spurts (or SPEs). This may be done by correlating specific temperature excursions evident in the Younger Dryas portion of the Cariaco Basin grey scale climatic profile with similar features seen in the GISP2 ice core oxygen isotope

Table 1.
Depth-Time Marker Horizons Used in Transferring the Cariaco Basin Chronology to the Greenland Ice Record Quarter Bag GRIP Oxygen Isotope Profile and to the GISP2 Oxygen Isotope Profile

Climatic Boundaries	Cariaco Years b2k	GISP2 Mid Depth (meters)	NGRIP Mid Depth (meters)
YD ends	11,614	1677.6	
	11,640	1678.55	
	11833	1684.9	
	12,211	1688.7	
	12,500	1699.2	
	12,645	1702.25	
temp. max.	12,820	1705.4	
temp. min.	12,853.5	1706.85	1520.45
cooling ends	12,877	1707.75	1521.30
temp. max.	12,881.5	1708.15	1521.70
warming begins	12,884		1522.08
acidity spike	12887	1708.65	1522.20
temp. max.	12,896	1708.8	1522.35
temp. min.	12,923	1709.55	1522.98
temp. min.	12,945	1710.35	1523.78
temp. max.	12,962	1711.25	1524.43
YD begins	13,007	1712.25	1526.9
IACP ends	13,183	1721.26	
IACP begins	13,350	1727.290	

profile. Table 1 matches a series of climatic excursions evident in both profiles and assigns them dates from the Cariaco Basin varve chronology. The Cariaco Basin chronology has been synchronized with the Holocene dendrochronology scale and is believed to be accurate to ±10 years. It shows the Younger Dryas as lasting for a period of 1393 years, while the GISP2 ice core chronology (49), which is based on counts of annual layers in the ice, shows the Younger Dryas as lasting only about 1251 years. The 142 year shortfall in the Greenland chronology may be attributed to a possible loss of about 4 meters of accumulated ice through melting at the Summit, Greenland site.

The GISP2 ice core record shows the presence of a solitary acidity spike at a depth of 1708.65 meters as revealed by electrical conductivity measurements (ECM) of the ice. This same ECM event is found at depth of 1657.51 m in the GRIP ice core and at 1522.2 m depth in the NGRIP ice core. It is unique in that a spike of such large magnitude is not seen for hundreds of years. It is the second largest acidity spike to occur in the Younger Dryas period. On the basis of the transferred Cariaco Basin chronology, this acidity event dates at 12,887±10 cal yrs b2k hence indicating that very acidic snows were being deposited around the time of the 12,887 cal yrs b2k ^{14}C spurt. The snows falling at the time of this event were so highly acidic that they were able to increase the electrical conductivity of the ice 1900 fold compared with background conductivity levels prevailing before and after the event. Highly acidic snows would be an expected outcome if, as suggested earlier, the atmosphere had been exposed to a high flux of cosmic rays during a large-magnitude solar particle event. A high resolution ECM plot of this acidity spike is shown in figure 6 (50).

The laser light scattering (LLS) data for this section of the ice core shows that ice opacity, an indicator of ice dust content, underwent a 100% increase above background levels at the time of the ECM spike (51). This relatively modest LLS peak, which spans about half a centimeter of ice, likely represents the true width of this acidity spike, as compared with 3 cm width for the ECM peak. The broader ECM width arises because the electrodes used in measuring ice core conductivity are half a centimeter in diameter, which tend to blur discrete acidity spikes and make them look broader than they really are. Also some peak broadening may be due to the tendency for ions to slowly diffuse through the ice. Based on the annual layer thickness of 6.5 cm/yr estimated for this portion of the ice core, a half centimeter wide ECM event would span less than one month. This is consistent with the

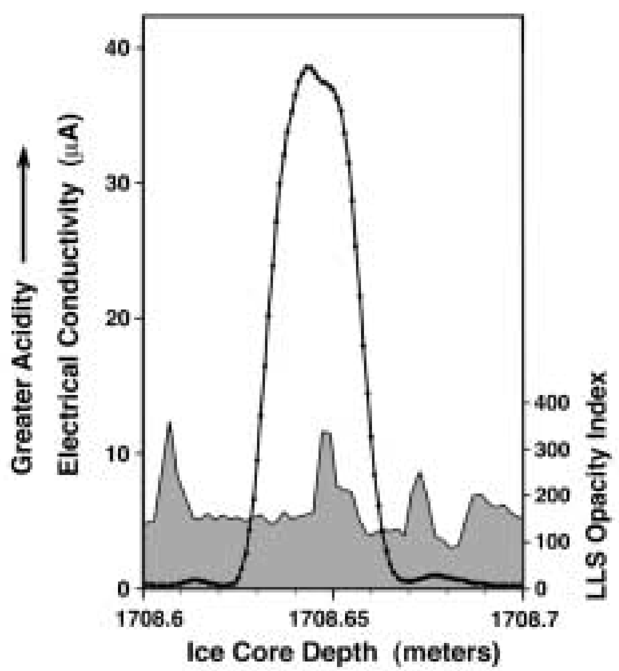

Figure 6. Ice core conductivity profile from the GISP2 Greenland ice core indicating a period of high ice acidity possibly due to the arrival of a super sized SPE. Shown for comparison is the relative scattered light intensity indicating ice opacity. The event has been dated by adjusting the GISP2 ice core chronology to the Cariaco Basin varve chronology. Data are from Taylor (50) and Ram (51).

suggestion that the event registers the occurrence of a solar proton event.

The ECM spike also coincides with a two to three fold increase in chlorine and sulfate ion, which raises the question of the alternative possibility of whether the acidity may have been due to a volcanic eruption. However, no volcanic eruption is known to have occurred at this time. The Laacher eruption dated at 11,063±12 ^{14}C years BP (52), or at 12,990 cal yrs b2k in the Cariaco Basin chronology, occurred one century prior to this event at the beginning of the Younger Dryas cooling. Also the duration of the acidity event is too brief since ECM signatures of volcanic eruptions usually span a longer period of time, on the order of a few years. Considering the unique magnitude of this spike, its 10^3 fold increase in acidity, and its proximity to the 12,887 years b2k ^{14}C spurt, it seems more likely that this particular spike records the occurrence of a solar particle event. This raises the question as to the origin of the Cl^- and SO_4^- ions and whether they may be of extraterrestrial origin. One possible source could be volatiles present in micrometeoritic material that may have entered the Earth's atmosphere at the time of the SPE.

The GISP2 ice core record shows that nitrate ion concentration (53) increased just before and just after the 12,887 years b2k ECM spike; see figure 7. One year after the SPE acidity event, it had increased to 200 ppb, its highest level for the entire Younger Dryas period. A continuous sampling for NO_3^- ion in the NGRIP Greenland ice core shows that nitrate ion reached a maximum of 400 ppb following this event, with the entire post-event peak lasting about two years (55). Nitrate ions are produced when the atmosphere is exposed to cosmic rays. Hence their presence here in high concentrations supports the suggestion that this ECM peak records the occurrence of an intense solar cosmic ray event. The NO_3^- concentration minimum registered at the time of the ECM peak may be due to dilution arising from an increase in snow precipitation rate occurring at that time. The high levels of nitrous and nitric ions that would have been present in the upper atmosphere at this time would have destroyed the Earth's ozone layer letting harmful UV penetrate to the Earth's surface (14). The UV exposure danger would have been greatest at that time, particularly during the occurrence of the 12,887 years b2k SPE.

A solar cause for this YD nitrate ion spike is further supported by a study by McCracken et al. (56) who have found that major nitrate concentration spikes present in the polar ice record over the period from 1551 to 1950 correlate with the dates of major SPEs. In particular, during the Carrington event of 1859, nitrate ion concentration in the Summit, Greenland ice core rose almost five fold to 280 ppb, the entire episode lasting about two months. McCracken et al. estimate that this event had a particle fluence >30 Mev of about $19 \times 10^9/cm^2$, hence about 20 times greater than that of the February 1956 SPE.

Ammonium ion concentration (57), an indicator of biomass combustion, is also seen to peak around the time of the 12,887 years b2k ^{14}C event, reaching its highest value for the Younger Dryas period. High concentrations were sustained over a period of about two decades with the exception of a decline around the time of the ECM spike which is possibly due to the aforementioned temporary increase in snow accumulation rate at that time. Concentrations of formate and oxylate ion, also indicators of biomass combustion, reached high levels around this time as well (58). High ammonium concentrations occurred during the warm intervals that both preceded and followed the ECM spike; see figure 8 (59). The discovery that biomass combustion occurred preferably during these periods of climatic warming is consistent with the findings of Marlon et al. who report that wildfires historically tend to occur at times of climatic warming possibly due to an associated increase

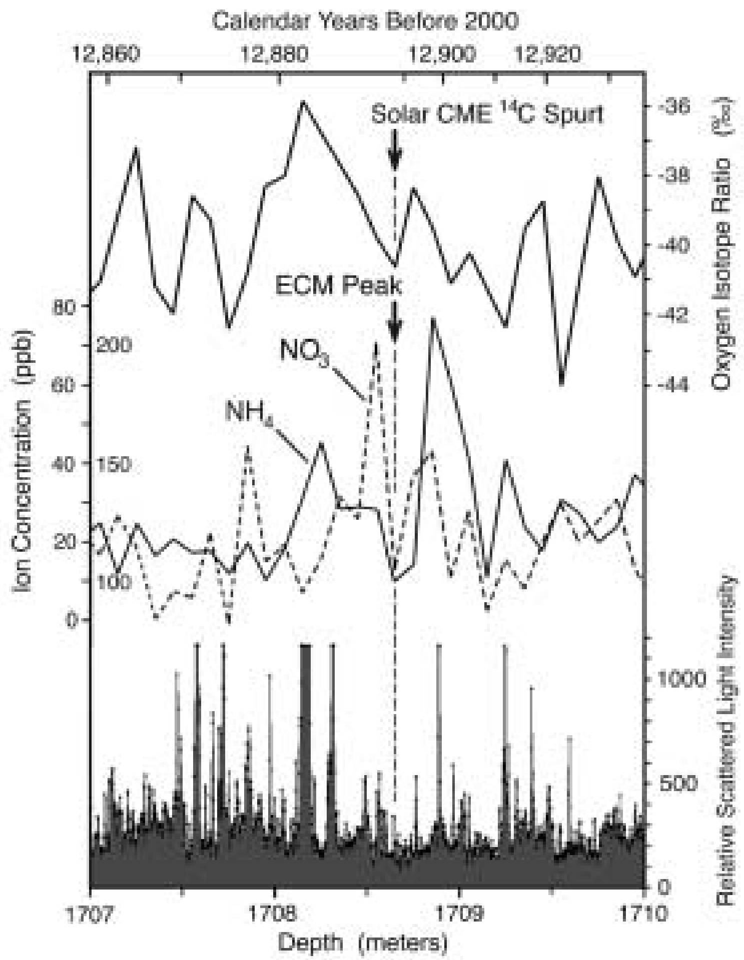

Figure 7. Nitrate and ammonium ion concentration in the GISP2 ice core (53, 57) compared to oxygen isotope ratio (upper profile) (54) and relative scattered light intensity (lower shaded profile) (51). The plots are charted according to the Cariaco Basin varve chronology. Arrows indicate the dates of the GISP2 ECM spike and the 12,887±10 cal yrs b2k ^{14}C spurt.

in climatic aridity (60).

Since these two temperature maxima are spaced apart by about one solar cycle period, this raises the question of whether these warmings may have been due to an increase in the Sun's total energy output during this period. Current observations show that solar irradiance is 0.1% higher at solar maximum as compared with solar minimum which is far too small to have any significant climatic effect. However, 10 to 20% of this irradiance variation is in the UV and UV output correlates positively with the level of solar flare activity. So if flare activity was a few orders of magnitude higher than current levels at this time, the solar constant could have increased by as much as one percent which would have substantially impacted climate.

The LLS data for the GISP2 ice core (51) registers a pair of very dark ice core layers at about 12,881 to 12,883 years b2k which date about 4 to 6 years (35 to 50 centimeters of ice) after the ECM spike. The bands are so dark that the LLS reading saturates at its maximum value. They are also quite thick. Two bands span 4 centimeters of ice (~0.5 years) and the

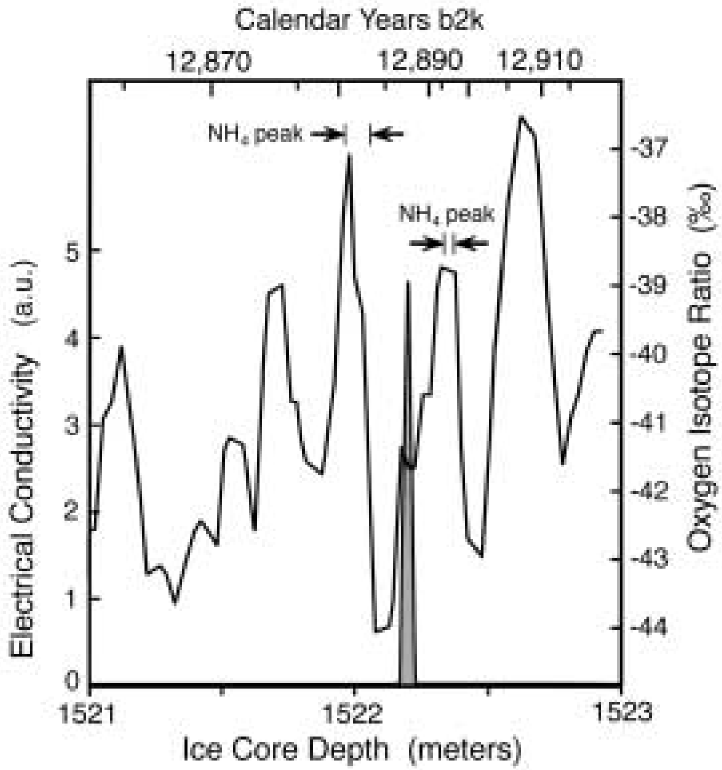

Figure 8. High resolution oxygen isotope profile for the NGRIP Summit Greenland ice core compared to relative ECM (shaded profile) (58). Dating is based on the Cariaco Basin varve chronology.

band at 12,881 years b2k spans 7 centimeters of ice (~1 year). They occur at a time when ammonium ion concentration reached a peak value; see figure 7. They are followed by additional dark bands that together span a period of about 14 years. A narrower, one-centimeter-thick band of dark ice dating around 12,894 cal yrs b2k is seen to coincide with the ammonium peak that preceded the ECM spike. Because of their proximity to the elevated ammonium ion concentrations, it may be surmised that these bands contain high concentrations of soot generated during this period of particularly intense biomass combustion. Future analysis of these dark ice layers should show if this is the case.

The proximity of these dark layers to the 12,887 years b2k acidity spike and to the date of the large ^{14}C spurt seen in the Cariaco record suggests that the wildfire interval that is associated with the YDB layer had a solar cause. If the atmosphere was so congested with particulate that sunlight was obscured at times for up to an entire year, as the LLS data appears to indicate, then even vegetation that had been spared from combustion would have withered from lack of light. Both effects together would have temporarily eradicated the food supply for herbivores. Along with the hazards of exposure to cosmic ray and UV radiation, food scarcity would have been another factor that contributed to the mammalian extinction.

Firestone et al. (9) have associated this biomass combustion episode with global wildfires that were responsible for the soot and polycyclic aromatic hydrocarbons they observed in the iridium-rich YDB layer found at certain southwestern U.S. Clovis sites. Although, Haynes (61) concludes that vitreous carbon, vitrinite, and charcoal found at the base of the

YD black mat at the Murray Springs Clovis site likely originate from a local Clovis hearth and are not of wildfire origin as claimed by Firestone et al. (9). The suggestion of Firestone et al. that a comet impact or explosion responsible for the formation of the YDB layer was also responsible for triggering the onset of the YD cooling is not supported by the ice core evidence. The elevated ammonium ion concentrations marking this wildfire episode date between 12,880 and 12,900 cal yrs b2k using the applied Cariaco Basin chronology whereas the Cariaco Basin grey scale record shows the YD cooling beginning its 150 year-long transition around 13,007 ± 10 cal yrs b2k, hence about 110 to 130 years earlier. One reaches the same conclusion on the basis of the GISP2 ice core chronology, which uses annual layer counting for dating, since the two chronologies differ in relative terms by less than a decade over this period of interest. A similar temporal offset is found for the radiocarbon date that Haynes (47) gives for the Rancholabrean termination. This converts to 12,915 ± 50 cal yrs b2k in the Cariaco Basin chronology which falls about 95 ± 50 years after the start of the YD cooling.

Extraterrestrial dust and the collapse of the circumterrestrial dust cloud. Firestone et al. (9) have suggested that the microspherules found in the YDB stratum underlying the black mat are debris from a cometary impact or aerial cometary explosion. However, other interpretations are possible. For example, cosmic spherules can be produced in the atmosphere during the high velocity entry of micrometeorite cosmic dust particles having diameters greater than 100 microns. They also are present in space, being found in the Earth's atmosphere at high altitudes and also on the Moon (62). To account for the spherules found on the Moon, Mueller and Hinsch (63) have proposed that dust particles had been melted by an intense outburst of solar radiation. Furthermore chondrules (microspheres) are believed to be a component of cometary ice and to be released into the interplanetary medium along with the more friable cosmic dust particles whenever cometary ice vaporizes. Dust collections sampled in Antarctica and other remote locations indicate that the Earth receives a continual influx of cosmic spherules, magnetic grains, and carbonaceous particles, including crystalline organics, the majority of which are unlikely to be meteorite ablation products but rather dust particles entering from the Earth's near space environment (64).

Pinter and Ishman (11) have suggested that the ET indicators found in the YDB layer could be explained by the normal influx of cosmic dust. The levels reported by Firestone, et al. (9), however, rule out this possibility since they indicate influx rates at least 10^5 fold higher than current cosmic dust influx rates. For example Firestone et al. report bulk sediment Ir levels of the about 2 to 4 ppb at Lake Hind, Manitoba and Blackwater, New Mexico. Assuming conservatively that the YDB layer in which they are found was deposited at these sites at the same rate as the stratigraphic layers that surround it, i.e., at the rate of 0.02 - 0.035 cm/yr, this yields a time span of 150 to 250 years for the deposition of a 5 cm YDB layer. Assuming further that the iridium in the deposited ET material has an abundance similar to that seen in carbonaceous chondrites (~514 ppb), this projects a cosmic dust deposition rate of the order of 3 - 5 X 10^{-4} g/cm^2/yr, whereas Takahashi, et al., analyzing Ir in Dome C ice, have determined the present deposition rate to be only 2 X 10^{-9} g/cm^2/yr (65, 17). Others who have analyzed the YDB layer have found no evidence of enhanced concentrations of platinum group metals. However, if high levels are present, an explanation is needed as to how they got there.

Given that the YDB layer was formed during a period of generally elevated solar activity around the time when the Earth appears to have been impacted by a very large magnitude coronal mass ejection, the possibility presents itself that the ET material found in this layer entered the Earth's atmosphere in connection with this solar event. The most likely cause would have been the CME-induced collapse of the magnetosphere bringing with it the collapse of the circumterrestrial dust cloud. Satellite and rocket observations have shown that the Earth is surrounded by a dust cloud extending radially outward from the Earth for a distance of 10^5 to 10^6 km, or 15 to 150 earth radii (66-69). Sunlight scattered from this dust cloud is believed to account for at least 10% of the light of the zodiacal cloud. Compared with interplanetary space, the number density of dust particles is estimated to be 10^5 fold higher for particles in the radial size range 0.1 to 10 μm, 3000 fold higher for particles having radii on the order of 100 μm, and tapering down to essentially no enhancement for 1 cm sized meteoroids. It is estimated that dust particles may have residence times in this cloud for upwards of thousands of years. Having acquired an electrical charge through photoionization by solar UV, they are susceptible to being picked up by the magnetosphere and magnetotail as the Earth sweeps through its orbit around the Sun. The cloud is also stocked by particles blown off the surface of the Moon by the impacting solar wind. The captured particles have very low velocities relative to the Earth and their motions are dominated by the geomagnetic field. For particles in the mass range 10^{-20} g to 10^{-15} g (r from 0.1 μm to 5 μm) the Lorentz force is stronger than gravity (70). Magnetic grains present in the cloud would be particularly susceptible to movement of the geomagnetic field.

Impacting coronal mass ejections are known to compress the magnetosphere inward on the side facing the Sun. In so doing they drag with them magnetically bound dust particles present in the circumterrestrial dust sheath. As mentioned earlier, a sufficiently intense CME, of the sort proposed to have impacted the Earth around 12,887 cal years b2k, would have weakened and overpowered the geomagnetic field allowing the impacting CME to contact the Earth's atmosphere. With the initial compression and subsequent collapse of the magnetopause, much of the dust in the circumterrestrial cloud would likely have been jettisoned into the Earth's stratosphere leaving its particles to float to the Earth's surface over a period of months to years.

The amount of dust present in the circumterrestrial dust sheath should have been sufficient to account for the ET material found in the YDB layer. Based on the abundances of magnetic grains reported by Firestone et al., it may be surmised that this layer contains about 0.1% ET material by weight within a depth of less than 5 cm, or about 15 mg/cm^2. Hence if this deposit covers 10% of the Earth's surface, it would contain about 8×10^{15} g of ET material. Ice core evidence suggests that cosmic dust mass concentrations in the interplanetary medium at the end of the last ice age may have reached as high as 5×10^{-20} g/cm^3, or 250 times the present interplanetary mass density (14, 17, 21). Figuring a 10^5 fold enhancement, the circumterrestrial dust cloud would have contained a dust mass density averaging around 10^{-14} g/cm^3. The required 8×10^{15} grams of material, then, could have been supplied from the portion of the cloud lying within fifteen earth radii of the Earth's surface, or r ~ 10^5 km. Magnetic particles present in this dust cloud would have been particularly susceptible to being transported toward the Earth with the compression and collapse of the geomagnetic field which could explain the abundance of magnetic grains in the YDB layer.

The incoming extraterrestrial dust would have served as condensation nuclei for water vapor present in the stratosphere, adding to the condensation nuclei ions being produced by the impacting solar cosmic rays. Both the formation of stratospheric clouds and the light scattering effects of the dust particles, most of which would have been in the submicron size range, would have dramatically increased the opacity of the stratosphere and reduced light transmission to the Earth's surface. This would explain why the NGRIP ice core oxygen isotope profile shows a sudden cooling lasting about two years immediately after the 12,887 years b2k acidity spike (figure 8). Along with the light occlusion contributed by the smoke from global wildfires occurring during this time, both effects would have seriously impaired the survival of plant life.

The circumterrestrial dust cloud could be a region where cosmic spherules are naturally formed when the cosmic ray plasma of an impacting CME heats trapped cosmic dust particles to their melting point. The most likely region where they would form would be between one and four earth radii from the Earth's surface where the cloud's dense inner portion is intersected by the storm-time radiation belts that girdle the Earth.

Fullerenes, nanodiamonds, and helium-3, which are reported to be present in the YDB layer should also be expected to be present in the circumterrestrial dust sheath. Fullerenes and nanodiamonds have been found in carbonaceous chondrites and interplanetary dust particle aggregates (71) so their presence in the YDB layer also does not exclusively imply the occurrence of a comet impact. Also helium-3 is a common component of interplanetary dust particles, being implanted during their exposure in space to the solar wind. So if there was a sudden influx of cosmic dust at the time of CME impact, elevated levels of helium-3 would be expected in soil sediments, as is observed.

Climatic Considerations. It is here proposed that the YD cooling may have had a solar cosmic ray cause. A rise in the solar cosmic ray flux would have increased cloud formation either through ion-induced formation of condensation nuclei (72) or through the increased production of ice crystals resulting from an increase in the ionosphere-Earth electric current (73). This, in turn, would have increased planetary albedo producing a climatic cooling trend. Corroborating this, Svensmark and Friis-Christensen (74, 75) have found that between 1980 and 1995 changes in the background cosmic ray flux correlated positively with changes in cloud cover, a 25% increase in cosmic ray flux translating into a 3% increase in cloud cover over the course of a solar half-cycle. The resulting increase in planetary albedo would have a cooling effect comparable to a 0.6% decrease in solar irradiance (75). During the onset of the YD, an elevated flux of solar cosmic rays, rather than of galactic cosmic rays could have produced the required increased cloud cover. The reason to suspect solar cosmic rays as a cause is the above mentioned occurrence of ^{14}C spurts separated in time by multiples of the solar cycle period.

McManus et al. (76) chart changes in $^{231}Pa/^{230}Th$ ratio in a core from the Bermuda rise as an indicator of the rate of meridional overturning circulation (MOC) and find that there was a partial decrease in MOC at the time of the onset of the YD cooling dating around 13 kyrs b2k (Cariaco Basin varve chronology). However, there is a question as to whether there is in fact a causal connection between thermohaline circulation and climate. The Bermuda rise $^{231}Pa/^{230}Th$ record shows that MOC, which had been shut down through most of the Bölling interstadial, abruptly increased to modern levels around 14,200 cal yrs b2k. So, if there is an MOC-climate connection, why did the increase in MOC follow, rather than precede, the onset of the Bölling warming, and why were these two changes separated in time by half a millennium. Meltwater discharge from the ice sheets was at a maximum around 14,200 cal yrs b2k and far higher than the meltwater influx rate prevailing at the time of the Younger Dryas (77). So considering that thermohaline circulation increased at the time of the meltwater influx rate max, the suggestion that overturning rate would decrease in response to glacial meltwater influx occurring just before the onset of the YD appears inconsistent.

Conclusion. Spurts of ^{14}C production evident in the Cariaco Basin varve record spaced at 22-year solar cycle intervals likely record times of super-sized solar proton events, some of which may have been intense enough to overpower the magnetopause sheath and contact the Earth's atmosphere. It is shown that the largest of these radiocarbon spurts, which dates at 12,887±10 years b2k in the Cariaco Basin record, correlates with a prominent short-duration acidity spike in the Summit, Greenland ice core record. It also falls in the midst of nitrate and ammonium ion concentration maxima indicative of increased atmospheric ionization by solar cosmic rays. Ammonium ion is also an indicator of biomass combustion and the finding that its concentration rises in conjunction with oxylate and formate ion suggests that this ice stratum registers a period of global wildfires likely correlative with the formation of the YDB layer seen in North America and the Usselo Horizon in Europe. The 12,887 cal yrs b2k SPE is proposed to have been the cause of the final disappearance of the Pleistocene megafauna. Increased solar flare activity that prevailed during the Bölling/Alleröd may also have contributed to the disappearance of many mammalian species prior to the Rancholabrean termination date.

It is suggested that the cooling at the beginning of the Younger Dryas was induced by the elevated flux of solar cosmic rays that may have been present at this time and which may have increased the Earth's albedo through the formation of high altitude clouds. It is noted that the YDB layer does not coincide with the beginning of the YD cooling as some have previously suggested, but occurs much later when the YD cooling trend had already been in progress for over a century. Hence wild fires associated with the formation of this layer could not have been a contributing cause of the YD cooling. The evidence, then, rules out a comet impact event as the simultaneous cause of the YD cooling and YDB layer formation.

It is shown that many of the ET indicators found in the YDB layer could have already been in particulate form prior to entering the Earth's atmosphere and could have been deposited in connection with the proposed SPE. Future analysis of the extraterrestrial dust content of this key ice core stratum as well as correlative strata in the Cariaco Basin varve record should provide a further test of the solar/cosmic dust hypothesis.

Accurate identification and dating of the YDB layer event in the ice record and its possible solar cause was made possible by the availability of ice core data charting oxygen isotope values at 5 to 10 centimeter intervals, ammonium, and nitrate ion concentration at 10 centimeter intervals, and ECM values at millimeter intervals. This points to the importance of obtaining high resolution data in paleoclimatology studies, since SPEs may go unnoticed in coarser data averages. ^{10}Be measurements spanning the early YD currently consist of 1.6 meter (30-year) sample averages. It is possible that a more high resolution study of this portion of the Greenland ice core made at 3 cm intervals could reveal the presence of a ^{10}Be peak coinciding with the 12,887 years b2k acidity peak.

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