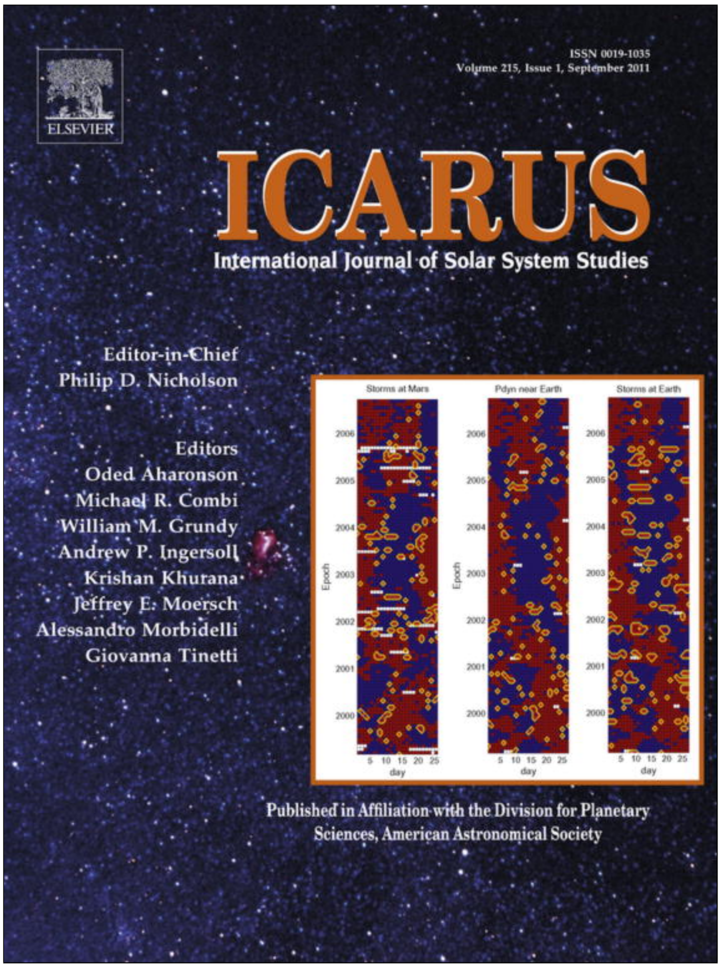

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Core-collapse supernovae and the Younger Dryas/terminal Rancholabrean extinctions

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ABSTRACT

Early predictions that some supernovae release large quantities of prompt high energy photons are now corroborated by optical identification of core-collapse supernovae associated with extragalactic GRBS (beamed γ-ray bursts) and XRFS (beamed or un-beamed X-ray flashes). Given the in-galaxy supernova frequency and GRB and XRF recurrence statistics, significant Earth-incident events during the past several million years very likely occurred and nearby events should have affected the Earth and other planetary atmospheres, including terrestrial surface solar UV, the Earth's climate, and its ecology. The Younger Dryas Stadial (~12,900 to 11,550 calendar yr BP) began with sharply cooler temperatures in the Earth's northern hemisphere, regional drought, paleoecological evidence compatible with increased UV, and abrupt increases in cosmogenic ^{14}C and ^{10}Be in ice and marine cores and tree rings. In North America, stratigraphic and faunal sequences indicate that a major pulse of mammalian extinctions (at least 23–31 genera) began very close to 12,830 calendar yr BP and was sudden: deposits one century younger are devoid of diverse extinct fauna remains. A 10 s beamed GRB within 2 kpc of the Earth delivers 100 kJ m^{-2} fluence to the Earth's atmosphere, where it causes spallation and catalytic reactions depleting 35–50% O^3, and producing excess NO$_x$ species (which favor cooling, drought, and surface fertility), ^{14}C, and ^{10}Be. An un-beamed, 10^{50} erg hard photon impulse at ~250 pc produces similar terrestrial atmospheric effects. A well-characterized massive star supernova, the unusually close Vela event ($d = 250 \pm 30$ pc; total energy of 1–2 × 10^{51} erg; age constrained from remnant nebula shock velocities considerations at 13,000–16,000 yr and from the pulsar characteristic age at ~11,400 yr) may have initiated the Younger Dryas climate change, and caused the extinction of the terminal Rancholabrean fauna.

1. Introduction

Early predictions (Clark et al., 1977; Klein and Chevalier, 1978) that some supernovae (SN) release large quantities of high energy photons are now corroborated by identification of massive-star core collapse supernovae associated with extragalactic GRBS (γ-ray bursts) and XRFS (X-ray flashes), with energies of 10^{49}–10^{52} erg. XRF-generating SN are more frequent than GRBs, may be emitted isotropically instead of as jets (Pian et al., 2006), and their remnants include pulsars. Given this observational information for distant galaxies, and observed in-galaxy SN rates, a series of such exogenic radiation events during the Earth's Quaternary Period (2.6 Ma to present) very likely did occur. Burst- or flash-emitting SN may have affected the Earth's atmosphere and ozone layer, its surface-incident solar UV, and its climate. The magnitudes of such perturbations depend on the intrinsic size of the event, the spatial orientation of any associated jet, and SN proximity to Earth (Gehrels et al., 2003). Other potentially important radiation sources, such as magnetars, short duration γ-ray bursts, and soft γ-ray repeaters (SGRs) have been observed to cause major transient changes in the Earth's ionosphere, even when the source object is 14 kpc distant (Inan et al., 2007). This emphasizes the potential effects of very-much closer SN hard photon bursts on the Earth and other planetary bodies.

The terrestrial Younger Dryas Stadial (~12,900 to ~11,550 calendar yr BP) began, at many locations, with sharply cooler temperatures, regional drought (Dorale et al., 2010; Haynes, 1991, 2008), paleoecological evidence compatible with increased UV, and abrupt increases in cosmogenic ^{14}C and ^{10}Be in ice and marine cores and tree rings (Hughen et al., 1998, 1996, 2000). Geological data at some locations suggest soil and inland water fertilization commencing at this time (Brakenridge, 1981): as expected in the case of increased atmospheric N$_2$ fixation and NO$_x$ rain-out resulting from upper atmosphere reactions and O$_3$ destruction. Also, in central North America, intensively dated late Quaternary stratigraphic and faunal sequences indicate that a major pulse of mammalian extinctions began at ~12,700 calendar yr BP and was sudden: deposits one century younger are devoid of extinct fauna remains (Haynes, 1991). In North America, the widely-documented Clovis hunting culture, flourishing at the start of the Younger Dryas

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throughout the continent, had vanished by its close, and probably as a result of changed lifeways due to the major losses of hunted fauna. This change in the archaeological record adds to the complexity of environmental change within a relatively compressed time interval. The dramatic and relatively sudden changes are congruent with possible exogenic perturbations, such as cometary impact (Firestone et al., 2007) or a near-by supernova (Brakenridge, 1981).

Exogenetic causation for terrestrial environmental changes requires a high standard of proof: there are abundant Earth system-internal causal mechanisms that can be invoked, and perhaps none of the changes to be discussed requires, by itself, causes external to the Earth. However, neither should possible exogenetic causes be left without careful scrutiny, especially when their potential efficacy has been verified by theory and modeling and an actual candidate event has been identified. It is not parsimonious or appropriate to consider a variety of system-internal cause and effect mechanisms for Younger Dryas changes, and not a system-external perturbation, when such very likely did occur.

The focus of this paper is not on the issue of biological extinctions in general, nor are all potential system-external perturbations (such as meteorite or asteroid impact, solar flares, other sources of high energy γ or X radiation) considered. Instead, this paper presents further evidence indicating that: (a) a particular well-characterized, high energy, late Quaternary SN (Vela) occurred exceptionally close to the Earth ($d = 250 \pm 30$ pc), (b) its output radiation may have been sufficiently large to affect the Earth, and (c) the high energy photons predicted for this event may have been received at the time of Younger Dryas climate changes, radioisotope anomalies, and biological extinctions. Based on current knowledge of hard photons energies from such SN, and known atmospheric effects of such radiation, the coincidence in time supports a specific causal relationship. The Vela event may have initiated the Younger Dryas, as well as the large mammal extinctions that are associated with this time interval.

2. The Rancholabrean extinctions and the Younger Dryas

No wide scientific consensus yet exists for the causation of extinction of the Rancholabrean (terminal Pleistocene) large mammal "megafauna". Neither climate change nor human predation (Martin, 1973, 2005) alone explain all of the evidence, although some combination of the two might suffice (Barnosky et al., 2004). At some locations, the evidence for locally sudden extinction of a suite of fauna is convincing. For example, at several intensively studied palaeontological sites in North America, the extinction of *Mammuthus columbi, Canis dirus, Equu*s, and *Camelops* is tightly constrained via radiocarbon dating to between 11,300 and 10,900 ^{14}C yr BP (years before A.D. 1950), or 13,230–12,830 calendar yr BP (Fairbanks et al., 2005). Similar dates apply also to many other North American late Pleistocene/early Holocene stratigraphic and faunal sequences (Haynes, 1991). At such time, climate change and human predation were both occurring. For example, at the Murray Springs and Lehner Ranch (Arizona) Paleoindian archaeological sites, hunting of the fauna is clearly demonstrated (Haynes, 1991). However, at these sites and beginning shortly before 10,900 ^{14}C yr BP, the local desert marsh and fluvial ("cienega") sedimentary records indicate geologically brief but severe drought conditions and lowered water tables. This drought had ended by 10,800 ^{14}C yr BP or 12,740 calendar yr BP. At that time, a thin ($\sim$30 cm) layer of organic rich "black mat" clays related to unusually abundant diatomaceous algal growth, ponded conditions, and a rising water table were deposited over both the faunal remains and the artifacts of Paleoindian hunting. Faunal extinction, human predation, and climate change at these sites all occurred at the same time and within a narrow time window (at Murray Springs, between 10,900 and 10,800 ^{14}C yr BP; (Haynes, 1991).

Changing atmospheric ^{14}C concentration affects the calibration of ^{14}C years to calendar years (during times of elevated ^{14}C, a ^{14}C year is longer). In order to discuss extinction dates consistently, this article uses the calibration provided by Fairbanks (Fairbanks et al., 2005) wherever the source information is radiocarbon, and because of the improved temporal control between 10,650 and 12,000 ^{14}C yr provided by that calibration. Several factors affect the accuracy of such calibration: tree-ring, coral, and sediment core techniques have all been used to accomplish calibration, and ^{14}C diffuses at somewhat different rates into the terrestrial and marine ecosystems. Changing radiocarbon concentrations (Bjoerck et al., 1996; Kromer and Becker, 1992) at the time of extinction are known to complicate interpretation of the actual chronology. In this case, however, the chronology of changing ^{14}C activity in the atmosphere is also of direct interest as a possible record of atmospheric perturbation.

The Younger Dryas Stadial is a well-documented, relatively brief (<1500 yr) interval of sharply cooler climate at many locations world-wide (Berger, 1990). It occurred after continental deglaciation was already underway (conditions nearly as warm as today were already established over much of the world by $\sim$13,700 ^{14}C yr BP). Commencing at very close to 12,900 calendar yr BP, the Younger Dryas was the latest in a complex series of Quaternary climate changes that accompanied the waxing and waning of the continental glaciers over several hundreds of thousands of year (Alley, 2000; Berger, 1990; Goslar et al., 1995, 2000). It is clear that the Rancholabrean fauna survived many prior changes in climate and terrestrial environments. Younger Dryas or other terminal Pleistocene climate changes as the solitary cause for extinction of these species is difficult to reconcile with this long term record, although the temporal proximity of extinction to climate change still suggests some causal connection. Similarly, in the western hemisphere, an experienced hunting culture (the Paleoindian, including Clovis, people) spread rapidly during this time period and these humans could have had a major impact on animal populations not previously exposed to humans (Barnosky et al., 2004; Martin, 1973, 2005). However, species not expected to be affected by human predation also became extinct in North America, and some large mammal species became extinct in Europe, Asia, and even in Africa: where they had long co-existed with humans (Barnosky et al., 2004).

The timing of, global geography of, and species affected by the terminal ice age extinctions in general is complex in detail, and not all extinctions may have occurred at the same time. Several large mammal species that became extinct in North America survived Younger Dryas time outside North America. Other species became extinct somewhat earlier. In some cases, the timing is not tightly constrained. World-wide, at least 97 genera of megafauna (animals >44 kg) became extinct sometime between 50,000 and 10,000 yr ago (Barnosky et al., 2004); the exact timing for many is not known. For the global event, on land, large animals, with low reproductive rates, were preferentially affected. Nearly all of the low birth-rate survivors of the Younger Dryas in Australia, Eurasia, the Americas, and Madagascar are nocturnal, arboreal, alpine, or deep-forest dwellers. The largest, open-country, diurnal, slow-breeding animals survived past this time only in low-latitude areas of Africa (Barnosky et al., 2004).

In this regard, in South Africa and in southern Cape Province, *Equus capensis*, *P. antiquus* (giant buffalo), *Megalotragus priscus* (giant hartebeest), and at least five other large land mammals (Klein, 1974; Martin and Klein, 1984) persisted to $\sim$12,000–10,000 ^{14}C yr BP (Peters et al., 1994). In northern Europe, Siberia, and Alaska, an early pulse of extinction of warm-adapted animals apparently occurred from 45,000 to 20,000 ^{14}C yr ago, during the ice age, but the major global extinction of cold-adapted animals occurred sometime between 12,000 and 9000 ^{14}C yr BP (Barnosky et al., 2004). In Australia and adjacent regions, late Quaternary megafauna extinctions may have occurred much earlier, with most genera lasting only to between 51,000 and 40,000 yr BP and approximately coincident to the arrival of humans (Barnosky et al., 2004). There were few large animal species available for extinction afterwards. However, see possible persistence of large kangaroos *Protemnodon nombe* and *tumbuna* at archaeological sites in this area of the Pacific to 13,000–11,500 yr BP (Flannery et al., 1983; Goede and Bada, 1985; Johnson, 2005). In South America, the major pulse of extinction was possibly coincident with the beginning of the Younger Dryas, but the timing is poorly constrained (Barnosky et al., 2004). Finally, as noted, in North America, the main pulse of extinctions is well-constrained and occurred very close to 11,000 ^{14}C yr, or 12,930 calendar yr BP. There, at least 23 and probably 31 genera became extinct suddenly as the Younger Dryas began (Barnosky et al., 2004; Faith and Surovell, 2009; Haynes, 1991). This extinction formally marks the end of the Rancholabrean Stage in North American stratigraphy, and it is, within the limit of dating precision, coeval to the initiation of the Younger Dryas climate change as recorded at numerous sites.

3. Cosmogenic isotopic changes during the Younger Dryas

The Younger Dryas was initially documented in northern European pollen cores. Throughout northern and central Europe, the postglacial lake and bog core pollen record indicates that, not long after the initial retreat of the continental and alpine ice sheets, sharply cooler and dryer conditions briefly returned: as indicated in part by a resurgence of abundant pollen from an alpine, high UV-adapted sedge, (*dryas* sp.). Some workers now believe this colder and dryer episode to have been global in extent, but, as a cooling event, it appears to have most strongly affected the higher northern latitudes and Europe, possibly due to the melting but still-existing continental ice cover and associated oceanic circulation changes (Alley, 2000; Berger, 1990; Moreno et al., 2001). As examples of responses far outside the temperate and high northern latitudes, however, pollen cores from Chile record a ~3 °C drop in temperature at ~11,400 ^{14}C yr BP (~13,320 calendar yr BP) at latitude 41°S, and geochemical assays of marine core terrestrial plant waxes at latitude 10.5° show a temporary change from wet montane forests to dry grasslands commencing at 12,800–13,000 calendar yr BP.

The initiation of the Younger Dryas occured after 11,480 ^{14}C yr BP and before 10,230 ^{14}C yr BP (corrected for the marine reservoir effect caused by mixing of deep and shallow water by subtracting 420 yr) in one intensively studied marine core from offshore Venezuela (Hughen et al., 2004a, 1996, 2000). Using the Fairbanks calibration, the corresponding initiation dates are sometime between 13,390 and 11,970 calendar yr BP; using an independent calibration developed for that core, the applicable initiation date is 12,980 calendar yr BP (Fig. 1).

Counting of yearly laminations from this core and multiple ^{14}C assays allowed correlation of ^{14}C variability to the early Holocene tree ring record of ^{14}C through wiggle matching (Friedrich et al., 2004; Hughen et al., 2004b) and thus to the calendar year record. The results confirm prior studies indicating that global atmospheric ^{14}C rose very rapidly to an unusually high concentration at the beginning of the Younger Dryas cold episode and synchronously with the onset of cooling (Hughen et al., 2000), and then began declining soon after. This rise has been replicated elsewhere (Litt et al., 2001) but its causation remains uncertain.

The ^{14}C increase may also have been accompanied by a sharp increase in another cosmogenic isotope: ^{10}Be (Fig. 2), as measured in ice cores (Finkel and Nishiizumi, 1997a). This is expected if the measured ^{14}C changes reflect cosmogenic production rates as well as terrestrial carbon cycle changes. Long-standing controversy concerning what part of the Younger Dryas ^{14}C increase was due to atmospheric production and what part due to carbon cycle changes caused by climate has still not been resolved: in part because ^{10}Be in ice cores is strongly affected also by snow deposition rates (Finkel and Nishiizumi, 1997a; Morris, 1991). For example, at the close of the Younger Dryas cooling, at approximately 11,600 calendar yr BP, Greenland ice cap snow accumulation rates at the GISP2 core site (Fig. 2) increased sharply, and this may be responsible for some of the ice core ^{10}Be decline shown in Fig. 2 at this time (Finkel and Nishiizumi, 1997a). However, the data shown in Figs. 1 and 2, and related information from independent ^{14}C assays of materials from this time period (Finkel and Nishiizumi, 1997a; Friedrich et al., 1999; Goslar et al., 1995, 2000, 2004a; Hughen et al., 1996, 2000; Spurk et al., 1998) are clearly compatible with a cosmogenic cause for Younger Dryas radioisotope changes. Recent isotopic studies comparing both isotopes, as well as modeling, also continue to indicate that an important component of the initial increase in both ^{14}C and ^{10}Be was indeed actual strong production increases in the atmosphere (Marchal et al., 2001; Muscheler et al., 2008; Renssen et al., 2000). In one case, the estimated cosmogenic ^{10}Be increase is, in fact, used to model the expected ^{14}C increase, in

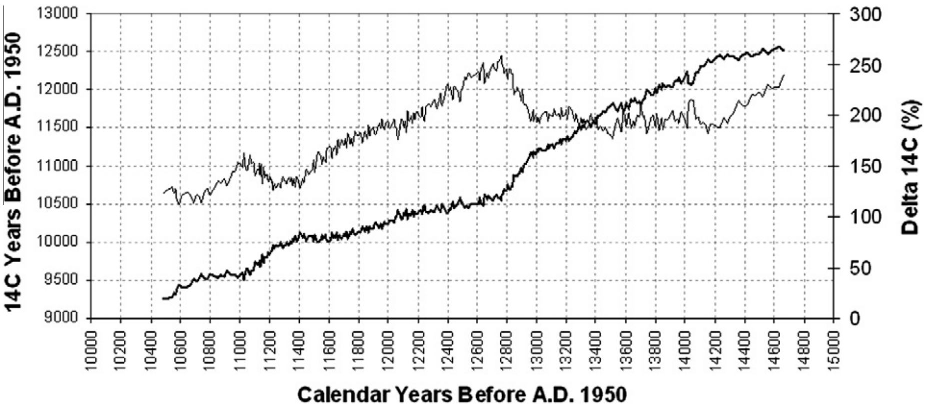

Fig. 1. Cariaco Basin marine core PL07-58PC radiocarbon dates plotted against the annual lamination-derived calendar year scale (thick solid line, left axis scale). Also, undetrended permil change in delta ^{14}C (departure of ^{14}C from A.D. 1950 level); thin solid line. Data from (Hughen et al., 2000); also available from the NOAA Satellite and Information Service, National Climatic Data Center, http://www.ncdc.noaa.gov/paleo/. On independent geochemical grounds (e.g. O isotopes), the Younger Dryas cold stadial and the increase in ^{14}C occurred synchronously as recorded by this core (Hughen et al., 2000).

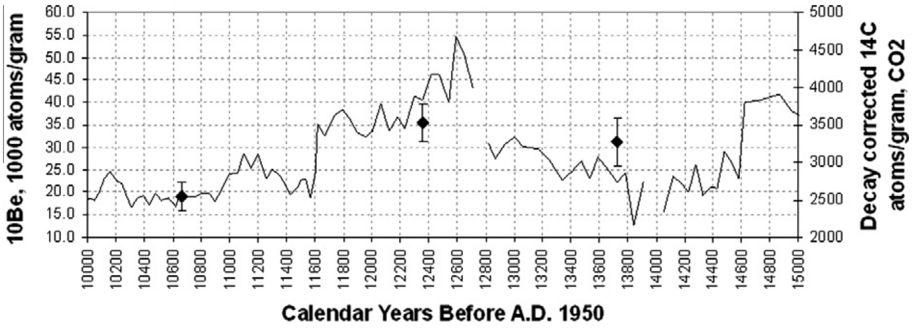

Fig. 2. GISP2 ice core ^{10}Be in-ice concentration (solid line) and ^{14}C gas bubble concentration (black symbols) plotted against the Meese–Sowers time scale for this core. ^{10}Be data from Finkel and Nishiizumi (1997b) and ^{14}C, corrected for decay, data from Lal et al. (1997); both also available from the NOAA Satellite and Information Service, National Climatic Data Center, http://www.ncdc.noaa.gov/paleo/. Data are not corrected for snow deposition rate.

order to evaluate the role of reduced deep ocean ventilation on atmospheric ^{14}C concentration at the beginning of the Younger Dryas (Muscheler et al., 2008).

Coincidence of the initiation of Younger Dryas climate change to a significant and temporary elevation of atmospheric ^{14}C has elicited several explanatory hypotheses. Either: (1) climate change and resulting carbon cycle changes are responsible for most of the increased ^{14}C (Hughen et al., 2000), or (2) a secular cause produced more ^{14}C and may itself have been a forcing function affecting the Earth's climate (Renssen et al., 2000). This second possibility has been controversial because of the apparent size of the anomaly: such a large increase was originally considered to be beyond the range of short term variations observed in Holocene/Postglacial time through tree ring dating, and commonly explained as a result of variation in the solar cosmic ray flux as modulated by the Earth's magnetic field (Goslar et al., 2000). However, the solar flux is not the only potential control. Recently, satellite-based gamma ray observations conjoined to ground-based optical telescopy has in fact established: (a) the extra-galactic locations of observed GRBs and XRFs, and thus their very high intrinsic energies, (b) the genesis of many of these events though massive star supernovae (which occur in our own galaxy as well), and (c) the very high intrinsic energies of the bursts or flashes. These findings now require that potential exogenic causation for terrestrial cosmogenic isotope anomalies and other environmental changes be further considered.

4. Terrestrial effects of a supernova hard photon burst or flash

Supernovae-related hard photon radiation was previously suggested for the Younger Dryas changes (Brakenridge, 1981), but without the availability of confirming evidence that such radiation events actually occur (although some theoretical SN models had indicated such possibility). Now it is clear that such flashes are a normal component of Solar System radiation history. Depending on their intensities, they would have directly affected the surface of planetary bodies that are unprotected by relatively dense atmospheres, and also effected temporary alterations of any dense atmospheres. In particular, observations of extragalactic GRBs and XRFs, and detailed description of their light curves, distances, and spectra (Campana and others, 2006; Pian et al., 2006; Scalo and Wheeler 2002; Thomas et al., 2005), can now be compared to the nebular records of in-galaxy supernovae (Green, 2004) in order to constrain the Earth's late Quaternary history of such events.

"Significant" events are here defined as those capable of producing environmental changes now measurable in various kinds of terrestrial paleoenvironmental records. In this regard, during the late 20th century, (Ruderman, 1974), and others used theory and modeling of putative SN photon radiation flashes (Colgate, 1975; Klein and Chevalier, 1978) and relatively simple atmospheric photochemistry calculations, to examine the possible terrestrial atmosphere effects of high energy photons from very nearby (10 pc) events. As summarized (Brakenridge, 1981), the expected effects include: "severe depletion (estimates range from 35% to 80%) of the ozone layer, greatly increased UV but decreased visible light at the Earth's surface, a small but significant global cooling (estimates ranged from 0.4 to 3 K), and a much-increased transfer of stratospheric nitrogen into the troposphere and fixed nitrogen onto the Earth's surface" (Clark et al., 1977; Hunt, 1978; Reid et al., 1978; Whitten et al., 1976). Some of these studies were accomplished without the assistance of contemporary computer-assisted atmospheric modeling techniques, and prior to the recent observations of prompt γ-ray and X-ray emissions associated with extragalactic SN (Pian et al., 2006; Soderberg et al., 2006). The uncertainty in the intrinsic size of any such events was also major: 10^{47} to 10^{50} erg for total explosion energies.

Since then, more detailed modeling uses the observed detailed light curve and spectra of post-detonation SN 1987A (unusual blue supergiant precursor) γ-rays between 0.02 MeV and 2 MeV (1.8×10^{47} ergs, 500 days duration), as predicted for a hypothetical SN at 8 pc distance (Gehrels et al., 2003). Other modeling efforts input a "typical" GRB emission: between 0.001 and 10 MeV; 5×10^{52} erg, 10 s duration; the Band spectral results are used (Thomas et al., 2005). Together, these results provide important new findings relevant to SN radiation event frequency, size, and terrestrial effects for the Earth's late Quaternary, as follows:

(1) Regarding near-Earth *frequency*: supernovae remnant nebulae (SNRs) are strong radio emitters and nearly complete radio surveys ($n = 265$ as of 2006) of those within our own galaxy have been accomplished (Green, 2004). After ~30,000 yr, SNRs expand to become indistinguishable from the interstellar medium (Clark et al., 1977). Thus, SNs occur at rates of approximately once per century in the Milky Way. The nearest SN within that time whose age and distance are well-constrained is Vela XYZ (G263.9–3.3) (Green, 2004), at 13,000–16,000 calendar yr BP as experienced by Earth, and at an unusually close distance of only 250 ± 30 pc (Cha et al., 1999). However, only a subset of SNs may emit very high energy photon bursts or flashes.

(2) Regarding near-Earth radiation event *magnitudes*: In-progress GRBs have so far been observed only in other galaxies. Optical telescopy has established an association of long-duration (10 s) GRBs observed via satellite sensors with supermassive (~30 solar masses) star core collapse supernovae that are ~30 times brighter than typical Type Ic SN (Pian et al., 2006). Based on long-GRB observational statistics, a

current estimate for frequency within the Earth's neighborhood (<2 kpc) and as actually incident on the Solar System and the Earth is only once per 10^9 yr.

Many GRB emissions may be as collimated jets, so that similar galactic SNs may occur without Earth-incident GRBs; the frequency estimate above is already corrected downward by .01 to account for this. The actual all-Milky Way GRB-producing SN are thus predicted to be 100 times more frequent (once per 10^7 yr) but still a tiny subset of all galactic SN. However, optical SN 2006j (Pian et al., 2006) was accompanied by a large, prompt X-ray flash (cataloged as XRF 060218); it was about half as luminous as the GRB optical SNs observed to date; its precursor mass was only ~20 solar masses, and its total energy was much less than GRB events but much greater than many SN (it was 10^{49} erg). The Milky Way rate of this class of hard photon-producing SN may be 100 times higher than those which produce GRBs: once per 10^5 yr (Pian et al., 2006; Soderberg et al., 2006).

XRF 060218 was not, apparently, radiated as collimated jets but instead was relatively isotropic (Pian et al., 2006). A rate of once per 10^5 yr for such events as experienced by Earth is thus reasonable and as based on present observational data. A continuum is now emerging (Pian et al., 2006) and carries with it implications for Earth history: (a) the most massive precursor stars produce unusually bright optical SN (five times more luminous than typical Type Ic SN), 10^{52} erg explosion energies, collapse to black holes, and may have occurred within the Earth's general neighborhood only several times in Earth's 4+ Ga history, as seen from Earth, because of jetted emission; (b) smaller massive stars produce SN 2–3 times brighter than typical Type Ic SN, 10^{49} erg explosion energies, collapse to spinning neutron stars (pulsars), and occur much more frequently (26 times within the Quaternary), and (c) the "standard" SN are less energetic but occur with a combined frequency (both Type I and II events, entire galaxy) of once per century· and much less frequently within 2 kpc.

(3) Regarding terrestrial effects: using the inverse square relation, an un-beamed, 10^{50} erg hard photon impulse at ~250 pc should produce roughly similar terrestrial atmospheric effects as a 10^{47} erg event at 8 pc. Such effects are estimated, via the Goddard 2-D atmospheric model, to include a 47% ozone reduction and approximate doubling of biologically active UV-B reaching the ground, as a global average (Gehrels et al., 2003). Somewhat similar results are modeled for a 2×10^{51}, beamed 2 kpc-distant GRB intersecting the Earth: 35% ozone depletion, reaching 55% at some latitudes and persisting for over 5 yr after the burst, a 300% increase in UVB (280–315 nm); largest percentage increase in temperate and higher latitudes, a cooling of the Earth's climate due to stratospheric solar absorption from the NO_x produced, and large amounts of rainout of NO_x species (Thomas et al., 2005) that would promote temporary algal blooms and other changes potentially measurable in the sedimentary record.

These predicted immediate effects are the outcome of established physics and photochemical and atmospheric modeling, coupled to the observational data concerning SN for other galaxies similar to our own. Less certain are the ultimate effects of such perturbations on the Earth's atmosphere, as the induced changes are propagated though already varying, complex, and interconnected oceanic, terrestrial, atmospheric, and biological systems. Hard photon radiation flashes from relatively energetic and nearby SN are an exceptionally transient perturbation: potentially severe in their immediate effects, but subject to rapid attenuation as diffusion of the energy occurs. As indicated also by the modeling, terrestrial records may be expected to record such causality by exhibiting unusually sudden onset: instantaneous, in most geological time frames of reference.

For example, consider the abrupt decrease in CH_4 gas and increase in NH_4 recorded with the initiation of the YD in the ice core record (Carlson, 2010; Grootes et al., 1993; Mayewski et al., 1997; Smith et al., 2010). Are these changes most simply explained by various Earth system-internal processes, or are they causally related to the Vela hard photon flash, which is known to have occurred? Not all proxy paleoenvironmental records have sufficient temporal resolution to provide unequivocal tests of sudden onset: sedimentary bioturbation and other mixing commonly limit such resolution in terrestrial and marine records, and ice cores also experience decreased sample-to-sample temporal resolution back several thousands of years in time. However, there is the possibility to use annual records such as tree rings (from collections of subfossil wood), varved lake deposits, or speleothems bracketing Younger Dryas time, in order to examine the detailed changes of cosmogenic isotopes, N fluxes, climate, and other effects that are predicted for the Vela event. The hypothesis here presented is testable through such means. It implies, as well, the probable occurrence of other significant SN radiation events during the length of the Quaternary and the need to further consider such causation in understanding other extinction events.

5. Summary and conclusion

Satellite detector and ground telescope-based observations and measurements of extra-galactic GRBs and XRFs pose implications for in-galaxy events that may have affected the Earth as they occur over geological time scales. Galactic GRB/XRF radiation events occur with sufficient frequency to have perturbed the terrestrial atmosphere even during late Quaternary time, and, depending on both distance and intrinsic magnitude, should have produced a range of severe but transient atmospheric effects, including varying amounts of cooling, other climate changes, significant ground-level UV-B increases for mid- and high-latitudes, and elevated atmospheric ^{14}C and ^{10}Be. Such changes should have a characteristic paleoenvironmental signature, as the energy is delivered over only seconds of time and the related spallation and catalytic chemical reactions and subsequent diffusion of reaction products require only days to some weeks.

Other planetary atmospheres, hydrospheres, and cryospheres (e.g. on the Moon and Mars) would also have been affected by these transient inputs of high energy photons (Scalo and Wheeler, 2002). For unshielded bodies such as the Moon, SN radiation events intersect one hemisphere of the surface lithology, and may cause radioisotope generation as well as surface melting (thin-skinned vitrification) of exposed lithologies or soil particles.

For the past 30,000 yr, there is the opportunity to study the preserved records of possible long duration (SN-related) GRB/XRF events in our galaxy via their remnant nebulae, and examine the case for terrestrial responses (Brakenridge, 1981). Distances to most such nebulae are measured in kpc; but one occurred quite close to the Earth: the Vela XYZ SN, at 250 pc ± 30 pc, and dated to sometime between ~13,000 and 16,000 yr BP (based on remnant nebular shock velocity considerations; (Wallerstein and Silk, 1971) or at ~11,000 yr BP, as dated by the associated pulsar characteristic age (Cha et al., 1999). The terrestrial environmental and geochemical changes predicted for this event if it was a strong hard photon emitter are significant and they appear to be observed in many terrestrial records.

The rapidly expanding knowledge of XRF and GRB radiation cross sections, frequencies, magnitudes, and associated optical counterparts will allow this hypothesis to be further evaluated using observational data. The calculated explosion energy of Vela ($1–2 \times 10^{51}$) erg (Cha et al., 1999), based on study of the SNR, agrees with a very energetic explosion. The presence of an associated pulsar (PSR 0833-45) created by the same SN (Aschenbach et al., 1995), also supports: a supermassive star precursor, relatively large amounts of prompt γ-ray and X-ray emission, and an isotropic character for such emission. Because of its proximity, if Vela produced even 10^{49} erg of non-beamed high energy photons, then significant terrestrial atmospheric effects should have occurred. Such effects do appear to be recorded at the onset of the Younger Dryas Stadial. Vela may also have caused extinctions of large, mostly diurnal, open-dwelling mammals at this time, across much of the temperate and higher latitudes, and it may have exerted a significant impact on the lifeways of the Paleoindian/Clovis hunters, whose well-dated lithic and other material remains dominate New World archeological records just prior to Younger Dryas time (Haynes, 2008; Waters and Stafford, 2007) and disappear shortly thereafter.

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