COMET ENCOUNTERS AND CARBON 14

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ABSTRACT

The ^{14}C production of shock-accelerated particles is calculated in terms of the total energy released in energetic particles. The recently reported 1.2% jump in the ^{14}C content of the atmosphere in the year C.E. 775, it is found, would require $\gtrsim 10^{34}$ erg in energetic particles, less than first estimates but far more than any known solar flare on record. It is noted that the superflare from a large comet (comparable to C/Hale–Bopp) colliding with the sun could produce shock-accelerated GeV cosmic rays in the solar corona and/or solar wind, and possibly account for the C.E. 775 event. Several additional predictions of cometary encounters with the sun and other stars may be observable in the future.

Key words: acceleration of particles – comets: general – Sun: flares

Online-only material: color figure

1. INTRODUCTION

Comets, asteroids, and giant solar flares each pose dangers. If a comet, its coma, or tail were to sufficiently rattle the Earth's magnetosphere, the electromagnetic disturbance so induced could threaten modern civilization, which depends on functioning microelectronics. A sufficiently large sun-grazing comet (or asteroid) $R \gtrsim 10^7$ cm would contain over 10^{36} erg, more than two orders of magnitude more kinetic energy near the sun than a reasonable estimate for the energy in the Carrington solar flare of 1859 (which damaged early telegraph lines), and its energy release near the sun's surface could traumatize the Earth with UV exposure and electromagnetic disturbance. A mid-size to large comet ($R \gtrsim 3$ km) impacting Earth could deposit $\gtrsim 10^{30}$ erg into the ocean, enough to supersaturate the Earth's atmosphere with water vapor, leading to something resembling legendary floods, and could dramatically heat at least parts of the atmosphere.

Sun-grazing comets are a fact of life (e.g., Schrijver et al. 2012; Sekanina & Chodas 2012). The possibility clearly exists that some of them could be, at some stage, quite large ($M \gg 10^{19}$ g) and collide with the sun, causing an explosive release of more than 10^{34} erg in energy (Brown et al. 2011). The lack of any known, reliable record of a major cataclysm associated with such past events could be interpreted—depending on the size and kinetic energy of the comet—as evidence that they were less conspicuous to a pre-electronic civilization than one might suppose, or that superstitions interpreting comets as bad omens had some historical basis. In any case, they could be far more disruptive to post-twentieth century civilization, and their event rate, even if small, is worthy of study.

Here we consider whether (1) a giant solar flare or (2) the close approach of a large comet to the sun could have occurred in the year 775, when the levels of ^{14}C rose by 1.2% within a year or so (Miyake et al. 2012). This rise would require 10 years worth of normal cosmic ray exposure within one year. While it could have been due to an extremely large but otherwise normal solar flare, its statistical deviation from other ^{14}C rises on record motivates us to consider whether a different type of event from normal solar flares could produce the ^{14}C enhancement. If it was indeed due to a giant comet closely encountering the sun, it would be evidence that such an event is survivable, and quantitative estimates of the energy it released are desirable. By the same token, it is worth considering whether a less close approach could have produced the enhancement by tapping the energy in the solar wind to produce a temporary rise in energetic particles.

2. PARTICLE ACCELERATION AND ^{14}C PRODUCTION

The energetic particle spectrum $F(p)d \ln p$ at momentum p for shock-accelerated ions at the shock is given as

$$
\begin{aligned}
F(p) \propto \exp \int_{\min}^{p} \frac{3}{2(r^{-1}-1)} \\
\times \left[\left(-1 + \left[1 + \frac{2\pi^2 D_\parallel(p') D_\perp(p')}{R_s^2 u_s^2} \right]^{1/2} \right) \right. \\
\left. + \left(r^{-1} + \left[r^{-2} + \frac{2\pi^2 D_\parallel(p') D_\perp(p')}{R_s^2 u_s^2} \right]^{1/2} \right) \right] d \ln p \quad (1)
\end{aligned}
$$

(Eichler 1981a).

Here, r is the compression ratio of the shock, $[D_\parallel D_\perp]^{1/2} = pvc/2^{1/2}\pi\eta ZeB$ is the geometric mean of the parallel and perpendicular diffusion coefficients of ions of momentum p, velocity v, and charge Ze in the magnetic field B, R_s is the radius of the shock, and u_s is its velocity relative to the pre-shock fluid. The spectrum cuts off exponentially at energy $E \geqslant E_o \equiv \eta ZeBR_s u_s/c$, where the dimensionless coefficient η is about $1/3$, based on observations of the energetic particles at Earth's bow shock (Ellison & Mobius 1987; Chang et al. 2001) at which $R_s \simeq 6 \times 10^9$ cm and $E_o \simeq 36Z$ KeV. For $pv \ll E_o$, the integral spectral index s is -1 for a strong shock of compression ratio 4 in the test particle approximation.

The spectrum of *escaping* particles, in the approximation of steady state, is proportional to their rate of production at the shock, which is proportional to $u_s(1 - 1/r)(dF/d \ln p)/3$. This expression includes particle escape by both convection and diffusion to a free streaming boundary. We assume that the particles mostly responsible for the ^{14}C, i.e., the most energetic, freely stream from a sunward acceleration site toward Earth and precipitate onto its polar caps. Particles trapped in the expanding flow are those at low energy, and their adiabatic losses can be recycled into the acceleration of the expanding blast wave.
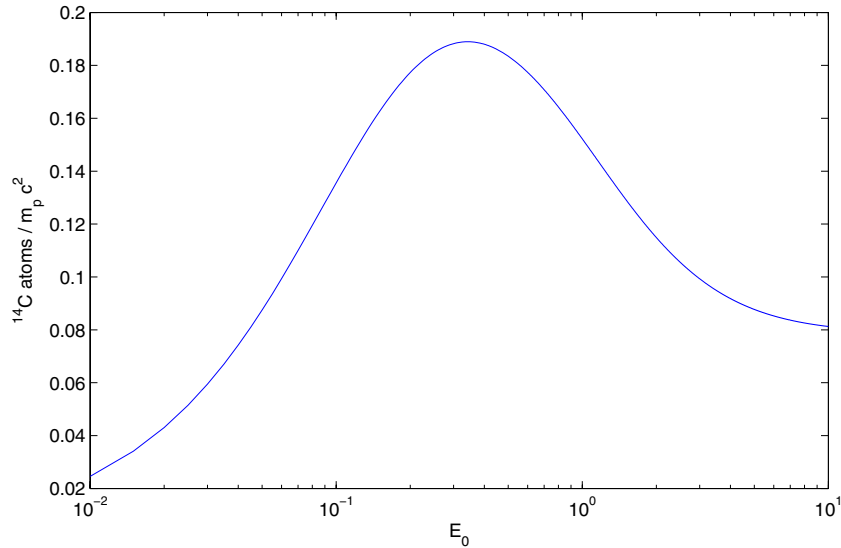
Figure 1. Total ^{14}C yield per total kinetic energy as a function of the spectral cutoff parameter E_0.
(A color version of this figure is available in the online journal.)

The ^{14}C production rate per unit particle energy $\int E(dF/d\ln p)\,d\ln p$ in Earth's atmosphere is independent of the normalization of F and is given by

$$Q = \int \frac{Y(E)}{\pi}\frac{\Omega(E)}{2\pi}\frac{dF(p)}{d\ln p}d\ln p \Big/ \int E\frac{dF}{d\ln p}d\ln p, \quad (2)$$

where E is the kinetic energy, hereafter expressed in units of $m_p c^2$, $Y(E)/\pi$, the neutron yield per primary cosmic ray of energy E, can be approximated as $4E^{2.35}/(E^2+E^{0.35})$ (Kovaltsov et al. 2012), $\Omega(E)/(2\pi) \simeq 0.13 E^{1/4}$ is the solid angle of the magnetic polar cap whose geomagnetic cutoff is E. (Here we have assumed that the angular distribution of the energetic particles is energy independent.) Using Equations (1) and (2), we numerically calculate the total ^{14}C yield per unit energy as a function of the parameter E_o. For reference, note that the most energy-efficient ion energy for making ^{14}C is at the maximum of $\Omega(E)Y(E)/E$, and that the yield is ~ 0.3 ^{14}C atoms per $m_p c^2$ of kinetic energy. The results for an actual shock-accelerated spectrum over a wide range of E_o are plotted in Figure 1, showing that over a wide range of E_o, the ^{14}C production efficiency ϵ is within a factor of several of the maximum.

An episode in which 6×10^8 ^{14}C atoms cm^{-2} are produced at Earth then requires a (kinetic) energy fluence at Earth of $\sim 6\epsilon^{-1} \times 10^8$ $m_p c^2$ cm^{-2}. A giant particle acceleration event near the sun that spewed out energetic particles over a solid angle of $\sim 2\pi$ would thus have needed to produce $8.4 \times 10^{35}\epsilon^{-1} m_p c^2 \simeq 1.3 \times 10^{33}\epsilon^{-1}$ erg in energetic particles. The total energy of the event, of course, could be more, though several observations in the heliosphere (e.g., Eichler 1981b; Ellison & Mobius 1987; Decker et al. 2008) support the theoretical assertion (Eichler 1979, 1985; Ellison & Eichler 1985) that energetic particles can contain a significant fraction of the total energy in a collisionless blast. The value of the cutoff energy $E_o = eBRu_s/3c$ obtained by using solar parameters—$B \gtrsim 0.3$ G, $R \sim 6 \times 10^{10}$ cm, $u_s/c \gtrsim 10^{-3}$—is comfortably above 1 GeV, so, even if the lateral extent of the shock is somewhat less than the above value of R, we may reasonably assume a value of ϵ in the range 0.1 to 0.2. A superflare yielding $\sim 10^{34}$ erg in energetic particles could thus account for the ^{14}C enhancement of 775. For $E_o \gtrsim 0.3 m_p c^2$, this energy requirement is less than the

estimate in Miyake et al. (2012), presumably because the particle spectrum predicted here is more efficient for ^{14}C production than the hardest recorded solar flare spectra, which was adopted by those authors. Nevertheless, our minimum energy estimate is far enough beyond the energy of recorded flares that we are motivated to consider whether the event could have been of cometary origin.

A superflare of energy 10^{34} erg could be produced by a solar encounter of a comet (or asteroid) of mass $\gtrsim 10^{19}$ g, which is nearly the mass of C/Hale–Bopp (Weissman 2007). It has been estimated that comet Hale–Bopp has a 0.15 chance of eventually colliding with the sun within several hundred orbits (Bailey et al. 1992, 1996). Given that its most recent apparition was less than two decades ago, let us assume that a comet this large appears about twice per century. Multiplying by 0.15, and assuming each one reappears ~ 300 times before colliding with the sun we roughly estimate, on the basis of this very small number statistic, a minimum solar collision rate of $\gtrsim 10^{-5}$ yr^{-1}.

The above estimate is a lower limit based on a single, long period comet. Of the $\sim 45{,}000$ Centaurs estimated to exist, whose orbital stability times are of order 10^6–10^7 yr many are thought to scatter off Jupiter or outer solar system bodies into the inner solar system, where some meet their demise by crashing into the sun (Horner et al. 2004). Thus a new Centaur enters the inner solar system every $\sim 10^2$ years or so. If ~ 0.06 of them collide with the sun (Levison & Duncan 1994), it would be plausible to expect such an event every ~ 1.5 millennia, comparable to the timescale spanned by the various tree-ring and ice core data sets.

The *Kepler telescope* data set reported superflares from 365 stars that displayed brightness variations ($\geqslant 10^{-3}$) indicative of a magnetic origin (Maehara et al. 2012). In addition, there were nine superflares from stars, out of a sample of 4.5×10^4 stars that showed otherwise steady emission to within instrumental error (H. Maehara 2012, private communication). The upper limit on the event rate for stars without periodic luminosity fluctuations greater than 10^{-3} is thus about 3×10^{-4} yr^{-1} for all stars, and the question is still open as to what fraction have planetary systems capable of driving comets into their host stars. We conclude that the hypothesis of a C/Hale–Bopp -size comet

hitting the sun every several millennia is consistent with present observations.

3. COMETARY BOW SHOCKS

We have also considered a scenario in which the comet converts solar wind energy to energetic particle energy at the bow shock made by its coma. Because the radial **B** field decreases with distance D from the sun as $B(D) \sim 10^{-5} b_5 [1 \text{ A.U.}/D]^2$ G, $b_5 \sim 1$, while the radius R_s of the bow shock could increase at most as D, it is clear that E_o decreases with D, and can never be more than $\eta e B D u_{sw}/c \sim 60 [1 \text{ AU}/D]$ MeV. For E_o to be above 300 MeV, D must be at most 0.2 AU, and the amount of time that the comet would spend within this distance can easily be shown to be about $\delta t = 4 \times 10^5$ s. Assuming the freely streaming energetic particles and the solar wind suffer the same inverse square dilution in getting from the sunward comet to Earth, it suffices to consider the kinetic energy flux of the solar wind[1] (sw) at Earth, $\rho_{sw} u_s^3/2$, times δt. This sets a maximum energy fluence in energetic particles at Earth of $\rho_{sw} u_s^3 \delta t/2 = 7.2 \times 10^7 (n_{sw}/5 \text{ cm}^3)(u_s/4 \times 10^7 \text{ cm s}^{-1})^3 m_p c^2 \text{ cm}^{-2}$ and a maximum ^{14}C production of $\lesssim 10^7 \text{ cm}^{-2}$. This upper limit falls short of the inferred ^{14}C production by more than an order of magnitude. A train of N large comet fragments ($N \gtrsim 10^2$), all from a single progenitor that fragmented, could each play out the scenario N times within a year, and thus enhance the above estimate. Moreover, the pitch angle of escaped particles arriving from a sunward source could be biased toward the parallel direction, thus decreasing the amount of mirroring at the poles relative to Galactic cosmic rays, and increasing the fraction of precipitating particles. Nevertheless, we believe the original scenario—a C/Hale–Bopp-size comet crashing into the sun—to be the more conservative, plausible scenario.

4. FURTHER DISCUSSION

If the most likely explanation of the C.E. 775 event is a superflare at the sun's surface—as opposed to an event within the solar wind per se—then the lack of any record of devastation of any sort at that time is reassuring, though not in regard to safety of power grids and satellites. On the other hand, it implies a huge blast and energetic particle flux, delivered impulsively, at Earth. If it were to repeat in the modern era, it could have devastating consequences for power grids and satellite electronics.

Most sun-grazing comets are of low mass, $M \lesssim 10^{12}$ g, and carry $\lesssim 2 \times 10^{27}$ erg of kinetic energy into the sun. This is probably not enough to be detectable in high energy particles or their secondaries. Comet Lovejoy, the one known sun-grazer that was large enough to survive the perihelion of a close solar encounter, probably had a surface area of about 10^{10} cm^2 and

deposited 10^{13} g to 10^{14} g (Sekanina & Chodas 2012) and 2×10^{28} to 2×10^{29} erg during its passage through the corona. Assuming a coma size of $10^9 R_9$ cm, a magnetic field of B_0 G, and a shock velocity of $10^{-2.5}\beta_{-2.5}c$, the value of the cutoff energy E_o is $E_o = 300 R_9 B_0 \beta_{-2.5}$ MeV. It is therefore conceivable that high energy ions, and/or secondary neutrons and gamma rays were produced at detectable levels during the passage. Results from the IMPACT mission of *STEREO* are therefore awaited at the time of this publication. It is possible that at some time in the near future a sun-grazing comet will produce an energetic particle event that will teach us a great deal. We have also noted that a more extensive data set from the *Kepler Observatory* could reveal non-magnetic superflares on solar-type stars.

Finally, the ^{10}Be enhancement during the same event sets an independent constraint on the spectrum of energetic particles that caused the C.E. 775 event (Miyake et al. 2012). Though beyond the scope of this Letter, a careful analysis of the ^{10}Be data during that time could test our rough estimate for the spectral cut-off parameter $E_o \gtrsim 1/3$ GeV, and the attendant value of the ^{14}C production efficiency ϵ.

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[1] With a modest correction for the comet's motion, which adds to u_s.