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Carrington-class Events as a Great Filter for Electronic Civilizations in the Drake Equation

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Abstract

The Drake equation is a calculation providing an upper bound on the likely number of intelligent species in our galaxy. In order to reconcile a potentially high occurrence of intelligent extraterrestrial species with the current non-observation of them, we frequently resort to some Great Filter which represents some inevitable, cataclysmic fate (such as nuclear war, pandemic, or asteroid impact) that tends to await enough worlds to negate the expectation that the galaxy ought to be teeming with intelligent life. This paper is intended to examine one potential Great Filter for electronic-based civilizations, the impact of a Carrington-class coronal mass ejection (CME) from the Sun. Carrington-class CMEs are classified as "once in a century" events caused by our Sun; this appears to place a time limit, following the development of a civilization dependent on electronic devices, either for hardening electronics against the geomagnetically induced currents that result from CMEs or for beginning interplanetary colonization.

Key words: extraterrestrial intelligence – astrobiology – Sun: coronal mass ejections (CMEs) – Sun: flares – (Sun:) solar-terrestrial relations

1. Introduction

Drake (1961) formulated an equation to estimate the number of intelligent species in our galaxy (N_C). The Drake equation begins with the number of stars in our Galaxy and multiplies this by several fractions, each reducing the number of potential species (Tyson et al. 2016):

1. $N_S \sim 3 \times 10^{11}$ number of stars in our Galaxy;
2. $f_{HP} \sim 0.006$ fraction of stars having a habitable planet;
3. $f_L \sim 1$? fraction of habitable planets on which life develops;
4. $f_i \ll 1$ fraction where life develops intelligence;
5. $f_C \sim 1$? fraction where intelligent species develop interstellar communications;
6. $L_C \ll 10$ Gyr average lifetime of communicating civilizations, compared with our Galaxy's approximate age, 10 Gyr.

Multiplying these together gives the Drake equation:

$$N_C = N_S \times f_{HP} \times f_L \times f_i \times f_C \times \frac{L_C}{10\ \mathrm{Gyr}}. \quad (1)$$

Unfortunately, we do not know many of these parameters with precision. We have a good idea how many stars are in our galaxy, but we lack sufficient a priori knowledge of each of the fractions. One could break up f_{HP} into the product of two fractions, the fraction of stars having planets (since we are seeing more planets all over our local neighborhood, this is probably close to unity) and the fraction of planets being habitable (Long 2012), which probably on its own accounts for the given value. Our data are so limited that we have no idea about the values of f_L, f_i, f_C, or L_C, so we guess them based on one anthropocentric data point (Earth).

One could downgrade either N_S or L_C by insisting that the number of communicating civilizations actually be capable of receiving a signal from us or transmitting a signal to us.[1] For example, we have been broadcasting radio signals for only about a century, so we should count in the Drake equation calculations only for civilizations within about 100 lt-yr of us, and vice versa. Another means of downgrading L_C is by applying what is called a Great Filter, which assumes the lives of intelligent civilizations typically are truncated by some process. Such a process, coupled with the downgrade in N_S, results in "shells" of observability that limit the number of civilizations we might detect (Grimaldi et al. 2018). Some examples of a Great Filter are planet-wide (but not galactic) catastrophes such as (in alphabetical order):

[1] Indeed, Drake updates his own equation in Grimaldi et al. (2018) to account for speed-of-light electromagnetic transmission, which leads to a significantly more depressed number of extraterrestrial electronic civilizations, depending on their respective lifespans.

1. asteroid impact;
2. astrophysical phenomena (supernova or other stellar death);
3. global pandemic; and
4. nuclear weapons (assuming most civilizations that develop nuclear weapons use them).

In short, any planet-wide catastrophe that wipes out a civilization should serve to remove that civilization from the Drake equation estimate. Additionally, this paper argues that any catastrophe that eliminates a civilization's ability to communicate over interstellar distances should remove that civilization from the Drake equation estimate. In particular, it argues that a Carrington-class coronal mass ejection (CME) impact might serve as a Great Filter against that planet's civilization.

2. 1859 and 2012: Two Great Filters We Missed

A CME is a magnetically driven ejection of coronal mass away from the solar atmosphere into interplanetary space. A typical CME is an ejection of between 10^{11} kg and 4×10^{13} kg of plasma into space at speeds ranging from 20 km s^{-1} to 2000 km s^{-1}, resulting in total kinetic energies between 10^{22} J and 10^{25} J (Priest 2014). It is possible, however, to have CMEs with speeds as high as 3000 km s^{-1} (Tsurutani & Lakhina 2014), and the fastest CME on record (at 2604 km s^{-1}) occurred on 2000 May 12 (Yashiro et al. 2004); this CME might be treated as a benchmark for how energetic they could be. CMEs occur both from prominences and from solar flares, so we expect to see them at any time in the solar cycle. The difference here, though, is that CMEs from quiet Sun regions (i.e., outside of active regions) tend to have lower speeds and weaker magnetic fields, whereas a CME from an active region can be much more energetic. The ejection is the manifestation of a release of magnetic energy in the corona, usually through a process known as magnetic reconnection, which is addressed in detail in chapter 12 of Priest (2014). If a CME is *geoeffective* (i.e., crosses Earth's path), it can cause significant—perhaps catastrophic—geomagnetic storming.

The Carrington event is named for British astronomer Richard Carrington. On 1859 September 1, he and Richard Hodgson, independently, were the first two researchers to report a solar flare (Carrington 1859; Hodgson 1859). This flare is associated with a CME that took only 17.6 hr to reach Earth[2] and severe geomagnetic storms that began days earlier. This is the most severe space weather event on record, and it was severe enough that aurora were visible as far equatorward as Honolulu (geomagnetic latitude 20° N) and Santiago (geomagnetic latitude 22° S) (Kimball 1960), and telegraph wires were set afire (Loomis 1861). The Carrington event is the benchmark—so far—for how severe a geoeffective space weather event can become, as it is the strongest on record to impact Earth. A more comprehensive review of the original Carrington event can be found in Tsurutani et al. (2003) and Lakhina & Tsurutani (2018).

On 2012 July 21, a similar CME was generated by the Sun. This CME was not Earth-directed (geoeffective), but it did directly hit the *STEREO-A* spacecraft. Because *STEREO-A* was relatively small and self-contained, it was not affected in the same way that Earth could have been were it struck. Eastwood et al. (2017) indicates that this CME, had it been ejected about a week earlier (due to the Sun's rotation) and impacted Earth, could have been another Carrington-class event. Some geomagnetic storming did occur on Earth within a couple of days, however, but that was probably caused by a co-rotating interaction region[3] due to a coronal hole that followed the site responsible for the CME. Although limited data are available, because we do not have sensors everywhere in the solar system, the ENLIL[4] solar wind model is available at NASA's Community Coordinated Modeling Center;[5] Figure 1 shows the result of an ENLIL model run for the 2012 July event. The model runs used in this paper were obtained from the iSWA cygnet. Models like this one, and the existence of in situ measurements from the *STEREO-A* spacecraft, make the 2012 July CME a useful event for examining potential severe space weather events.

3. Potential CME Impacts to an Electronically Dependent Civilization

Eastwood et al. (2017), the National Academy of Sciences (2008), and the Royal Academy of Engineering (2013) outline the potential economic impacts of severe space weather. In particular, major direct impacts from a Carrington-class CME could be outlined as including the following.

1. Power grid failure due to destruction of large transformers by geomagnetically induced currents. The large transformers in question here generally cost about \$1 million per unit and require about 18 months to manufacture, ship, and install. The National Academy of Sciences (2008) report estimates such a power grid failure would cost \$1–2 trillion per year[6] and last four to ten years.
2. Outages or failures of LEO (low Earth orbit) space assets due to enhancement of the inner Van Allen belt. A severe solar storm can also cause ionospheric uplift which can dramatically increase satellite drag (Tsurutani et al. 2012). Additionally, LEO spacecraft operation could be disrupted by solar energetic protons (SEPs) generated in

[2] At an average speed of 2300 km s^{-1}, this was faster than a typical CME and about five times faster than the average solar wind speed.

[3] The initial discovery of co-rotating interaction regions was reported by Smith & Wolfe (2016).

[4] Named for the Sumerian god of wind and storms.

[5] Located at https://ccmc.gsfc.nasa.gov/models/modelinfo.php?model=ENLIL.

[6] The NAS report does not specify if this is a cost for replacing U.S. power grid components or a global cost, but one could infer from the source that the \$1–2 trillion cost might be only to the U.S. and that the global cost could be greater.

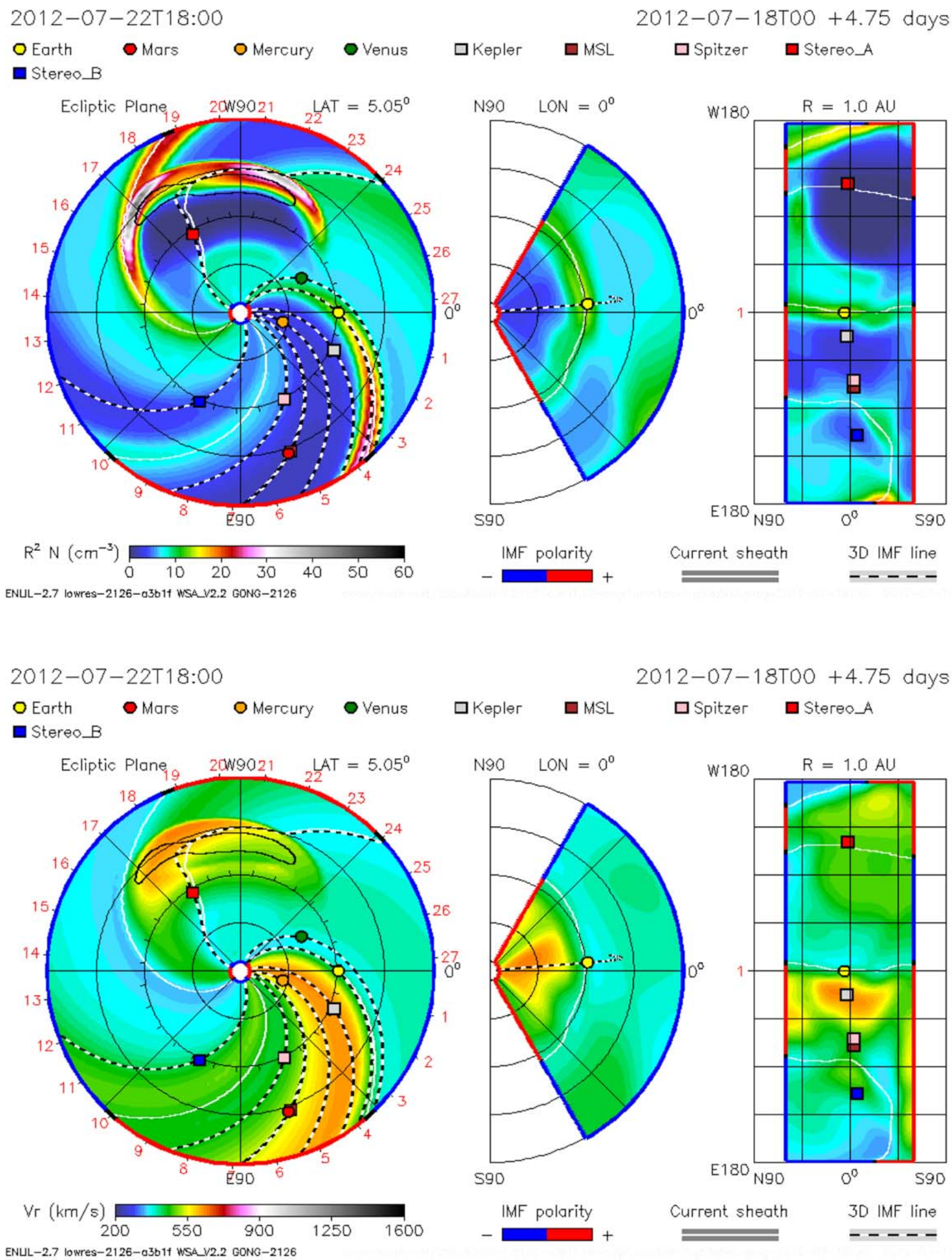

Figure 1. ENLIL model output of proton density (top) and radial velocity from the Sun (bottom) for the 2012 July 23 solar storm. The storm is the result of a co-rotating interaction region that has just impacted Earth in this picture. Shown also is a CME that launched from the Sun approximately two days earlier and did not hit Earth. (Courtesy: NASA/GFSC, Community Coordinated Modeling Center).

the shock of the CME passage through the solar wind (Royal Academy of Engineering 2013).

3. Outages or failures of GEO (geosynchronous equatorial orbit) space assets due to enhancement of the outer Van Allen belt or due to SEPs generated in the shock of the CME passage (Royal Academy of Engineering 2013).
4. GPS outages due to GEO spacecraft outages or failures, or GPS degradation due to ionospheric uplift and enhancement, potentially lasting several days or longer.
5. Communications outages due to high-frequency and ultra-high-frequency radio blackouts, as well as cellular communication network and internet collapse due to extended power outages beyond the limits of generators and stored fuel. In particular, although optical fiber cables are the foundation of much of the global communication network, electrical power is still needed to power optical repeaters and transmitters (Royal Academy of Engineering 2013).
6. Increased radiation doses to astronauts and airline passengers (Royal Academy of Engineering 2013). This is more of a risk for long-haul airline flights or manned spaceflight.

Major indirect effects could include, but are by no means limited to, the following:

1. water and waste water shortages due to reduced or eliminated pumping from power grid failure;
2. fuel shortages due to reduced or eliminated pumping from power grid failure, which could result in transportation stoppages;
3. food shortages due to transportation stoppages, which could contribute to increased death rates and incite rioting and/or looting;
4. reduced hospital care due to water shortages and power outages, which could contribute to increased death rates and rates of infection; and
5. a years-long power grid and internet degradation or outage might irrevocably damage the global economy, in turn greatly prolonging the time to restore the power grid beyond the estimate of four to ten years.

If one recalls major disasters caused by terrestrial weather events like hurricanes Katrina (New Orleans, 2005) and Maria (Puerto Rico, 2017), one can imagine the sorts of major effects on people and life in those areas. The most striking difference is that, whereas humanitarian aid came to bear on these disasters, a Carrington-class event would be a global catastrophe with little or no aid forthcoming. Much greater loss of life could result, and our civilization could be driven back to a much more fractured and pre-electronic one. For the purposes of another planet's Drake equation, our civilization would be eliminated from the calculation. Conversely, another planet whose electronic civilization were struck by a Carrington-class CME would be eliminated from our calculation.

Riley (2012) estimates the probability of another Carrington-class event occuring within the following decade at about 12%. This estimate preceded the solar storm of 2012, but a good rule of thumb would be to estimate this to be the probability of having a Carrington event during any given solar cycle. Love (2012) and Kataoka (2013) have calculated probabilities in rough agreement, but there are a wide range of probabilities in the literature, ranging from once per 60 years (Tsubouchi & Omura 2007) to once per 500 years (Yermolaev et al. 2018). This work will retain the result of Riley (2012), which is also used in National Academy of Sciences (2008) and Royal Academy of Engineering (2013). This roughly agrees with the "once in a century" designation usually given to the Carrington event. Royal Academy of Engineering (2013) indicates that this designator is not well understood given the relative lack of data, but also that there are several tens of Carrington-class CMEs every century that either miss Earth or have lesser impact due to a northward orientation of the interplanetary magnetic field. As shown in Figure 1, such a CME has a very wide angular extent (in the 2012 July event, the CME extended in about a 135° arc from the Sun), which could strike Earth in three out of eight occurrences.

There is also some indication that a solar storm could trigger other Great Filter events. Knipp et al. (2016) outlines a solar storm in 1967 May that nearly triggered a nuclear war, as American radar operators initially mistook a solar storm for Soviet jamming. It might also be possible that a Carrington-class event could unleash or exacerbate an infectious disease due to reduced hospital care at a critical time, resulting in a pandemic.

4. Recommendations for Future Work

Schrijver et al. (2015) provides an extensive catalog of recommendations for enhancing the space weather community with respect to solar storm and CME prediction; this paper does not repeat them. However, there are two recommendations that will be made here.

1. We need better understanding of the physics governing space weather. In particular, there is still a relative lack of understanding of magnetic reconnection, the primary process driving solar flares and CMEs. As this is a scientific obstacle, it is difficult to project when (or even if) a solution will be forthcoming; however, this work imagines significant progress toward understanding solar processes within the next five to seven years as theory and civilization advance and as data start rolling in from the recently-launched *Parker Solar Probe*.
2. We need to make our electronic civilization more "resilient." Here, the quotation marks indicate a lack of societal definition of the word, but this work necessarily defines "resilient" as being able to weather a Carrington-class CME

impact without collapse. Some of this is outlined in the National Space Weather Action Plan (National Science & Technology Council 2015). This is a problem with known scientific and engineering solutions, and is now a job for our societal will to survive.

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