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Key Points:

- A perfect ICME leads to a magnetic storm more intense than the Carrington storm
- A shock with Ms =45 will be created, comparable to astrophysical shocks
- Magnetospheric electric field forms a new relativistic electron radiation belt

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An extreme coronal mass ejection and consequences for the magnetosphere and Earth

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Abstract A “perfect” interplanetary coronal mass ejection could create a magnetic storm with intensity up to the saturation limit ($Dst \sim -2500$ nT), a value greater than the Carrington storm. Many of the other space weather effects will not be limited by saturation effects, however. The interplanetary shock would arrive at Earth within ~12 h with a magnetosonic Mach number ~45. The shock impingement onto the magnetosphere will create a sudden impulse of ~234 nT, the magnetic pulse duration in the magnetosphere will be ~22 s with a dB/dt of ~30 nT s^{-1}, and the magnetospheric electric field associated with the dB/dt ~1.9 V m^{-1}, creating a new relativistic electron radiation belt. The magnetopause location of 4 R_E from the Earth’s surface will allow expose of orbiting satellites to extreme levels of flare and ICME shock-accelerated particle radiation. The results of our calculations are compared with current observational records. Comments are made concerning further data analysis and numerical modeling needed for the field of space weather.

1. Introduction

Coronal mass ejections (CMEs) coming from our Sun have been observed by SOHO coronagraph observations to have speeds of up to 3000 km s^{-1} near the Sun [*Yashiro et al.*, 2004; *Gopalswamy*, 2011]. If these structures happen to collide with the Earth’s magnetosphere, under the right conditions they could cause extremely intense magnetic storms and sudden magnetic field changes (and electric field pulses) both in the magnetosphere and at the Earth’s surface. Such an interplanetary CME (ICME; CMEs in interplanetary space are called ICMEs, due to the possible changes in their nature during transit) collided with the Earth on 1–2 September 1859 and caused the Carrington magnetic storm [*Carrington*, 1859; *Tsurutani et al.*, 2003; *Lakhina et al.*, 2012], the biggest magnetic storm in recorded history. A U.S. *National Research Council Report* [2008] mentioned that power grids may be disabled due to magnetic storms with intensities approaching an event of this scale. A much weaker magnetic storm brought down the Canadian Hydro-Quebec system in 1989 [*Allen et al.*, 1989; *Bolduc*, 2002]. The Carrington storm caused fires and electrical shocks on Earth [*Loomis*, 1861]. Oxygen ion uplift during extreme storms can substantially increase low-altitude satellite drag [*Tsurutani et al.*, 2012]. Sudden changes in the magnetospheric electric fields can lead to the acceleration of electrons to relativistic energies and the formation of new radiation belts [*Blake et al.*, 1992; *Li et al.*, 1993]. We explore the possibility of one of these extreme ICMEs coming to the Earth and its effects on the magnetosphere-Earth system. Current observations are used and only simple assumptions are needed to quantitatively derive some interplanetary, magnetospheric, and ionospheric phenomena of interest.

It has been observationally determined that a maximum CME speed near the Sun is ~ 3000 km s^{-1} [*Yashiro et al.*, 2004; *Gopalswamy*, 2011]. In this work, we will use this number to estimate the maximum values of important interplanetary, magnetospheric, and ground quantities such as the interplanetary shock strength, magnetospheric compression, the magnetospheric and ground electric and magnetic field pulses, and the magnetic storm maximum intensity. This will give an upper limit on the geoeffectiveness of the ICME for various phenomena occurring in geospace. Hopefully, these values can be used by modelers to develop worst case scenarios and to mitigate the effects by preventative measures. If conditions under which higher speed ICMEs exist, the resultant numbers can be simply scaled based on the expressions and reasoning given in this paper.

2. Results

2.1. Shock Speed at 1 AU

The CME speed at 1 AU is not as high as that near the Sun because CMEs typically run into the high-density $(5-10) \times 10^6$ m^{-3}, slow solar wind along its propagation path. Thus, the effect of mass loading (the creation of a sheath) and momentum transfer (acceleration of the upstream plasma as it flows across the shock) will decelerate the CME as it propagates from the Sun to 1 AU. The scenario for the instantaneous shock speed upstream of the ICME is somewhat different. Close to the Sun, the local magnetosonic wave speed is much higher than the CME speed due to the high-intensity coronal magnetic fields. Thus, very close to the Sun, CME shocks are not believed to be present at all. Shocks are predicted to first form at ~5 to 15 R_s from the Sun (R_s is the solar radius), depending on the local plasma conditions. The shock Mach number starts at 1.0 and then increases as the upstream magnetosonic speed decreases, then the Mach number decreases again close to 1 AU.

It is well-known that solar active regions generate multiple CME releases (and multiple flares) and it is believed that these ICMEs tend to "clean out" the upstream solar wind plasma, creating a low interplanetary drag environment. We will therefore use a decrease of ~10% as a maximum ICME drag, or a speed ~2700 km s^{-1} at Earth, for our calculations.

The shock speed in the spacecraft frame is given by the Rankine-Hugoniot conditions [see *Tsurutani and Lin*, 1985]

$$V_S = \rho_2/(\rho_2 - \rho_1)\ [V_2 - V_1].n + V_1 \tag{1}$$

where ρ_2 and V_2 are the downstream density and solar wind velocity, respectively. The same quantities with a "1" subscript correspond to the upstream values, and n is the shock normal direction. For conditions for a maximum shock, the upstream velocity (V_1) and downstream velocity (V_2) and shock normal (n) must all be radially aligned. We use a value of ~350 km s^{-1} for the upstream velocity V_1 and an upstream plasma density ρ_1 of ~5×10^6 m^{-3}. Both of the above values are typical of the slow solar wind. For a downstream density value, $\rho_{2,}$ a maximum jump of ~4 times is theoretically possible [*Kennel et al.*, 1985]. We will therefore use a value of 20×10^6 m^{-3} for ρ_2. As previously mentioned, the velocity of the ICME "driver," V_2, is 2700 km s^{-1}. Applying the above, one gets a shock speed V_S of ~3480 km s^{-1}. The shock speed calculated above was relative to the spacecraft frame, which is essentially the same as that of the Earth. Thus, it will therefore be possible for an ICME shock to transit the 1 AU distance from the Sun to the Earth in a time of ~12.0 h, assuming the above conditions.

2.2. Shock Mach Number

As previously mentioned, the quiet solar wind has a density of ~5×10^6 m^{-3} and a magnetic field strength of ~5 nT. Thus, the in situ Alfvén wave speed is ~50 km s^{-1}. The quiet solar wind plasma has a temperature of ~1.5×10^5 K. The magnetosonic wave speed is thus ~70 km s^{-1}. The shock upstream of the ICME will have an Alfvén Mach number of ~63 and a magnetosonic Mach number of ~45. These extreme values for interplanetary shocks have not been detected during the space age.

2.3. ICME Magnetic and Electric Field Intensities

If one uses the empirical scaling law between the speed of the ICME (at 1 AU) and the magnetic cloud (MC) magnetic field [*Gonzalez et al.*, 1998] (in this situation, the magnetic cloud will be the geoeffective part of the CME)

$$B \approx 0.047\ V_{sw}$$

where B is the peak ICME magnetic field in nanotesla and V_{sw} the peak ICME speed in km s^{-1}, one gets a MC field strength of ~127 nT. The interplanetary motional electric field is given by

$$E = -(V_{sw} \times B)$$

If one assumes that the MC magnetic field is directed entirely southward, orthogonal to the solar wind flow (V_{sw}), then the maximum (dawn-to-dusk, as viewed from a northern hemispheric observer) interplanetary electric field will be ~340 mV m^{-1}.

2.4. Magnetospheric Compression

The solar wind impinges on the dayside magnetosphere limiting the sunward extent of the Earth's magnetic field. At the magnetopause, there is a balance between the solar wind ram pressure and the Earth's magnetospheric magnetic pressure [*Spreiter et al.*, 1963]. An empirically derived expression for this is

$$k\rho {V_{SW}}^2 = (2fB)^2/2\mu_o \tag{2}$$

where k is the fraction of the solar wind ram pressure applied to the magnetosphere, μ_o is the permeability of free space, and f is the enhancement of the magnetospheric magnetic field strength over dipolar values. An empirical value of f^2/k is ~1.77 for low–solar wind ram pressures and ~2.25 for high–solar wind ram pressures [*Sibeck et al.*, 1991]. Clearly, these coefficients were empirically determined from much lower solar wind speeds than considered here, so higher values of f^2/k are possible. We will use these for the "before" and "after" situations, respectively, in our calculations. The nominal (before) solar wind ram pressure $P = (\rho {V_{SW}}^2)$ will be 1.02 nPa. The ram pressure downstream of the ICME shock will be 244 nPa or an increase in pressure by a factor of ~240.

Assuming an equatorial surface magnetic field strength of ~30,000 nT, the above numbers give a quiet time magnetopause location of ~11.9 R_E, where a R_E is an Earth radius (6371 km). For the above ICME shock case, the new subsolar magnetopause position will be at ~5.0 R_E from the center of the Earth. Thus, all geosychronous spacecraft ($r = 6.6\ R_E$) and outer magnetospheric spacecraft will be exposed to the solar wind and the full brunt of solar flare particles during the compression.

2.5. Sudden Impulse Intensity

A relationship between the solar wind ram pressure and the maximum sudden impulse (SI^+) amplitude has been established by experimental means [*Siscoe et al.*, 1968; *Araki et al.*, 1993]. It is

$$\Delta H = k \times \alpha \times f \times \Delta P^{0.5} \tag{3}$$

where ΔH is the change in the horizontal component of the magnetic field at the surface of the Earth and P is the solar wind ram pressure (in nPa). Constants k, α, and f are taken as 10 nT/(nPa)$^{0.5}$, 1.5, and 1.0, respectively. The constant α is the effect of the induced currents in the Earth and f is a factor determining the interaction between the solar wind and the magnetosphere. Using the previous numbers, one gets a ΔH of ~234 nT. Nonlinear effects for magnetospheric compression will reduce the amplitude on the ground.

2.6. d*B*/d*t*

The magnitude of the SI^+ is an important parameter for space weather effects. However, an even more important parameter is the change of the magnetospheric magnetic field intensity B as a function of time, or dB/dt. Through Faraday's law, $\nabla X\, E = -\frac{\partial B}{\partial t}$ the space-varying electric field can be calculated giving values that can be used in particle acceleration modeling. If we assume that the time can be estimated by the propagation of the shock through the geoeffective length of the magnetosphere, L, one gets ~21.7 s for a shock speed of 3480 km/s and $L = 11.9\ R_E$. The assumption that the rise time for the steepest part of the magnetic pulse occurs over a 1/e scale is made to obtain dB/dt = ~30 nT s^{-1}. Faraday's law thus gives curl E = 30 mV km^{-2}.

3. Summary and Discussion

The estimated upper limit of an ICME shock transit time from the Sun to the Earth is ~12.0 h under ideal conditions. The maximum shock speed at 1 AU will be ~3480 km s^{-1}. The highest transit speed of an ICME shock on record was the August 1972 event [*Vaisberg and Zastenker*, 1976]. The time delay from flare onset to shock detection at 1 AU was ~14.6 h, giving an average speed of 2850 km s^{-1}. The transit time of the Carrington event was ~17.5 h. If higher ICME speeds than assumed here are possible, then the time duration could be even shorter than 12 h. For example, if the Sun had flares with energies of 10^{26} or 10^{27} J, as has been shown to occur at solar-type stars [*Maehara et al.*, 2012], and the ICMEs were likewise more energetic, all of the above numbers can be scaled accordingly.

The ram pressure associated with the shock impingement onto the magnetosphere will push the magnetopause in to a distance of 5.0 R_E from the center of the Earth, or 4.0 R_E from the Earth's surface. The current record for the lowest magnetopause observation is 4.2 R_E for the August 1972 event [*Hoffman et al.*, 1975].

With a magnetopause distance of 4.0 R_E, the many low-altitude satellites orbiting the Earth will be directly exposed to solar flare/interplanetary shock energetic particle radiation.

The forward shock magnetosonic Mach number will be ~45. This value will be higher or lower depending on the upstream plasma conditions at the time of the shock. Typical ICME interplanetary Mach numbers are 1 to 3 [*Tsurutani and Lin*, 1985; *Echer et al.*, 2011], although occasionally they have been noted to be as large as ~9 [*Tsurutani et al.*, 2014]. Such an extremely high shock Mach number of ~45 might lead to a record interplanetary energetic particle event. We suggest modelers consider extreme events of this type. Of particular interest is whether a shock of this intensity could possibly explain the AD774-775 [*Miyake et al.*, 2012; *Usoskin et al.*, 2013] and AD992-993 [*Miyake et al.*, 2013] cosmic events. These extreme events, which were identified in tree ring data, have signatures quite similar to those of solar flares.

A maximum sudden impulse (SI^+) is estimated to be $\Delta H = \sim 234$ nT, less ground effects. An extremely large SI^+ occurred on 24 March 1991 with a magnitude of $\Delta H = 202$ nT, measured at Kakioka, Japan [*Araki et al.*, 1997].

A maximum of the magnetospheric electric field can be obtained if one assumes that the curl of E extends a distance of ~10 R_E, a reasonable fraction of the magnetospheric scale size. Putting in the proper numbers, one gets an electric field of order ~1.9 V m^{-1}. On 24 March 1991 an interplanetary shock created a new radiation belt composed of ~15 MeV electrons low in the magnetosphere [*Blake et al.*, 1992; *Li et al.*, 1993]. An electric field of amplitude ~300 mV/m was calculated for this event [*Wygant et al.*, 1994]. Thus, it is possible that an electric field ~6 times the intensity of the 1991 case may occur in the future. However, one should consider that the sharply decreased size of the magnetosphere during the pressure pulse may complicate the modeling of such an event.

The maximum interplanetary electric field at Earth is estimated to be ~340 mV m^{-1}. For the *Carrington* [1859] storm, the largest storm on record, estimates of the interplanetary electric field are ~200 mV m^{-1} and ~160 mV m^{-1} using two different techniques [*Tsurutani et al.*, 2003]. Thus, a maximum that can be expected will be twice that experienced ~155 years ago.

What will be the maximum storm intensity? Estimates for the Carrington storm intensity were derived to be $Dst \sim -1760$ nT [*Tsurutani et al.*, 2003; *Lakhina et al.*, 2012]. The storm intensity has been noted to scale approximately linearly with the interplanetary electric field amplitude [*Burton et al.*, 1975; *Echer et al.*, 2008a]. Thus, based on the above analyses, the magnetospheric response to the MC might be up to $Dst \sim -3500$ nT. However, from a calculation based on plasma beta arguments, a maximum *Dst* for the Earth's magnetosphere of −2500 nT has been derived [*Vasyliunas*, 2011]. Clearly for this extreme MC, this predicted maximum will be reached.

The interplanetary electric field value for the dayside ionospheric superfountain effect [*Tsurutani et al.*, 2004; *Mannucci et al.*, 2005] for the Carrington magnetic storm has been recently estimated [*Tsurutani et al.*, 2012]. The uplifted oxygen ion densities pose serious problems for low altitude orbiting spacecraft. New calculations are needed to determine the ion densities at high altitudes with the greater electric fields presented here. However, what is currently lacking is modeling of enhanced neutral densities caused by ion-neutral drag.

3.1. Caveats and Final Comments

In order to estimate the numbers derived in this paper, we often had to extrapolate from typical/common event data to extreme values. Of course, one cannot be certain that the relationships remain linear up to extreme values. This is the best that one can do until extreme event information becomes available through future measurements. However, we can say that in comparing our estimations of these extreme space weather values (assuming this particular scenario), they seem to fit well with what has been historically high extreme events.

It is our hope that by providing basic numbers for an extreme ICME/MC event impacting the Earth, others will be able to use these values to determine interplanetary and magnetospheric particle acceleration and fluxes and terrestrial transformer damage under these maximal conditions.

Concerning our thoughts on the probability of this "event" happening, we should first say that there are many branches to this event. To come up with a reasonably accurate value, the probability of each step of the space weather phenomenon of interest needs to be estimated. For example, we have assumed that "the CME near the Sun has a speed of 3000 km s^{-1}, that the interplanetary space is "cleared out" so the deceleration is only slight, that the ICME shock is perpendicular, and that the magnetic cloud magnetic field direction is southward" for various parts of the study. Clearly, the IMF *Bz* direction is only important for the magnetic storm and magnetospheric dawn-dusk electric fields, so they need not be appraised for identifying the maximum magnetospheric compression or SI^+. Scientists do not typically focus on this part of space weather (probabilities), but with sufficient incentive (and financial support), they could do. Research experts in these narrow fields of study are the only ones who can make accurate and well-reasoned estimates.

There have been many reports on the space weather effects of the Carrington solar flare [*Carrington*, 1859] and the Carrington magnetic storm [*Tsurutani et al*., 2003; *Lakhina et al*., 2012]. The best of these is the *Royal Academy of Engineering Report* [2013]. This report is available online at www.raeng.org.uk/spaceweather, and we recommend people read it. Although not without flaws, it is the most comprehensive and well-researched report available. However, one common misconception (perhaps taken for simplicity) is that it is the solar flare that causes all space weather effects [*Gosling*, 1993]. Specifically, the flare intensity does not correspond directly to CME speed. Also, the flare intensity (and CME speed) may not be well related to solar energetic particle flux, other than in a general fashion. And we all know that to create an extreme magnetic storm, a portion of the ICME has to have southward directed magnetic fields [*Gonzalez et al*., 1994]. Sheath fields cannot create magnetic storms with extreme intensities because the magnetic field magnitudes are not intense enough [*Tsurutani et al*., 1992; *Echer et al*., 2008b]. Furthermore, the magnetic storm intensity may not be directly related to geomagnetically induced currents (GICs) at the surface of the Earth. Thus, one has to know the details of the specific physics of the phenomenon in question in order to understand its properties. We recommend that substorm, ionospheric, magnetospheric, interplanetary, and solar experts be consulted for future studies of this type.

Many space weather reports have focused on GICs. GICs are related to the intensity of the ionospheric current and its temporal/spatial variations flowing at ~100 km altitude (the auroral electrojet). The flow of this current over power lines may be one of the main contributors to the causes of transformer damage and power outages [*Bolduc*, 2002; *Kappenman*, 2010]. It should be noted that interplanetary shocks (mentioned in this paper) can have two other ionospheric effects that have not been discussed in these studies. Interplanetary fast forward shocks can cause sudden dayside auroras and field-aligned currents [*Brown et al*., 1961; *Zhou and Tsurutani*, 1999; *Tsurutani et al*., 2001; see *Zhou et al*., 2013 and references therein]. Shocks can also trigger the release of stored magnetospheric/magnetotail energy in the form of particularly large substorms, or supersubstorms [*Heppner*, 1955; *Zhou and Tsurutani*, 2001; *Zhou et al*., 2003] in the nightside sector, events which will be accompanied by particularly large ionospheric currents. If a second shock occurs while a magnetic storm is ongoing (where the aurora is at relatively low latitudes), this type of dual event could be particularly geoeffective. Multiple ICMEs/shocks have been noted to occur at 1 AU when complex sunspots known as active regions are present at the Sun [*Tsurutani et al*., 2008, 2014]. The GIC effects of these dayside and nightside shock-related auroral events should be studied. Researchers should note that the physics occurring on the dayside and nightside are quite different and should be appraised separately. Again, the probability of multiple shock events occurring can be determined by a combined group of solar, interplanetary, and magnetospheric scientists.

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