Three-dimensional global simulation of multiple ICMEs’ interaction and propagation from the Sun to the heliosphere following the 25–28 October 2003 solar events

C.-C. Wu a,f,*, C.D. Fry b, M. Dryer c,b, S.T. Wu a, B. Thompson d, Kan Liou e, X.S. Feng f

a CSPAR/University of Alabama, Huntsville, AL 35899, USA
b Exploration Physics International, Inc., Huntsville, AL 35806, USA
c NOAA Space Environment Center, R/E/SE, 325 Broadway, Boulder, CO 80305, USA
d NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
e JHU/APL, Laurel, MD 20723, USA
f Key State of Laboratory for Space Weather, Chinese Academy of Sciences, Beijing 100080, China

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Abstract

This study performs simulations of interplanetary coronal mass ejection (ICME) propagation in a realistic three-dimensional (3D) solar wind structure from the Sun to the Earth by using the newly developed hybrid code, HAFv.2+3DMHD. This model combines two simulation codes, Hakamada–Akasofu–Fry code version 2 (HAFv.2) and a fully 3D, time-dependent MHD simulation code. The solar wind structure is simulated out to 0.08 AU (18 Rs) from source surface maps using the HAFv.2 code. The outputs at 0.08 AU are then used to provide inputs for the lower boundary, at that location, of the 3D MHD code to calculate solar wind and its evolution to 1 AU and beyond. A dynamic disturbance, mimicking a particular flare’s energy output, is delivered to this non-uniform structure to model the evolution and interplanetary propagation of ICMEs (including their shocks). We then show the interaction between two ICMEs and the dynamic process during the overtaking of one shock by the other. The results show that both CMEs and heliosphere current sheet/plasma sheet were deformed by interacting with each other.

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1. Introduction

The first time-dependent 3D simulations of interplanetary shock propagation were performed by Han et al. (1988). Using this model, some parametric studies utilized 3D MHD simulations of interplanetary magnetic field changes at 1 AU as a consequence of an interaction with a flat heliospheric current/plasma sheet (HCS/HPS, Wu et al., 1996) and also with a tilted HCS/HPS (Wu and Dryer, 1997). In addition, Dryer et al. (1997) used the code to simulate the April 14, 1994, interplanetary CME and its propagation to Earth and Ulysses (in the southern hemisphere at ~4 AU). Wu et al. (2005a) recently performed a parametric study, via 3D MHD simulations, of the shock time of arrival at Earth. In a more recent study (Wu et al., 2007a), we found that the background non-uniformity of the solar wind plasma and IMF is of negligible consequence for shock wave arrivals provided the energy output of the solar disturbance is unusually large, e.g., $10^{34}$ ergs or higher. All of these studies, however, were limited by having a lower boundary at 18 Rs (where Rs = solar radius = $6.95 \times 10^3$ km) and with an ideal steady state.
solar wind condition. This motivated us to relax this restriction and to perform a global three-dimensional (3D) numerical simulation from the Sun to the Earth. Therefore, we linked the space weather-validated kinematic 3D Hakamada–Akasofu–Fry version 2 (HAFv.2) model (cf., Fry et al., 2001; Dryer et al., 2004) to the full 3D MHD model of Han et al. (1988). Thus, solar surface magnetograph observations can now drive, continuously, the HAFv.2 model and, then, the Han et al. model throughout the heliosphere. We will refer to this hybrid model, henceforth, as “HAFv.2+3DMHD”.

In this study, we use this newly developed global 3D simulation model to simulate part of the Halloween 2003 events that are described observationally by Veselovsky et al. (2004) and Gopalswamy et al. (2005) and, previously, with a 1.5D MHD numerical simulation by Wu et al. (2005b, 2006, 2007a). In related works, Odstrcil et al. (2004, 2005), who presented an approach to the simulation of the 12 May 1997 flare/CME/shock event during solar minimum, were mainly concerned with the interplanetary differences caused by various coronal outflow models (cf., Arge and Pizzo, 2000 and variations thereof) for small-scale structures in the pre-event background solar wind. These authors concluded: “It is always an advantage to use different models for the same problem improved in the future. Not only can one obtain higher confidence in predicted features and effects, but also the differences in results are very helpful in estimating their accuracy, in understanding the physics, and in learning what should be improved in the future.” The present work is presented in this spirit. We will use a different assumption from that used by Odstrcil et al. (2004, 2005) for mimicking the solar origin and launch of the ICMEs (interplanetary coronal mass ejections). Other techniques (cf., “loss-of-equilibrium”) for launching CMEs and flares, CMEs without flares, or flares without CMEs (cf., Zhang et al., 2001) are considered to be beyond the scope of this paper. We will use the classical deterministic initial boundary value problem wherein changes in one or more observable physical conditions (cf., any one or more of emerging magnetic flux, pressure increases generated by reconnection, etc.) can initiate a deviation from the steady state.

Our goal is to provide a validation procedure for the newly coupled model described above. As noted in the first paragraph, the HAFv.2+3DMHD model can be driven continuously and, therefore, can be used as a second generation operational tool, the first being the HAFv.2 model (Fry et al., 2001). The numerical simulation model is described in Section 2; observations are discussed in Section 3; and simulation results are described in Section 4. Discussion and conclusions are given, respectively, in Sections 5 and 6.

2. Simulation model

The non-uniform background conditions of the solar wind plasma and IMF are essential for the model coupling of the corona to the solar wind modeling codes. We use this hybrid model to simulate CME/ICME/Shocks propagating from the Sun to the Earth and beyond with a realistic solar wind background condition.

As noted in Section 1, HAFv.2+3DMHD combines two simulation codes, Hakamada–Akasofu–Fry code (HAFv.2) (Fry et al., 2001 see, also, references therein) and a fully three-dimensional, time-dependent MHD simulation code (Han et al., 1988; Detman et al., 1991, 2006). We briefly summarize below two basic steps: (i) from the Sun to 2.5 Rs, thence to 0.08 AU and (ii) from 0.08 AU to the Earth and beyond. That is, source surface data at 2.5 Rs, provided by NOAA (http://sec.boulder.noaa.gov), are input to the HAFv.2 model. The output from this model at 0.08 AU (18 Rs) are then input to the 3D MHD model.

2.1. Model for simulating CME/ICME/Shock from 1.0 Rs to 0.08 AU (18 Rs)

This physics-based code is a kinematic model, HAFv.2 (Fry et al., 2001). The model uses a modified kinematic approach to simulate the solar wind conditions out to 18 Rs with data from Carrington Rotation maps (2.5 Rs), provided by NOAA’s Space Environment Center, as the input. The output of HAFv.2 at 18 Rs (0.08 AU) provides inputs for the time dependent 3D MHD solar wind model. The pre-event, globally non-uniform, solar wind plasma and IMF (interplanetary magnetic field) co-rotating system is driven by a time series of photospheric magnetic maps composed from daily solar photospheric magnetograms (http://wso.stanford.edu). Use of these data to provide solar wind velocity and radial IMF at 2.5 Rs is described by Arge and Pizzo (2000). Table 1 lists the three different flow velocity pulses provided to the HAFv.2 code at 2.5 Rs. This type of study has been carried out by Fry et al. (2001) and Wu et al. (2000) and is of the kind noted in a previous 3D MHD simulation by Wu et al. (in press) for the 12 May 1997 event.

2.2. Model for simulating CME/ICME/Shock from 0.08 AU to the Earth and beyond

The numerical 3D MHD scheme used in this analysis is an extension of the two-step Lax–Wendroff finite difference method (Lax and Wendroff, 1960). We found that using the Lax–Wendroff (L–W) method is still a valid approach (see next paragraph). The details of the computational procedures can be found in the work of Han et al. (1988) and Detman et al. (1991). When using the two-step Lax–Wendroff finite difference method, the governing equations are required to be written in conservation form. A complete description of this conversion can be found in Han (1977). The governing equations, for an ideal, single fluid, perfect gas, include conservation of mass, equation of motion, conservation of energy, and induction equation.
The computational domain for 3D MHD simulation is a Sun-centered spherical coordinate system \((r, \theta, \phi)\) with the \(r\)-axis in the ecliptic plane. Earth is located at \(r = 215\) Rs, \(\theta = 0^\circ\), and \(\phi = 0^\circ\). The domain covers \(-87.5^\circ \leq \theta \leq 87.5^\circ; 0^\circ \leq \phi \leq 360^\circ\); 18 Rs \(\leq r \leq 285\) Rs. An open boundary condition at both \(\theta = 87.5^\circ\) and \(\theta = -87.5^\circ\) is used so that there are no reflective disturbances. A constant grid size of \(\Delta r = 3\) Rs, \(\Delta \theta = 5^\circ\), and \(\Delta \phi = 5^\circ\) is used. The two angular grid sizes are chosen to be equal to those provided by the photospheric magnetic maps discussed by Arge and Pizzo (2000). The radial grid size, at this time, is chosen to be also large but still sufficient to provide insight for global structures such as shocks. We emphasize the point that these pulses generate coronal mass motions that exceed the local characteristic fast mode speed, thereby generating shocks (Wu et al., 2006). Thus, no CME model, per se, is required, although we still do not understand the CME generating mechanism, nor whether a 3D realistic or reliable, CME model exists. For example, performing a 3D MHD simulation, Odstrcil et al. (2004, 2005) studied the May 12, 1997, magnetic cloud event by adding a pressure pulse (4 times the original density magnitude) at \(\approx 0.1\) AU to simulate an empirical CME cone model’s propagating from 0.1 AU to 1 AU.

### Table 1

<table>
<thead>
<tr>
<th>Occurrence of flares(^a)</th>
<th>Class</th>
<th>Location</th>
<th>(V_s)(^b)</th>
<th>(V_{\text{CME}})(^c)</th>
<th>Shock</th>
</tr>
</thead>
<tbody>
<tr>
<td>0552 UT, 2003-10-25</td>
<td>LDE M1.7/SF</td>
<td>N00W15</td>
<td>316</td>
<td>585</td>
<td>0854 UT, 2003-10-28(^d)</td>
</tr>
<tr>
<td>0617 UT, 2003-10-26</td>
<td>LDE X1.2/3N</td>
<td>S18E33</td>
<td>1302</td>
<td>1245</td>
<td>0150 UT, 2003-10-28</td>
</tr>
<tr>
<td>1102 UT, 2003-10-28</td>
<td>X17/4B</td>
<td>S15E08</td>
<td>1875(^c)</td>
<td>1800</td>
<td>0600 UT, 2003-10-29</td>
</tr>
</tbody>
</table>

\(a\) The flare time is listed as the radio metric Type II start time that is close to the maximum of the soft X-ray emission in 1–8 A˚.

\(b\) Estimated coronal shock speed, km/s, based on metric Type II radio drift (Dryer et al., 2004).

\(c\) CME speed, km/s, based on near real time estimates listed in Dryer et al. (2004).

\(d\) Actually, this time marks the arrival of the directional discontinuity, DD, as discussed in the text as a product of the interaction of two shocks (Wu et al., 2005b).

\(e\) Based on an average of several real-time radio observatory reports (Dryer et al., 2004).

4. Simulation results

4.1. The effect of background solar wind speed

Fig. 1 shows the profile of simulated solar wind speed that followed the famous flares of October 25, 26, and 28. In preliminary attempts to mimic medical magnetic resonance “MRI” images, we show the solar wind speed on the surfaces of three angular cones that are centered at the Sun’s center: 22.5° North; 2.5° North, close to Earth’s latitude in the solar equatorial coordinate system; and 22.5° South, representative of a southern heliospheric response. The thin solid circle is at 1 AU with the Earth at 0° heliolongitude. Thus, the East limb (relative to Earth) is at the top, 90° East; and the West limb is at the bottom of each panel, 90° West. The outer boundary of the simulation is at \(\approx 290\) Rs. The non-uniformity of the entire global structure of the CME/ICME/Shock at Earth and elsewhere within the inner heliosphere is apparent.

Figs. 1a,f,k show the solar wind speed profiles at 1800 UT on October 25 which is \(\approx 12\) h after a flare, located at N00W15, occurred at 0552 UT on October 25, 2003. These profiles show that the ICME has already passed...
18 Rs. The brighter blue spiral stripes represent the solar wind that emanated from a solar coronal hole; several of these zones are marked in dotted ovals. Earth’s location is marked in Fig. 1f. Figs. 1f,b,g,l show the solar wind profiles at 0000 UT on October 27 which is ~18 h after the second flare was observed at S18E33, 0617 UT, on October 26, 2003. It is clear that the ICME’s central axis (subjectively defined) is directed into the southern hemisphere. The ICME’s size is larger in that direction than in the ecliptic plane or northern hemisphere. Figs. 1b,g,l,c,h,m show the process of the overtaken ICME’s interaction. Additionally, the dashed ovals show the feature of the strongly attenuated backside portion of the large ICME. Figs. 1d,e,i,j,n,o show the solar wind speed profiles at 0200 UT and 2200 UT, respectively, on October 29, 2003, which was ~15 and ~35 h after the third flare was observed at 1102 UT on October 28, 2003. The solid arrows show a deformation of ICME structure that propagated faster than the adjacent western material due to the faster background flow and lower density from the coronal hole. Finally, Figs. 1e,j,o show that the ICME arrived in the southern hemisphere earlier than at the equator or in the northern hemisphere. This effect is clearly due to the ICME’s source location at S15E08.

4.2. The deformation and overtaking of ICMEs

Fig. 2 shows an additional set of medically-inspired “MRI” global density (upper row) and velocity (lower row) profiles that followed the flare/CMEs of October 25–28, 2003. These profiles are in the Earth’s meridian plane from 1800 UT, October 25, 2003, to 2200 UT, October 29, 2003. The temporal snapshots for the five columns are for the same times as in Fig. 1. Figs. 2a,f show the steady state solar wind condition, primarily, but also with a very small density and velocity increase for the ICME from the first flare (Table 1). The location of Earth, indicated in Fig. 2e, is in the center of the meridional plane. The simulated ICME in Figs. 2b,g is from the second flare during this epoch: namely, the X1.2/3N flare at S18E33 on October 26, 2003, at ~0617 UT which is the metric Type II start time that is nearly coincident with the soft X-ray maximum. Fig. 2, in the other views, shows the velocity response that followed this and the other flares. The lightly-dotted ovals (inclined to the south) call attention to the heliospheric plasma/current sheet (HPS/HCS) and its boundaries with the solar wind stream from the polar coronal holes. The HPS/HCS, located near the solar ecliptic plane, is clearly seen as well as its subsequent...
deformation. The shape of the ICME, indicated by the two, dashed arrows and the heavily-dashed ovals, was distorted after interacting with the HPS/HCS (lightly-dashed ovals). Figs. 2g–h (see the heavily-dashed ovals) show the deformation of the merged ICMEs by interacting with each other and the non-uniform solar wind, becoming two non-symmetric structures. The leading edges of the two ICMEs (including their shocks) propagated slower in the HPS/HCS region because of the lower speed there.

4.3. Comparison of simulation results with observation

Fig. 3 shows the observed ACE/SWEPAM/SWICS/MAG (black dots) and simulated (dashed lines) solar wind plasma and magnetic field data between October 26 and 30, 2003. Three shocks (marked by the vertical dotted lines) occurred on October 28, 29, and 30, 2003. The first two shocks are listed in Table 1. We made no attempt to simulate the third shock as noted earlier. A directional discontinuity, marked DD (discussed in Wu et al. (2005b)), is noted by a vertical solid line at a smaller velocity increase from ≈600 km/s to 650 km/s at 0852 UT on October 28, 2003. The bottom to the top panels of Fig. 3 show solar wind speed, number density, temperature, total magnetic field, and the $x$-, $y$-, and $z$-components of magnetic field. The proton density is not available (Skoug et al., 2004) in a reliable form during the period after 0600 UT, October 29, 2003. The simulation results compared to ACE data look reasonably good for solar wind velocity, number density, and total magnitude of magnetic field. The second (simulated) shock arrived about ~12 h later than actual because our pulse also for that mimicked flare was not large enough. SWEPAM Level 1 data for density, temperature, and velocity are not reliable after 1200 UT, October 28 because of the energetic proton “snowstorm” from the X17/4B flare and shock wave. The actual temperature plotted here is from the ACE/SWICS instrument. We do not simulate the temperature very well because thermal conduction and damping of Alfvén waves are not included in our model; however, we consider temperature to be a secondary objective at this time. For magnetic field, we get the general trend and shocks but not the correct amplitudes. The transverse component, By, is simulated reasonably well but not Bx or Bz. So, in general, we still have open questions about how to initialize our inputs. As noted above, we did not attempt to simulate the ICME nor its shock from the X10/2B flare and CME on October 29, 2003.

5. Discussion

Wu et al. (2005a) recently performed a parametric study concerning the arrival times of shock passages at Earth by performing 3D MHD simulations. They demonstrated that the shock arrival time at Earth depends on the background solar wind speeds, the initial speeds of solar disturbances,
their size, and their source location on the Sun relative to the Earth’s central meridian. However, the lower boundary used (Wu et al., 2005a) is 0.08 AU instead of the surface of the Sun. We have initiated basic studies of shocks that have already evolved from the Sun (thus within 0.08 AU) and by tracking their evolution and interactions to 1 AU by using a 1.5 D MHD model (Wu et al., 2005b, 2007a) for the events discussed here. This earlier work, the latter one in particular, provided the motivation to extend the initialization process to the present 3D MHD hybrid procedure.

Recently, we applied the HAF+3DMHD code to simulate CMEs/ICMEs propagating into the realistic solar wind during a solar minimum (e.g., the May 12, 1997) event (Wu et al., in press). In the present study, we simulated multiple events during the declining phase of solar Cycle 23, i.e., Halloween 2003 event as shown in Figs. 1 and 2. Fig. 2 shows: (1) the deformation of ICMEs after interaction with the HPS/HCS; (2) the overtaking and interaction process between two ICMEs; and (3) the ability and location of a strong flare that can be inferred when only a backside CME is observed. Item (3) refers to the thin solid arrows in Fig. 1,n,j,o that point to increased speed “pimples” (and likely density increases as well) at the ICME/Shock flanks. Expanding on this point, the reader is asked to be a hypothetical observer who would be located (roughly) opposite Earth’s location. Our interpretation is that the combined shocks (in this particular case) from the flares, listed in the top of Fig. 1, expanded around the Sun to more than 2π steradians. The combined ICME ejecta were sufficiently compressed so that it might be observed via the Thomson effect in the plane-of-sky for this hypothetical observer.

Several fully 3D MHD simulations exist for studying solar eruptions from the Sun to the Earth. However, each model has its own limitation. For example, Han et al. (1988) first used a 3D, MHD, time-dependent numerical model to study supersonic and super Alfvénic MHD flow from 18 Rs to 1 AU. Their code can study solar phenomena from 0.1 AU but not the evolution of shocks within 0.1 AU. Another 3D MHD numerical model used to investigate the temporal and spatial evolution of large-scale solar wind structures was developed by Odstrcil and Pizzo (1999a,b). These workers studied the evolution of coronal mass ejections launched at several heliographic positions into a tilted-dipole ambient solar wind flow which is appropriate around solar activity minimum and declining phase (Odstrcil and Pizzo, 1999b). However, the 3D model used by Odstrcil and Pizzo (1999a,b) can only simulate solar wind structures beyond 21.5 Rs. It has the same limitation as the 3D model developed by Han et al. (1988).

Numerical simulations were previously used to study the interaction of CMEs. Using a 2.5D MHD simulation model, Schmidt and Cargill (2004) studied the interaction between two CMEs from 1.7 to 32 Rs. They found: (1) the interaction of CME pairs will tend to lead to large merged structures, at least when the outward CME trajectories are close to each other and (2) CMEs “stick together” rather than tending to bounce off each other. Thus, they realized that multiple CME compressible interactions were inelastic rather than like billiard ball elastic collisions. Their analysis considered a uniform background solar wind with no consideration of the IMF. Recently, more extensive 2.5D MHD studies on CME “cannibalization” have been done with solar minimum type bimodal solar wind backgrounds together with the HPS/HCS. In this work, Xiong et al. (2006a,b) also used a meridian 2.5D MHD model to simulate the overtaking of an initial ICME by a trailing ICME. Their results, with more extensive details, show that the trailing shock first overtakes the preceding magnetic cloud, then penetrates through it, and finally merges with the MC’s first shock, forming a stronger compound shock. This process (without the use of a MC) was also demonstrated, together with reverse shock
formation, in detail by Wu et al. (2005b) in the 1.5D MHD approximation. We might also mention another study pertaining to the October 28–30, 2003, event within the context of an empirical electrodynamical approximation. This non-MHD study by Krall et al. (2006), however, required numerous free parameter adjustments in order to provide an appropriate MC arrival time at ACE.

The 3D MHD studies have been progressing rapidly within the context of the solar minimum bimodal background solar wind and the popular flux rope model for magnetic clouds. Lugaz et al. (2005b) used this approach to study the interaction of two identical CMEs. Two identical CMES were launched in the same direction into this pre-existing solar wind, the second one 10 h after the first one. This approach followed their earlier work (with a single ICME) by Lugaz et al. (2005a) who also used an unbalanced self-similar flux rope within the initially undisturbed corona in order to cause the disturbance. This latter work also examined the total mass and energetics of the CME.

It is worth noting, returning to the 1.5D MHD context, that Wu et al. (2005b, 2006, 2007a) simulated the overtaking of two forward fast mode shocks (as in the 2.5D and 3D studies mentioned above) as well as the collision between forward and reverse fast mode shocks using multiple ICME interactions during the period of October 25–November 1, 2003. The Wu et al. studies not only simulated the real solar events by mimicking solar flare inputs to interplanetary space, but the results also matched, via tuning only the single required free parameter, the flares’ pressure pulses, with the unusual ACE solar wind velocity observations. There is no flux rope structure in the Wu et al. studies. Fortunately, this omission is not a handicap (perhaps considered as such by some workers since this structure is used by the authors mentioned above). We make this comment with the support of Richardson and Cane (2005) who showed that only ~15% of all ICMEs measured at Earth during Solar Cycle 23 (1996–2005) were of the magnetic cloud (flux rope) category.

The present study, also neglecting consideration of flux ropes, used the newly developed HAFv.2+3D MHD model to simulate the interaction of ICMEs for the period of October 25–29, 2003, the dates of their associated solar flares. The background solar wind includes the inhomogeneity caused by stream-stream interactions, not merely the bimodal solar wind. The study showed the overtaking of an ICME by a second one from behind in several cases. We showed that the slower ICME was, as expected, totally overtaken by the fast shock as in the general case 2.5D cases studied by Xiong et al. (2006a,b). We interpreted their fast shock as being followed by the second ICME that was generated, not as a flux rope (as in their first ICME), but by compressed plasma and IMF ejecta as a consequence of their initializing pressure pulse. This approach, with a single ICME, was examined by Lugaz et al. (2005a) who used the same unbalanced self-similar flux rope within the initially undisturbed corona in order to cause the disturbance. This work provided realistic 3D-calculated energetics and mass of the ICME. The shock’s propagation speed (or “leading edge” of the ICME) was affected by the upstream solar wind speed as shown in our “magnetic resonance imagery” plots (see Figs. 1b–c, g–h, 1–m, Figs. 2b–c, and g–h). It is difficult to tell what the effect of the ICMEs’ interaction is on their size changes after interaction since the size of the fast ICME is bigger than the slow CME in this study. The answer would require more detailed studies to make a final conclusion. For example, we would have to simulate two separate cases wherein each simulation should consider only a single ICME. Then, we could compare the sizes between the individual pre-collision ICME (either the slow or faster one) with the merged ICME. That kind of study, however, is beyond the scope of the present one.

6. Conclusions

This study performs a simulation example of coronal mass ejection and shock propagation that includes a realistic 3D solar wind structure from the Sun to the Earth. The following statements are concluded. (1) This simulation procedure can provide a tool to link the general cases of ICME at 1 AU to their solar sources, as well as to identify the possible origins of shock formation due to CME interaction. We refer to an example shown in Figs. 1c,h,m when two ICMEs and their shocks collide. The 3D interaction should, in principle, be studied in higher resolution as in the 2.5D examples of Xiong et al. (2006b). (2) The results can be extended to simulate a variety of coronal and heliospheric observations, including the essential ambient medium’s non-uniformity provided by the HAFv.2 model in a continuous temporal mode. (3) The results also help understanding the effect of background solar wind speed on the propagation of ICMEs and their deformation by interacting with the heliosphere plasma/current sheet. (4) The results help understanding the procedure of multiple CMEs’ overtaking each other. (5) The arrival times of ICMEs/Shocks at 1 AU are affected by the location of solar sources. (6) Both CMEs and HCS/CPS were deformed by interacting with each other.

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