



On the Origin of ULF Magnetic Waves Before the Taiwan Chi-Chi 1999 Earthquake

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The ultra low frequency (ULF) electromagnetic (EM) wave activity usually recorded on Earth's ground has been found to depend on various types of space weather. In addition ULF waves observed before an earthquake have been hypothesized to be a result of geotectonic processes. In this study we elaborate for the first time the origin of sub-ULF (<1 msec) magnetic field waves before an earthquake (Chi-Chi/Taiwan, 20.9.1999) by comparing simultaneously obtained measurements in the interplanetary space (ACE satellite) and on the Earth's ground (Taiwan). The most striking result of our data analysis, during a period of 7 weeks, is that the detection of four groups of sub-ULF waves in Taiwan coincide in time with the quasi-periodic detection of two solar wind streams by the satellite ACE with approximately the solar rotation period (~28 days). The high speed solar wind streams (HSSs) in the interplanetary space were accompanied by sub-ULF Alfvén wave activity, quasi-periodic southward IMF and solar wind density perturbations, which are known as triggering agents of magnetic storm activity. The four HSSs were followed by long lasting decreases in the magnetic field in Taiwan. The whole data set examined in this study strongly suggest that the subULF magnetic field waves observed in Taiwan before the Chi-Chi 1999 earthquake is a normal consequence of the incident of HSSs to the magnetosphere. We provide some observational evidence that the sub-ULF electromagnetic radiation on the Earth was most probably a partner to (not a result of) geotectonic processes preparing the Taiwan 1999 earthquake.

Keywords: ULF waves, earthquake generation process, space weather, earthquake electromagnetic precursors, earthquake prediction, sun-earth relationships, environmental electromagnetism

INTRODUCTION

The Origin of Terrestrial Ultra Low Frequency Electromagnetic Waves and the Taiwan Chi-Chi 7.7M_w 1999 Earthquake

Ultra low frequency (ULF) waves observed by terrestrial observatories is a matter of scientific research of great interest. ULF waves provide significant information about geomagnetic processes and earthquake (EQ) preparation processes and they have significant influence on biological organisms (Reichmanis et al., 1979; Pilipenko, 1990; Poole, 1993; Kivelson and Russell, 1995; Poole et al., 1993; McPherron, 2005; Pulnits and Boyarchuk, 2004; Grimalsky et al., 2010; Anagnostopoulos, 2015, 2016). Despite the extensive research done so far, there exist many open questions about their generating mechanisms. For instance, sub-ULF (<1 msec) waves have been reported before several earthquakes. However, low geomagnetic storm activity has been

considered as a criterion of their terrestrial origin, without any other direct evidence. Therefore the question is: is it possible that sub-ULF (<1 msec) wave activity and moderate or low geomagnetic storm activity are related with solar activity and subsequent space weather? The answer to this question is positive from the side of space science. However, there is not, as far as we know, any study which directly compares space weather and terrestrial observations to address the above question of ULF activity before a particular earthquake. For this reason, in this case study, the subULF wave activity before the great Taiwan 1999 earthquake is reexamined in order to elaborate its origin.

The Taiwan 7.7 M_w earthquake (EQ) was one of the most catastrophic earthquake of the 20th century in Taiwan (Ma et al., 1999). The EQ struck the small town Chi-Chi at 1:47 local time (17:47 UT), 21 September (20 September), 1999. The earthquake epicenter was located at geographic latitude 23.85°N and longitude 120.78°E, with a depth of 8.0 km. In this earthquake, approximately 2500 lives were lost, about 11,305 people injured, more than 100,000 people made homeless, thousands of buildings were destroyed and NT\$300 billion worth of damage was done. One month after the disastrous Chi-Chi earthquake (October 22, 1999) another great EQ (M_w 6.4) occurred in Chia-yi, in southern Taiwan (Chang and Wang, 2002; Huang et al., 2006).

Several investigators have reported various types of precursory electromagnetic (EM) phenomena, which occurred before the Chi-Chi 1999 earthquake. Almost all of the relative studies suggested that the precursory electromagnetic signals were the results of terrestrial processes. Since most researchers accept the hypothesis that seismic activity is a phenomenon related with a physical process in the interior of Earth, no systematic research has been made on the space weather and its possible effects on the Chi-Chi pre-EQ EM signals as well. The presence of a “weak” geomagnetic activity before the Chi-Chi EQ was hypothesized as an evidence of non space effects in Taiwan before the great 1999 EQ (Yen et al., 2004), according to the generally accepted geocentric paradigm.

Today the situation is different in understanding the importance of space weather on the planet Earth. In this respect, several studies have recently provided overwhelming evidence that the quiet Sun producing “weak” storms is a significant agent provoking terrestrial seismicity (Anagnostopoulos et al., 2021 and references therein). However, despite the great achievements in space weather, the scientific literature lacks any studies examining the possible space origin of any pre-EQ electromagnetic (EM) precursory signals based on a direct comparison of simultaneously obtained space and terrestrial measurements.

The Sun is the principal source of energy in our Solar System and the agent of many physical processes taking place in Earth's magnetosphere, ionosphere, atmosphere, lithosphere and biosphere (Odintsov et al., 2007; Gray et al., 2010; Vencloviene et al., 2012; Anagnostopoulos and Papandreou, 2012; Anagnostopoulos et al., 2015; Patsourakos et al., 2016; Kumar, A., and Kumar, S., 2018; Firoz, 2019; Tsurutani et al., 2020). Moreover, nowadays our knowledge about the Sun-Earth electromagnetic relationships allows a new insight into important physical and biological phenomena of great social interest (Anagnostopoulos et al., 2021; Zenchenko and Breus, 2021).

The solar wind-magnetospheric interaction is one of the most important issues in space research. In particular, space science has provided significant information on the role of solar wind turbulence on the energy and momentum transfer from the Sun to the Earth's environment (Dungey, 1961; Borovsky and Valdivia 2018). Moreover, in recent years, rich information has been accumulated concerning the impact of high speed solar wind streams (HSSs) on the status of the geomagnetosphere, and, in particular, on the trapped radiation belts (Kataoka, R. and Miyoshi, Y. 2006; Borovsky and Denton, 2006; Potapov, 2013, Baker et al., 2018; Richardson, 2018). Furthermore, HSSs periods were found to be related with enhanced seismicity occurring during “quiet” geomagnetic periods (Anagnostopoulos et al., 2021 and references therein).

This paper is devoted to elaborating on the space processes preceding a great earthquake. To this end, we investigate, for the first time, simultaneously obtained space and terrestrial observations for a specific earthquake, in order to extract information on the space weather – seismicity relationship additional to that received from our previous statistical study (Anagnostopoulos et al., 2021). We address the question of whether the ULF waves (<1 msec) recorded by the magnetic field observatories in Taiwan some weeks before the Chi-Chi EQ could be the result of space weather, during a quiet Sun.

THEORETICAL AND OBSERVATIONAL FRAMEWORK

Ultra Low Frequency Electromagnetic Waves in Space and on the Ground

ULF waves in the magnetosphere and on Earth, known as Pc or Pi pulsations (McPherron, 2005), are one of the most known phenomena in space science. There is a wide variety of ULF types, which are classified according to their form and frequency band.

ULF waves of different frequencies and polarizations observed on the ground may originate from different regions of the magnetosphere, the distant space or the Sun's environment. Ultra-low frequency waves are detected on the ground as geomagnetic pulsations, ranging in frequency from some Hz to less than 1 mHz and numerous theories have been proposed to explain their origin (Pilipenko, 1990; McPherron, 2005; Pulinets and Boyarchuk, 2004; Grimalsky et al., 2010)

On the other hand, there have been many reports of ULF waves observed before an earthquake, which have been considered as originating from tectonic processes. Many other electromagnetic EM field changes have also been reported before earthquakes on the ground, in the atmosphere and in a wide range of frequency of the EM spectrum as sub-ULF, ULF/ELF, VLF, IR (Hayakawa and Fujinawa, 1994; Molchanov and Hayakawa, 1998; Ouzounov and Freund, 2004; Hattori, 2004; Liu et al., 2004; Balasis and Mandea, 2007; Hayakawa et al., 2010; Uyeda et al., 2009, Pulinets and Ouzounov, 2011; Athanasiou et al., 2011, 2014; Freund et al., 2012; ZhangShen et al., 2012; Tramutoli et al., 2015, De Santis et al., 2015, 2017; Ouzounov et al., 2018; Han, 2020). Furthermore, some characteristic charged particle variations have been reported in

the ionosphere and the inner radiation belt before great EQs, as, for instance, variations in TEC and in radiation belt electron precipitation as well as ionospheric plasma perturbations (Lui et al., 2000, 2001; Pulnits and Boyarchuk, 2004; Akhoondzadeh et al., 2010; Pulnits and Ouzounov, 2011; Sidiropoulos et al., 2011; Anagnostopoulos et al., 2012). Broad band VLF wave activity is related with electron precipitation from the inner radiation belts. Extensive summary of pre-earthquake phenomena have been reported by Ouzounov et al. (2018) and Pulnits and Ouzounov, 2018.

Enhanced ULF EM activity has been considered to be a significant earthquake precursory signal (Hattori, 2004; Hayakawa et al., 2007; Zhang et al., 2012; Athanasiou et al., 2014). In general, the detection of various electromagnetic perturbations before fault ruptures has been proposed as a useful way to monitor activities of Earth's crust.

An increasing number of investigators have used electromagnetic methods in the last two decades in order to achieve earthquake prediction. Furthermore, satellite observations have been extensively used in earthquake prediction research. The first space mission dedicated to the detection of pre-EQ EM emissions was the French satellite DEMETER (Parrot et al., 2006; Sauvaud et al., 2006), during the years 2004–2010. DEMETER mission greatly aided the scientific community in improving its methodologies on earthquake prediction research. Similarly, a second space mission, the Chinese satellite CSES (Shen et al., 2018) is currently in orbit around the Earth and provides us with current data.

In the scientific community the ultra low frequency electromagnetic radiation has been considered to be an important earthquake precursor, because of its deeper skin depths (Hattori and Han, 2018). ULF magnetic field activity has been recognized as a precursor to well-known and broadly discussed earthquakes, such as in Loma Prieta, Guam, Sumatra 2004, and Haiti 2010 (Fraser-Smith et al., 1994; Hayakawa et al., 1996; Athanasiou et al., 2011).

A short discussion about the origin of ULF wave activity before an EQ was made in the case of the Loma Prieta earthquake. Campbell (2009) compared magnetic field records from Fresno, Bolder and Tucson with magnetic field observations from Stanford University (Fraser-Smith et al., 1994) near Loma Prieta, and he found that a similar trend for the ULF wave activity characterized all these locations. Campbell concluded that the ULF waves recorded before the Loma Prieta earthquake was not a local signal originated from local preparation processes.

Thus, we think that we should address the following questions: 1) Are all types of pre-EQ ULF magnetic field waves the result of tectonic stresses? 2) Is it possible for some types of preearthquake ULF wave activity to originate from tectonic processes and some other types from some space phenomena? 3) Is there any observational evidence supporting the space origin of the subULF electromagnetic radiation observed before the Chi-Chi 1999 earthquake?

Space Weather and Solar Wind Ultra Low Frequency Waves

There is increasing evidence that supports the concept of two supplementary sources contributing to the generation of

earthquakes: tectonic stresses and space weather phenomena. There are several studies, which have provided significant evidence that seismicity is related with solar cycle (SC) phase (Simpson, 1967; Gousheva et al., 2003; Bakhmutov et al., 2007; Odintsov et al., 2007; Khain and Khalilov, 2008; Straser and Cataldi, 2015) and geomagnetic activity (Sobolev et al., 2001; Duma and Ruzhin, 2003; Bakhmutov et al., 2007; Urata et al., 2018). Love and Thomas (2013) disputed the solar-terrestrial interaction in triggering great earthquakes, but they tested an incorrect hypothesis (active Sun affects seismicity) and wrong time scale (1 year) of averaged sunspot number (Anagnostopoulos et al., 2021).

The long-term (1964–2013) relationship between the occurrence of earthquakes with magnitudes $M \geq 5$ was investigated by Gulyaeva (2014); it was found that the global number of earthquakes tends to grow towards the solar cycle minimum.

Anagnostopoulos et al. (2021) performed various statistical studies based on solar, space and seismological data between 1900 and 2017 and we also found strong evidence that both the great earthquakes as well as high global seismic energy release occur during the rising and the decay phase of SC as well as at specific times of the maximum solar cycle phase with temporal (# months) weak solar activity. In general, the analysis of monthly averaged solar sunspot number (SSN) confirms a systematic and significant negative correlation of the seismic activity with the SSN (Gulyeva, 2014; Rekapali, 2014; Anagnostopoulos et al., 2021).

During periods with small SSNs, coronal hole (CH) driven-recurrent HSSs and corotating interaction regions (CIRs) rotate in space with the solar rotation period of ~ 27 days. This periodicity is clear in various kinds of observations in the interplanetary space, the terrestrial magnetosphere and the ionosphere. For instance, solar wind speed and auroral electron power exhibit solar rotational periodicities (Emery et al., 2009). Since the ~ 27 -days period recurrent solar wind structures influences Earth via EM interactions, the ~ 27 -days-periodicity might be found in seismological data. Indeed, the power spectrum analysis of 4-h averaged global energy release values demonstrated a ~ 27 -days periodicity during the decay phase of SC22 and SC23 and at the maximum of SC23 (Anagnostopoulos et al., 2021). This result is consistent with the concept that HSSs, which emanate from the coronal hole of the quiet Sun, provoke seismic activity on the planet Earth.

Since we found strong evidence that the impact of CH-driven HSSs/CIRs on the Earth's magnetosphere trigger earthquakes, the next question is how the magnetosphere mediates the energy transfer of the solar wind plasma to the ionosphere and the lithosphere. Anagnostopoulos et al. (2021) put forward the hypothesis that solar wind magnetohydrodynamic (MHD) waves, which are transformed into electromagnetic waves in the ionosphere, may mediate space weather with seismicity. Indeed, Alfvén waves are present in the environment of HSSs and CIRs (McPherron, 2005; Richardson, 2018).

Alfvén waves often reach the Earth's magnetosphere in a quasi-periodic southward direction, which is a condition for triggering magnetospheric storms (Dungey, 1961). HSSs and CIRs, which guide the Alfvén waves, cause weak or moderate, but long lasting (several weeks to some months) geomagnetic storms, which are characterized by almost continuous UV

Auroras often covering the entire dayside and nightside auroral zones (Tsurutani and Gongalez, 1987). Under such space conditions, ionospheric electric fields and thermospheric winds from the high latitudes can affect the middle and the low latitude ionosphere (Abdu et al., 2006). At these times, magnetospheric and ionospheric EM variations produce electromagnetic effects on the ground (Marhavilas, 2007).

Since solar wind sub-ULF Alfvén waves are transformed into sub-ULF electromagnetic waves reaching Earth's surface, they could probably mediate space weather with seismic activity. Furthermore, HSSs themselves are highly related to sub-ULF electromagnetic waves observed at Earth (Kim et al., 2002; McPherron, 2005).

Geomagnetic Ultra Low Frequency Waves Before the Taiwan Chi-Chi 1999 Earthquake

The first reason why we choose the Taiwan 1999 earthquake as a case study is the fact of CIR-induced extreme geomagnetic activity in late 1999 (Borovsky and Denton, 2006). A second reason is that sub-ULF waves were observed in Taiwan before the Chi-Chi 1999 EQ and they have been discussed in the scientific literature extensively. Geomagnetic sub-ULF fluctuations recorded by several stations in Taiwan before the 1999 Chi-Chi EQ have been reported and discussed among others by (Lin, 2013), Liu et al. (2000, 2004), Ohta et al. (2001), Akinaga et al. (2001); (Shin, 2004), Yen et al. (2004), Freund and Pilorz (2012), Tsai et al. (2018).

Yen et al. (2004) hypothesized that the geomagnetic sub-ULF fluctuations were connected to the process of accumulation and releases of crustal stress, and the subsequent severe surface ruptures. They noted that the mechanisms producing the geomagnetic fluctuations are not clearly understood.

Freund and Pilorz (2012), Tsai et al. (2018) suggested that the sub-ULF geomagnetic fluctuations before the Chi-Chi EQ, were the result of a large current generated by accumulation and release of crustal stress.

Pulinets and Boyarchuk (2004) noted that the near Chi-Chi earthquake magnetic anomalies were probably connected with effectiveness of solar events, while Anagnostopoulos et al. (2021) reported that HSSs/CIRs transferred Alfvén waves in the magnetosphere before the Chi-Chi 1999 EQ.

Given that there exist several reports on the existence of ULF EM waves before the Chi-Chi earthquake, in this study we investigate the hypothesis that the ULF geomagnetic fluctuations in certain frequency bands may be originated from solar wind. To this end we reasonably address the question whether sub-ULF geomagnetic anomalies are not the result of the microseismicity observed for ~7 seven weeks before the Chi-Chi earthquake, but an agent of micro-earthquakes.

Geomagnetic Ultra Low Frequency Waves of Space Origin

ULF waves of space origin are observed on Earth, in particular at low frequencies around 1 mHz (Barnes, 1983). Some of these waves originate at the Sun and are both carried by, and propagate through the solar wind.

The location of the regions on the Earth where ULF waves are observed depends on the solar wind dynamic pressure, the interplanetary magnetic field, and the conductivity of the Earth underneath the observer (Kivelson and Russell, 1995; McPherron, 2005). Changes in orientation of the interplanetary magnetic field (IMF) or Alfvén waves in HSSs/CIRs have dramatic effects on the type of waves seen on the Earth.

Besides the ULF waves transferred by the solar wind, waves are also locally produced upstream from the Earth's bow shock, at the bow shock and the magnetopause and they are sources of ULF waves penetrating into the magnetosphere (McPherron, 2005). Another type of ULF waves is produced by oscillatory dynamic pressure fluctuations in the solar wind (Kepko et al., 2002).

Many observations obtained simultaneously by satellites in space and on the ground have shown that solar wind perturbations deeply penetrate into the magnetosphere. Furthermore, it was found that the lower-latitude data on the nightside are important in monitoring the external source variations (Kim et al., 2002; Villante and Tiberi, 2016). The ULF signal seen at the ground is an electromagnetic wave radiating from electric currents induced in the ionosphere (and not the magnetohydrodynamic waves themselves).

Russell et al. (1992) reported that the best correlation between ground level changes and the change in the solar wind dynamic pressure occurs at geomagnetic latitudes from 15° to 30° .

Sarafopoulos (2005) demonstrated that sometimes monochromatic or quasi-periodic geomagnetic pulsations were exo-magnetospherically excited by a wave-source with a periodicity from ~3 to ~10 min and that the magnetosphere in these cases can respond to solar wind ULF waves in such small time scales as 2.7 min.

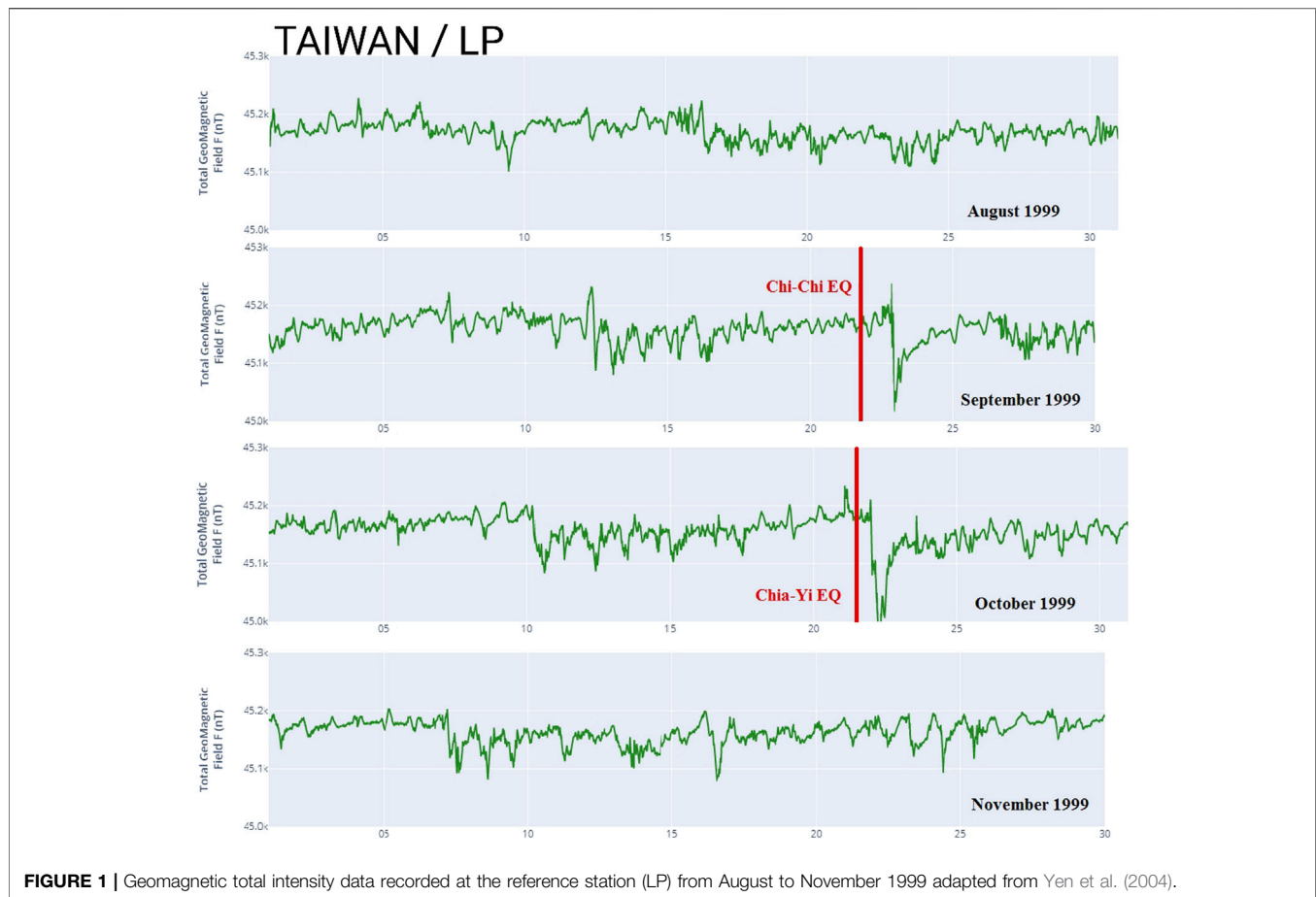
In the next section we compare space and terrestrial observations in order to identify the origin of the sub-ULF (<1 mHz) magnetic field waves observed before the catastrophic Taiwan 1999 earthquake.

RESULTS

In this section we compare space and terrestrial observations in order to test two hypotheses on the origin of the sub-ULF magnetic field waves observed before the occurrence of the Chi-Chi earthquake (21/20 September 1999), that is a space versus a geotectonic model of the magnetic field wave generation. To this end, we compare observations from the Advanced Composition Explorer (ACE) spacecraft (http://www.srl.caltech.edu/ACE/ace_mission.html), which is in orbit around the L1 Sun-Earth libration point, magnetic field observations in Taiwan, along with geomagnetic indexes (http://wdc.kugi.kyoto-u.ac.jp/ae_provisional/199809/index_19980913.html)

The ACE spacecraft was launched in 1997 and thereafter has been remained in a halo orbit about the L1 point.

The ACE instruments used in this study are the Electron, Proton, and Alpha Monitor (EPAM) (Gold et al., 1998), the Magnetometer Instrument (MAG) (Smith et al., 1998), and the Solar Wind Electron, Proton, and Alpha Monitor (SWEPAM) (McComas et al., 1998).



EPAM was constructed to investigate energetic ions and electrons, and it is composed of five telescope apertures of three different types; the Composition Aperture (CA), two low energy magnetically shielded telescopes (LEMS30 and LEMS120) and two low energy foil shielded telescopes (LEFS60 and LEFS150). The telescopes use the spin of the spacecraft to sweep the full sky. Solid-state detectors are used to measure the energy and composition of the incoming particles. ACE/EPAM data consist of electrons and ions in the energy range from ~50 keV to 5 MeV (Gold et al., 1998; Maravilas et al., 2015).

The NASA Advanced Composition Explorer (ACE) ACE spacecraft is used, in a routine basis, in investigating space weather (<https://www.swpc.noaa.gov/products/ace-real-time-solar-wind>). The ACE satellite enables United States National Oceanic and Atmospheric Administration (NOAA) Space Weather Prediction Center (SWPC) to give advance warning of geomagnetic storms and recognize their types.

Test 1. A Space Origin of Magnetic Activity Before the Taiwan 1999 Earthquake Is Not Impossible

Geomagnetic Conditions Before the Chi-Chi Earthquake

The first question we examine relating to the origin of the sub-ULF (<1 mHz) magnetic field activity observed before the Taiwan

1999 earthquake (Akinaga et al., 2001; Yen et al., 2004; Freund and Pilorz, 2012) is whether there exists direct observational evidence that the sub-ULF magnetic field waves were produced by some tectonic process in the Earth's lithosphere.

Figure 1 shows the total geomagnetic intensity at the station LP, between mid-August and November 1999 (adapted from Yen et al., 2004). Yen et al. (2004) noted that a magnetic storm was observed ~2 days after the Chi-Chi earthquake and another one about 1 month later, at almost the time of occurrence of the Chia-Yi earthquake. These authors claimed that no other space-induced magnetic anomaly was observed except for these two storms and they concluded that the total geomagnetic intensity at the reference station LP did not show a disturbance at the times of the Chi-Chi earthquake and the Chia-Yi earthquake or times previous to the two EQs. However, this argumentation presupposes the unproven hypothesis that, beyond a terrestrial source, a space agent of the magnetic field wave activity could be a CME-induced short-lasting strong geomagnetic storm. Based on the absence of such a storm before the Chi-Chi and Chia-Yi EQs, a terrestrial origin is inferred.

The above argumentation follows the generally accepted hypothesis that only a short time great magnetic field variation might be an alternative physical process related with a future earthquake. However, it is well known from space science literature that there are two main types of geomagnetic storms

(Borovsky and Denton, 2006), which are followed by a similar magnetic field pattern on the ground: 1) a short time great magnetic field variation and 2) a weak or moderate long lasting but long lasting magnetic field depression.

Actually, in **Figure 1** we identify both types of imprints of geomagnetic storms. The two intense short lasting events (green arrows), which are obviously induced by Coronal Mass Ejections (CMEs) and three quasi-periodic (orange horizontal lines in **Figure 1**) long lasting moderate magnetic field depressions, which originate from a ~27-days recurrent HSS/CIR. Since, it is generally accepted that “in order to detect changes in the geomagnetic field associated with tectonic stress, it is necessary to eliminate the changes originating from external sources in the observed data”, a space influence cannot be eliminated on the magnetic field data shown in **Figure 1** before both the Chi-Chi and Chia-Yi earthquakes.

In the next subsection we describe in some more detail the basic features of the two types of geomagnetic storms, since this information is crucial for the present study as well as the general research of the pre-EQ electromagnetic phenomena.

Coronal Mass Ejections and ~27-days Recurrent High Speed Solar Wind Streams Triggering Geomagnetic Storms

The most dramatic effect of the Sun in the interplanetary space is of course the Coronal Mass Ejections (CME). CMEs are large explosions of plasma and magnetic field from the Sun's corona, which are released into the solar wind and they often follow solar flares (Tsurutani et al., 2020). CMEs most often occur during solar maxima. On the other hand, the coronal holes are the least active regions of the Sun. They have magnetic fields opening freely into the heliosphere and they are associated with rapidly expanding open magnetic fields and the acceleration of the high-speed solar wind. They are the source of HSSs and CIRs, which are most often observed during the decay and the rising phase of the solar cycle (Richardson, 2018; Badruddin et al., 2018). During the year 1999 the solar activity was in the rising phase of solar cycle and in late 1999 (including July and August) ~27-days recurrent CIRs were noted as triggering long lasting storms (Borovsky and Denton, 2006).

However, despite the fact that dramatic solar flares and large CMEs are known to be associated with strong geomagnetic storms (Patsourakos et al., 2016 and references therein), the importance of the CH-driven HSSs in triggering geomagnetic storms is also significant (AGU collection of papers in Geophysical Monograph #167 edited by Alfvén, 1950; Kivelson and Russell, 1995; Tsurutani et al., 2006; Abdu et al., 2006; Kavanagh and Denton, 2007; Cranmer, 2009; Richardson and Cane, 2011; Tsurutani et al., 2011; Richardson and Cane, 2012a; Richardson and Cane, 2012b; Gerontidou et al., 2018; Richardson, 2018; Watari, 2018, and references therein).

HSSs dominate in the declining phase of the solar cycle, and in general during times of low SSNs, when polar CHs extend towards lower solar latitudes. Therefore, the flow of plasma from the solar corona is non-uniform in both time and space (Phillips et al., 1995). The fast solar wind emanating from a large coronal hole catches up with upstream slow solar wind and a

compressive region is formed at the interface of the two streams. These structures reappear with the ~27-days rotation period of the Sun. When these CH-associated streams are long lasting, they lead to the formation of corotating interaction regions (CIRs) in the interplanetary space and when the CIRs are well developed, they are bound by fast forward (FS) and fast reverse (RS) shocks. It is interesting to note that HSSs and CIRs can drive important physical processes over longer periods than the more transient CMEs can (Tsurutani et al., 2006; Borovsky and Denton, 2006; Kavanagh and Denton, 2007).

The CME-driven storm is a strong, but short lived phenomenon, which usually lasts from a few hours to a few days (Tsurutani et al., 2006). The HSSs/CIRs cause weaker storms than the CMEs. However, the “weak” HSS-induced storms last for long times; the recovery phases of CIR-induced magnetic storms can last for a few up to 27 days. Furthermore, since during a quiet Sun, CH-driven HSSs corotate with the Sun's 27-days period, one or more HSSs, can affect semi-continuously the Earth's magnetosphere for several months. The important point to note is that during such long time periods, HSSs/CIRs can transfer much more energy in the magnetosphere than a single CME. During HSS-induced storms, the D_{st} value normally ranges between -25 nT and -75 nT and typically does not reach intensities of -100 nT.

Long-duration high-speed-stream-driven geomagnetic storms also lead to the strongest electron-radiation-belt radiation hazards, to the strongest plasma sheet spacecraft-charging hazards, and to the related spacecraft anomalies (Wrenn et al., 2002; Wrenn, 2009).

The semi-continuous arrival of HSS structures cause almost continuous UV Auroras, which often cover the entire dayside and nightside auroral zones for days to many weeks (Tsurutani and Gongalez, 1987). The Aurora phenomenon is known as High Intensity Long Duration Continuous Aurora Electrojet Activity (HILDCAAs).

Periodicities of ~14/27–28 days in Taiwan Geomagnetic Data in Late 1999

Imprints of the two types of storms, CIR-induced storm and CME-induced storm, on the geomagnetic field observed in Taiwan are evident in **Figure 1**, as we mentioned above. In particular, from **Figure 1** we see the imprints of a long-lasting storm between days 12–20.9.1999 before the ChiChi (September 20, 1999) EQ, and a short-lasting CME-induced storm after the EQ, on days 2223.9.1999. We also see a similar pattern in the magnetic field data before the Chia-Yi EQ.

The geomagnetic field data in Taiwan, which show a moderate, but long lasting magnetic field decrease with sub-ULF wave activity, between days 12–20 in September 1999 and ~27-days recurrent similar magnetic field patterns in October and November (**Figure 1**), during a period of ~27 days recurrent storms (Borovsky and Denton, 2006), suggest that we cannot reject the hypothesis that an external (space) agent might be the source of the sub-ULF waves between days 12–20.9.1999. On the contrary, since HSSs/CIRs trigger long-lasting weak to moderate magnetic storms, which produce sub-ULF EM waves at Earth, we infer that the presence of sub-ULF waves before the Chi-Chi EQ is consistent with a space source.

Since we cannot eliminate an external origin for the sub-ULF magnetic field waves before the Chi-Chi and Chia-Yi earthquakes, the question is: is there any direct observational evidence that they were the result of geotectonic processes? Freund and Pilorz (2012) compared the sub-ULF (<1 mHz) magnetic field waves with seismological data before the Chi-Chi earthquake, in order to directly test such a possibility. To this end, they compared the intensity of the ULF fluctuations by using LY/HL observatory 12-h running average data with the excess seismic energy output from August 1 to September 21, 1999 (their Figure 19).

Their study suggested a dominant periodicity at ~14 days in the ULF magnetic activity. The periodicity was attributed to strong influence from the Earth's tides. However, if the ~14 days ULF periodicity was due to some gravitational effects of the Sun or the moon, then a clear argumentation on the correlation of the ULF ~14-days periodicity with the moon phase or the Sun-Earth relationship should be demonstrated. Instead, the authors noted that "Because the gravitational forces are relatively weak, the seemingly tight coupling between the Earth tides and both, ULF emission and regional seismicity, comes as a surprise». Therefore, we think that until a correlation between the ULF ~14-days periodicity and direct gravitational features can be shown, the attribution of the ULF ~14-days periodicity to gravitational forces cannot be accepted as a reliable explanation of the data.

A second argument by the same authors for a geotectonic source of the magnetic anomalies was based on the correlation between the curves of the ULF activity and the pre-EQ energy output excess between August 1-September 20, 1999. It was suggested that there exists a correlation and causal link between Earth tides, the frequency distribution of earthquakes, and the emission of ULF signals. However, in such a case, if the seismicity was the cause of the ULF fluctuations, the seismic energy release increase should have preceded the increase of the ULF activity.

However, the opposite pattern is obvious in Figure 19 of the paper by Freund and Pilorz. The pre-EQ excess seismic energy output curve E is shifted relative to the ULF line in such a way that both the onset and the maximum of the ULF activity reach earlier than the excess seismic energy E in all the four long lasting events analyzed (except for the onset of the last event, where the increases of the two parameters occurred almost simultaneously). Thus we cannot reject the hypothesis that space weather triggered the ULF EM waves at the LY station/Taiwan (red). Moreover, the time delay between ULF activity and seismic energy E are consistent with an external source of the ULF activity.

Test 2. The Taiwan Magnetic Activity Is Correlated to Geomagnetic Storm Activity

Here we check the hypothesis that the anomalous magnetic field activity in Taiwan and the geomagnetic storm may have a common space agent. For this reason we investigate the possible relation of the Taiwan magnetic field decrease associated with the sub-ULF magnetic activity between 12 and

21 September 1999 with the Earth's geomagnetic storm activity as provided by the global Dst index (Borovsky and Shprits, 2017), [http://wdc.kugi.kyotou.ac.jp/dst_final/199909/index.html].

For this reason, In **Figure 2** we compare the local B-field measurements by the LP/Taiwan observatory (Panel A) with the global geomagnetic index *Dst* (Borovsky and Shprits, 2017; http://wdc.kugi.kyoto-u.ac.jp/dst_final/199909/index.html) (panel B) during the whole of September.

The *Dst* index shows the strength of the Earth's ring current, which flows toroidally around the Earth, centered at the equatorial plane and at altitudes of 10,000–60,000 km. Changes in the ring current are responsible for global decreases in the Earth's surface magnetic field and reveals the occurrence of a geomagnetic storm (Daglis et al., 1999).

The *Dst* index also reacts to the partial ring current (Liemohn et al., 2001), the cross-tail current (Ohtani et al., 2001), and the Chapman-Ferraro dayside-magnetopause current (Burton et al., 1975) and is primarily a measure of plasma pressure in the bipolar magnetosphere (Dessler and Parker, 1959; Greenspan and Hamilton, 2000). *Dst* is also often used to define the duration of a storm, and to distinguish between quiet and disturbed geomagnetic conditions (Borovsky and Shprits, 2017). A *Dst* categorization that is often used to categorize storm intensity is (I) a weak storm ($-30 \text{ nT} > Dst > -50 \text{ nT}$), (II) a moderate storm ($-50 \text{ nT} > Dst > -100 \text{ nT}$), (III) a strong storm ($-100 \text{ nT} > Dst > -200 \text{ nT}$), (IV) a severe storm has ($-200 \text{ nT} > Dst > -350 \text{ nT}$), and a (V) great storm ($Dst < 350 \text{ nT}$) (Loewe and Prolss, 1997). *Dst* is derived from a network of geomagnetic field observatories around the globe and its changes occur every time when B_z component of IMF B turns negative. The energy transfer is closely related to the B_z component of the IMF through a large-scale reconnection process, on the dayside, when a negative IMF meets the northward magnetic field of Earth's and a fraction of the available solar wind energy is able to penetrate our magnetosphere (Dungey, 1961).

Figure 2B reveals two different patterns of geomagnetic storms (Borovsky and Denton, 2006): 1) a long lasting CIR-induced Type II (moderate) storm, between 12 and 20.9.1999 and 2) a short time Type III CME-induced storm, on days 22–24.9.1999.

A comparison of Panels a and b suggests that the values in both panels follow a similar pattern during the whole of September 1999: 1) an increase between days 1–6, 2) a disturbance between days 7–11, 3) an abrupt decrease on day 12, 4) a general decrease along with a fluctuating profile between d. 12–16, 5) a recovery between d. 16–20, 6) an intense decrease on day 22, 7) a recovery phase until d. 26, and 8) a general small decrease between days 27–31. The impressive similarity of the local magnetic field in Taiwan with the index *Dst*, which reflects the global variation of magnetic field suggests that: 9) the magnetic field profile in Taiwan reflects not local physical processes but global variations in the Earth's magnetic field, and (b) the long lasting weak magnetic field decrease (days 12–20.9.1999) and the abrupt intense decrease (22–25.9.1999) in Taiwan reveals a CIR-induced storm and a CME-induced storm, respectively. In particular, we infer that the striking similarity of the profiles of two profiles strongly suggests a dependence of the local magnetic field before the Chi-Chi 1999 earthquake (days 12–20.9.1999) on space physical processes.

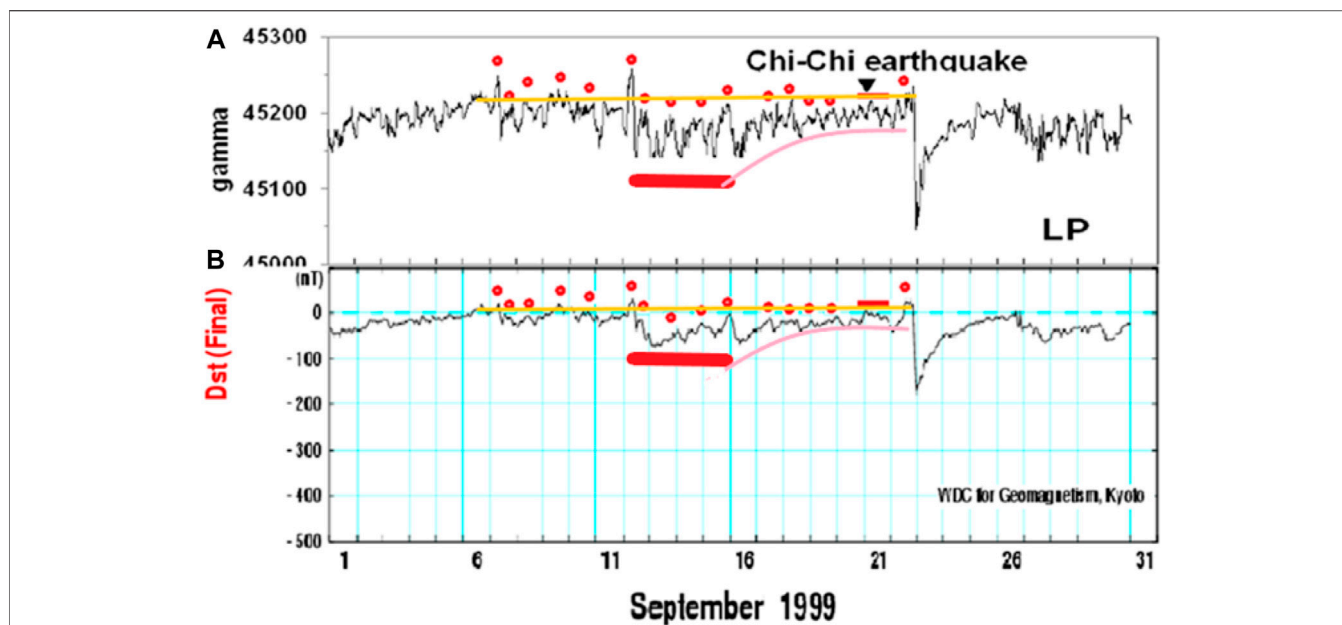


FIGURE 2 | Local magnetic field B at LP observatory, Taiwan (top panel) along with the Global Dst index of the geomagnetic storm activity in September 1999, including the time of the catastrophic Chi-Chi, 1999 earthquake. It is obvious that the two profiles are similar (**A**, **B**) during almost all September, and enhanced fluctuation occurs almost simultaneously in (**B**) and Dst values, during a general decrease in both profiles, before the time of the Chi-Chi earthquake (black arrow in **A**). The pre-earthquake magnetic profile in Taiwan obviously reflects the geomagnetic storm activity as indicated by the index Dst (see in the text).

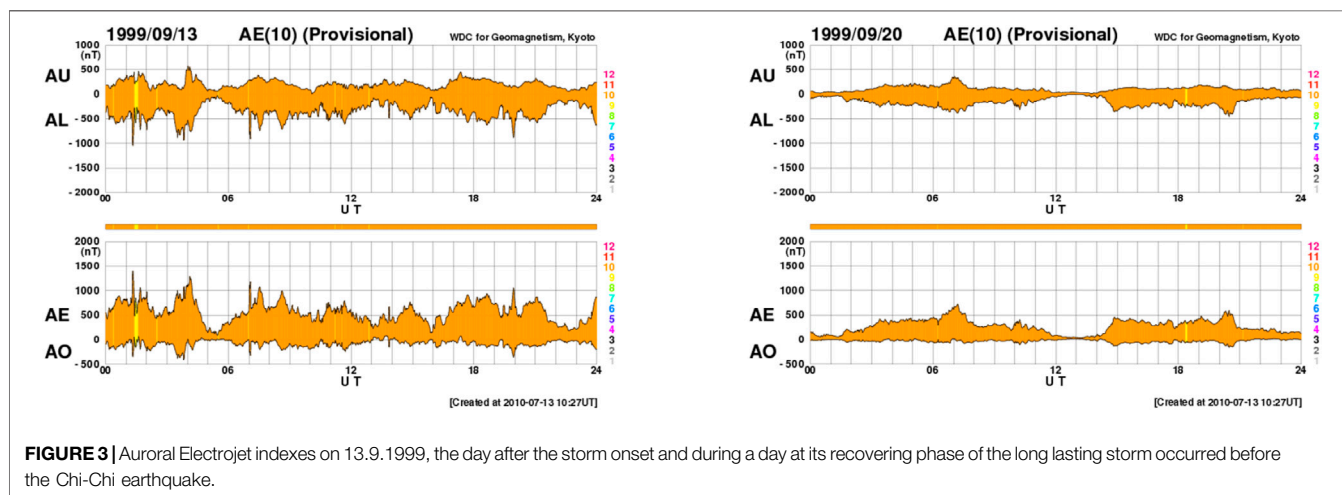


FIGURE 3 | Auroral Electrojet indexes on 13.9.1999, the day after the storm onset and during a day at its recovering phase of the long lasting storm occurred before the Chi-Chi earthquake.

In order to further check the nature of the magnetic field variations in September 1999, we also check the presence of geomagnetic storm activity at high latitudes by examining the auroral electrojet indexes AU, AL, AE and AO. The Auroral Electrojet indexes monitor the magnetic signature of the eastward and westward auroral electrojets in the Northern hemisphere and they have been usefully employed both qualitatively and quantitatively as a correlative index in studies of substorm morphology. To calculate the AE index, magnetograms of the H components of 12 observatories have been uniformly distributed over the longitude in the northern hemisphere at auroral or subauroral latitudes between 60° and 70° (Shadrina, 2017).

In **Figure 3** the AU, AL, AE and AO indexes are shown on a day near the beginning of the long lasting magnetic field disturbance in Taiwan (13.9.1999), and on a day at the recovery phase of the field. It is evident that the auroral electrojet indexes AU, AL, AE and AO show a strong storm activity on day 13 (http://wdc.kugi.kyoto-u.ac.jp/ae_provisional/199809/index_19980913.html) and a weak activity on day 20.9.1999 (http://wdc.kugi.kyoto-u.ac.jp/ae_provisional/199809/index_19980910.html), in agreement with the Dst variations seen in **Figure 2B**. We infer that the local magnetic variations in Taiwan between days 12–20.9.1999 reflect the progress of a geomagnetic storm recorded at both the low and the high

latitudes. The comparison of **Figure 3B** to **Figure 2B** and **Figure 3** confirm a space and not a local (terrestrial) physical process being the cause of the Taiwan magnetic field variations (including sub-ULF activity) for about 10 days before Chi-Chi EQ.

Test 3. The Magnetic Variations in Taiwan Is Controlled by Space Weather Conditions

We mentioned earlier that the flow of plasma from the solar corona is non-uniform in both time and space (Phillips et al., 1995), and a compressive region is often formed at the interface of the fast stream with the upstream slow stream. When these structures last for long times they form corotating interaction regions (CIRs) in the interplanetary space and when the CIRs are well developed, they are bound by a fast forward (FS) and fast reverse shock (RS).

The most typical variations of plasma parameters of a CIR are: 1) an increase in the solar wind plasma density N and the interplanetary magnetic field B , due to the 'pile-up' of material at the leading edge of the fast wind, 2) a long lasting high speed solar wind and 3) the presence of large amplitude low frequency (Alfvén) waves, in particular within the CIR, between the FS and the RS. When the CIR incident on the Earth's magnetosphere trigger long lasting weak or moderate magnetic storms (Tsurutani et al., 2006; Borovsky and Denton, 2006; Kavanagh and Denton, 2007; Richardson, 2018) and various other important phenomena in the Earth's environment. We investigate now the possible incident of a CIR as possible agent of the long duration time moderate geomagnetic storm (**Figure 2B** and **Figure 3**) and the subsequent magnetic field imprint in Taiwan (**Figure 1**), between September 1220, 1999.

In order to apply Test 3, that is the possible relation of the geomagnetic variations between 1220.9.1999 with the arrival of a CIR, we analyze space observations from the Advanced Composition Explorer (ACE) spacecraft, which is in orbit around the L1 Sun-Earth libration point, at a distance of $\sim 220 R_E$ from Earth (R_E : the Earth's radius). The ACE is a satellite, which is in general used in space weather studies in order to predict or explain space induced variations in the environment of Earth, as, for instance, geomagnetic storms, radiation belt electron variation status etc. (Stone et al., 1998).

Figure 4 shows magnetic field data in spherical coordinates (B , θ ϕ) in the three top panels, A, B and C, from the Magnetometer Instrument (MAG) (Smith et al., 1998) and solar wind density, temperature and speed in panels D, E and F from the Solar Wind Electron, Proton, and Alpha Monitor (SWEPAM), for the time interval September 8–22, 1999.

In this figure we can see characteristic features of a CIR structure bounded by a MHD FS on day 12 of September and a RS on day 15.9.1999. For instance, we can notice an increase in magnetic field magnitude B (panel A), in solar wind speed V_p (panel F) in solar wind density N_p (panel D), and proton density which indicate the arrival of the FS, on day 12th of September. Furthermore, we see a long lasting increase of the solar wind speed V_p , which starts with the arrival of the CIR, on September 12, 1999 and drops to pre-CIR values on September 20, 1999,

along with intense northsouth sub-ULF magnetic field direction fluctuations (values; panel B).

By comparing **Figures 1, 2, 4** we infer that both the long lasting geomagnetic storm and the magnetic field decrease in Taiwan started on day 12.9.1999 at almost the same time as the arrival of the CIR in the near Earth interplanetary space (ACE). Furthermore, the time interval of the most intense magnetic field fluctuations recorded in Taiwan coincides with the time interval of the CIR at ACE; the intense magnetic field fluctuations started on day, 12.9.1999, the day of FS and lasted until 15 September 1999, the day of RS (red bar in **Figure 1A**).

The ACE observations shown in **Figure 4** obviously confirm the hypothesis that the longlasting geomagnetic variations between 12 and 20.9.1999 in Taiwan and in the magnetosphere are related with the arrival of a CIR, which evidently was the cause of the magnetic field variations (Kavanagh and Denton, 2007; Badruddin et al., 2018; Richardson, 2018) observed in Taiwan between 1220.9.1999. Test 3 definitely confirms that a CIR was the cause of the long lasting geomagnetic storm (**Figures 2, 3**) and of the related magnetic field anomalies in Taiwan (**Figure 1**) observed before the Chi-Chi earthquake.

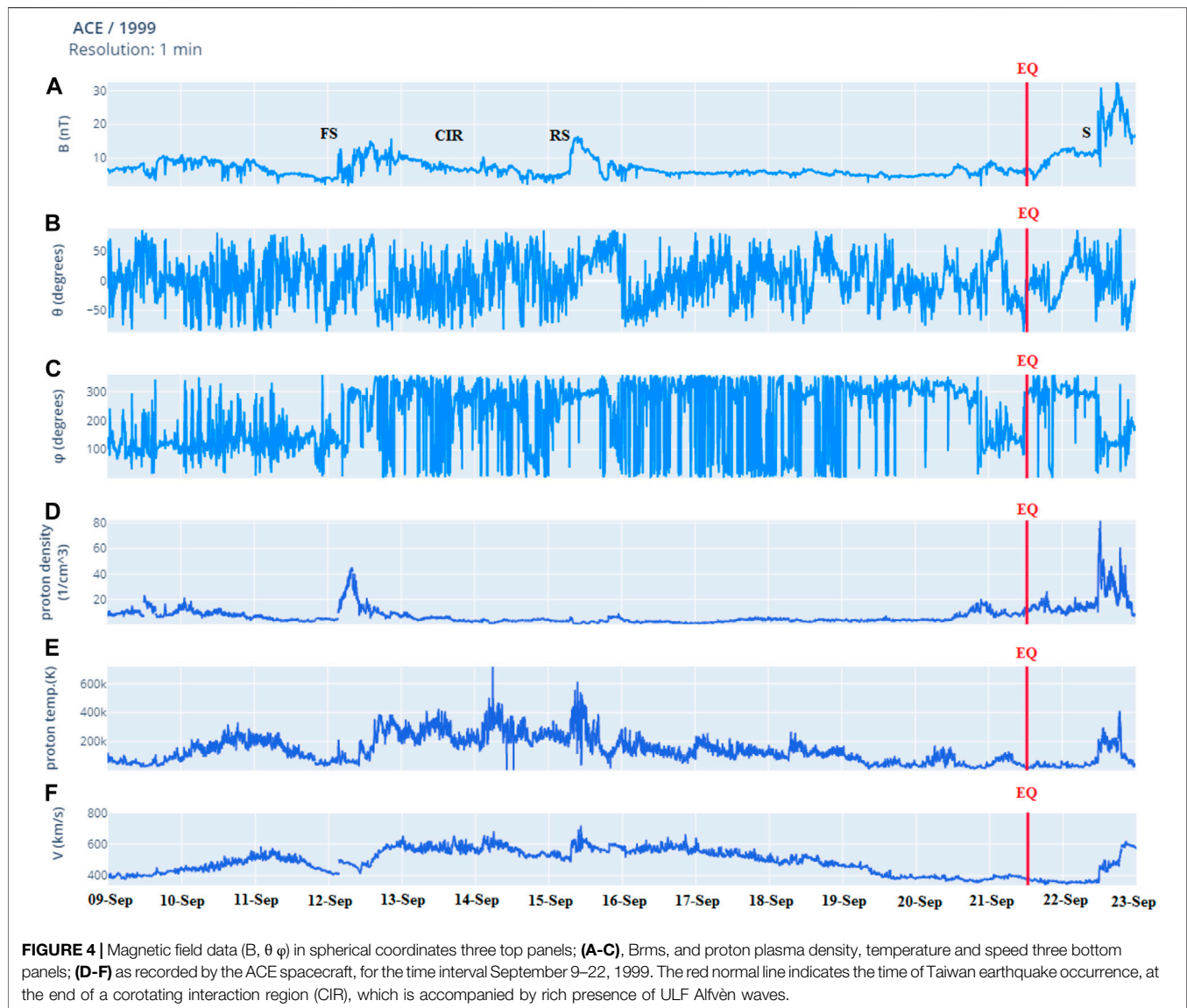
Test 4. Magnetic Sub-Ultra Low Frequency Waves in Taiwan Are Related With Magnetohydrodynamic Wave Activity

Since we found strong observational evidence that the long lasting magnetic field decrease before the Chi-Chi EQ (12–20.9.1999) was a signature of the CIR incidence on the Earth's magnetosphere, we now further focus on the generation process of the pre-EQ sub-ULF magnetic field waves themselves.

In the previous (sub)sections we provided significant evidence that not only the pre-EQ magnetic field decreases, but also its general profile, including the sub-ULF magnetic field wave activity, is consistent with an external (space) cause. Now we investigate the exact generating mechanism of the sub-ULF magnetic field fluctuations between 12 and 20.9.1999.

It has been found that solar wind speed, solar wind ULF waves, the negative component B_z of the IMF and solar wind density perturbations are correlated with ULF magnetic pulsations on the ground (Bentley et al., 2018; Hynönen et al., 2020). Although solar wind speed has been considered as having the largest effect on the ground ULF power compared to the other parameters (solar wind ULF waves, the negative IMF component B_z and solar wind density perturbations), we examine here the (possible) contribution of the solar wind ULF Alfvén waves to the ground sub-ULF fluctuations before the Taiwan 1999 EQ. For this reason we compare here, for the first time, simultaneously obtained measurements in space, by the ACE spacecraft, and on Earth, by magnetic field observatories in Taiwan.

We have already mentioned that the solar wind is a source of MHD sub-ULF Alfvén waves, particularly at frequencies around 1 mHz (Barnes, 1983). In particular a series of studies has also confirmed that Alfvén waves are a ubiquitous feature of CIRs (Smith et al., 1995; Richardson, 2018) and that they have important implications for coupling of the interplanetary space



to the magnetosphere (Tsurutani et al., 2006). Two processes transform the ULF wave energy that enters the magnetosphere from outside: the field line resonance and the cavity resonance (Southwood and Hughes, 1983). The two processes interact with each other. Standing waves in the cavities feed energy to the field line resonances. Many of the pulsations seen at the ground are caused at the ends of field lines set into motion by a complex process involving coupling of the propagating waves to resonant cavities, and these, in turn coupling to field line resonances (McPherron, 2005). Furthermore, it has been confirmed that the 2–10 mHz EM power increases with an approximate power law dependence on solar wind speed, at all local times (Hynönen et al., 2020). Finally it worths noting that the space controlled signal seen at the ground is not the MHD waves themselves, but electromagnetic waves radiating from electric currents induced in the ionosphere by the external source (McPherron, 2005).

In **Figure 5** we compare magnetic field data obtained by the ACE spacecraft upstream from the Earth's bow shock (panels A and B) and by the LNP observatory in Taiwan (panels C and D) on day 13 September 1999, between 0 and 12UT. In particular, the two upper panels display the magnetic field magnitude (panel A) and the angle in polar coordinates (panel B), as measured by the magnetometer instrument MAG onboard ACE. The two bottom panels show the magnetic field component B_z (panel C) as well as the magnitude of the total magnetic field, as measured at LNP observatory in Taiwan.

We have seen that day 13 was characterized by intense geomagnetic storm activity (**Figure 3**), which was caused by the arrival of a CIR on day 12.9.1999 (**Figures 3, 4**). **Figure 5** suggests that day 13, 0-12UT, was also a period of large amplitude magnetic field fluctuation at the position of the ACE spacecraft, far upstream from the Earth's magnetosphere. From **Figure 5** we also see that the magnetic field gradually decreases and it shows a

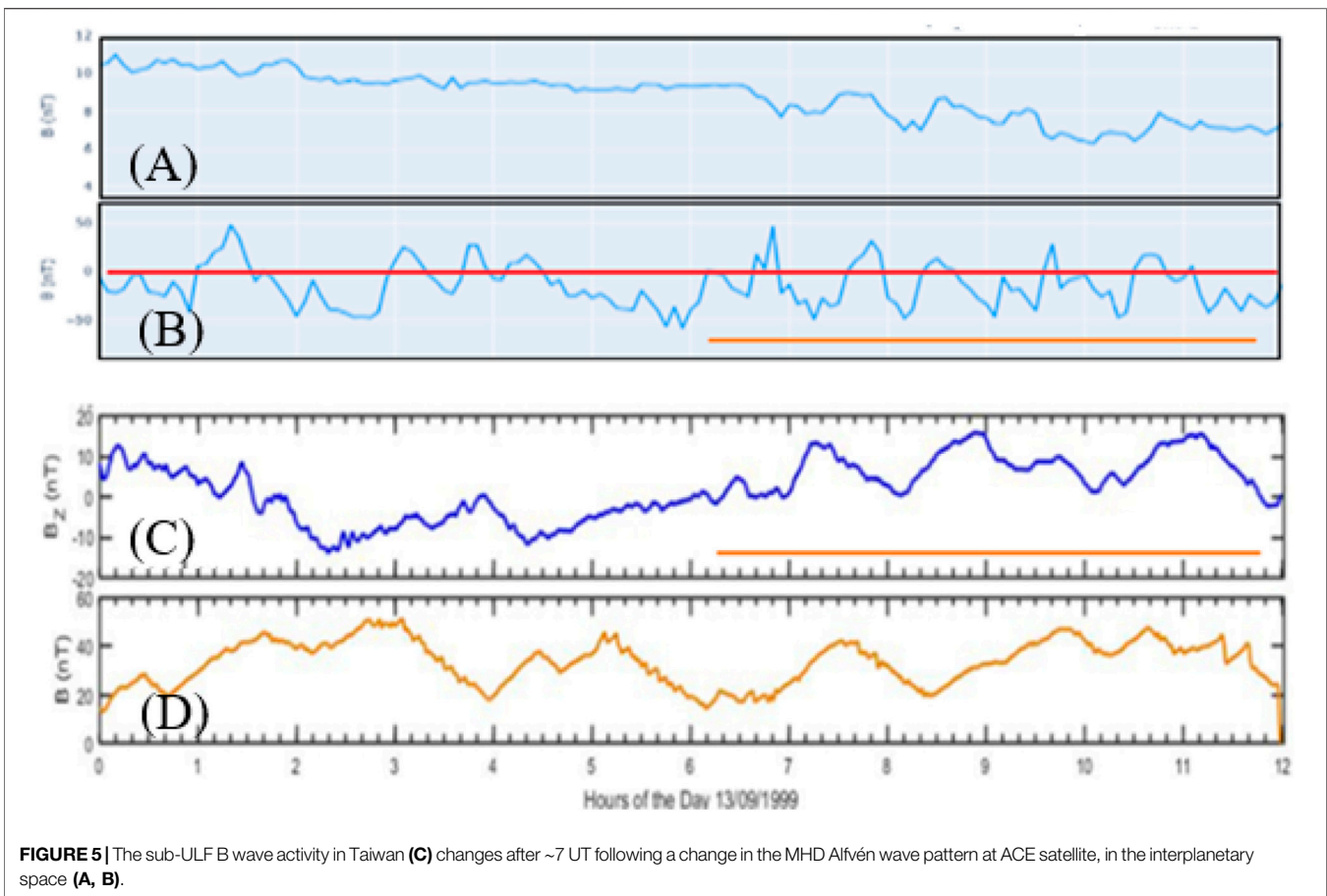


FIGURE 5 | The sub-ULF B wave activity in Taiwan **(C)** changes after ~ 7 UT following a change in the MHD Alfvén wave pattern at ACE satellite, in the interplanetary space **(A, B)**.

variable magnetic field direction during the whole 12-h period examined.

Panel b suggests that the magnetic field turns quasi-periodically in the southward direction. The southward IMF turning is the main condition that triggers geomagnetic storms (Dungey, 1961) and, indeed, we see that the storm activity is high at the same time period (Figures 2, 3). The type of the waves are MHD Alfvén waves, as inferred from the almost stable magnetic field magnitude and the large variations of the azimuthal angle (Chen, 2016), which sometimes changes from $\sim -50^\circ$ to $\sim +50^\circ$ (panel b).

From the comparison of the curves in panels a, b, c, and d, we infer that the magnetic field at the LNO/Taiwan observatory also fluctuated. In particular, we see that the wavy pattern changes after ~ 6 UT both in the interplanetary space (ACE) and on the ground (LNO/Taiwan) in the first and the second part of the time period examined. After ~ 6 UT (horizontal orange lines in Figure 4) both the IMF and the terrestrial magnetic field become much more turbulent than between 0 and 6 UT; this evident when we compare the latitudinal magnetic field angle at ACE (panel B) and the north-south magnetic field variation in Taiwan (panel C).

There is another interesting point to note in Figure 5. The increased magnetic field fluctuation at Earth after ~ 6 UT is preceded by successive southward turning of IMF, which is a cause of magnetic storms and a more turbulent magnetic field on

Earth. Furthermore, some variations in the IMF magnitude, after $\sim 07:00$ UT, might contribute to geomagnetic triggering due to changes in the electromagnetic pressure on the Earth's magnetosphere (Takahashi et al., 2012). The magnetic field fluctuation variation at both sites, in the interplanetary space and in Taiwan, shows a period of ~ 1 h, that is a frequency < 1 mHz (with somewhat longer period waves at Earth than at ACE).

We infer that the wave patterns in Taiwan and at ACE seen in Figure 5 show remarkable relations. Since a variety of physical factors influence the propagation of an electromagnetic signal from the position of ACE, in the interplanetary space, to the Earth's surface, the above noted relations are remarkable and suggest that the sub-ULF activity in the solar wind made a significant contribution on the ground magnetic field waves (Fraser, 2009; Shi et al., 2020)

Test 5. The Geomagnetic Activity in Taiwan Is Correlated With a ~ 28 -days Corotating Interaction Region of Solar Origin

Tests 1 to 4 support the concept that the sub-ULF magnetic field wave activity observed in Taiwan before the Chi-Chi EQ (12–20.1999) is consistent with a CIR-induced long lasting geomagnetic disturbance.

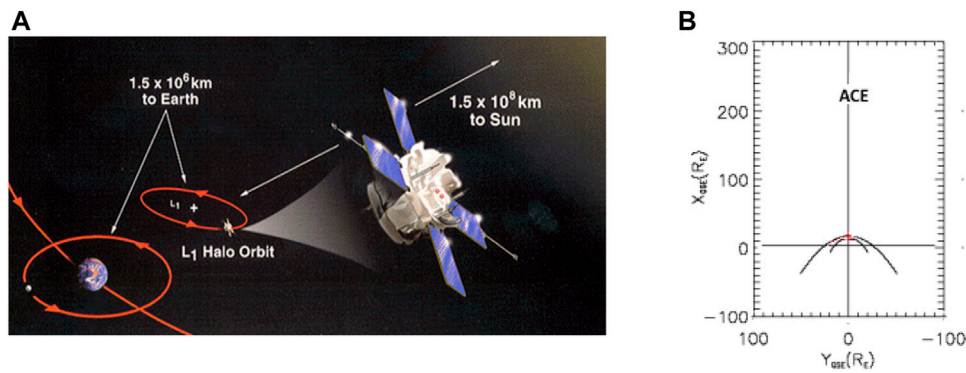


FIGURE 6 | ACE circulating around the L_1 Lagrangian point (A), at a distance of $\sim 220 R_E$ (B).

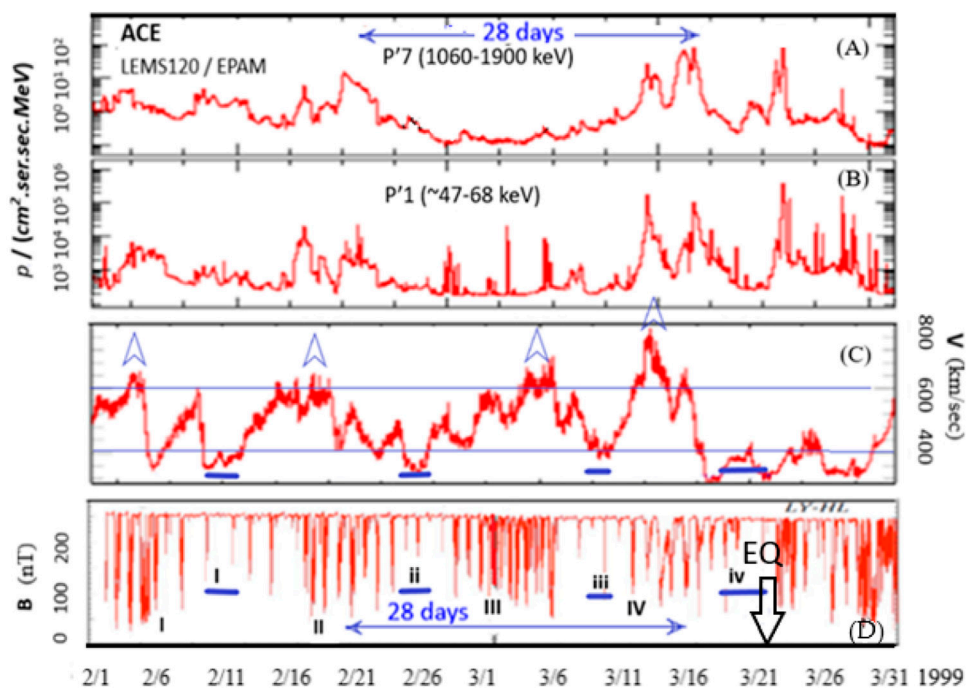


FIGURE 7 | From top to bottom: proton flux of low (ACE/LEMS120/P'2) and high (ACE/LEMS120/P'7) energy protons in the interplanetary space from the solar direction (A, B), solar wind speed (C), and (D) the magnetic field fluctuations. Tests 5, 6 and 7 are based on the comparison of simultaneous measurements obtained by the ACE spacecraft in the interplanetary space and by the magnetic field observatories in Taiwan for time long enough to cover at least two successive, about 28 days separated CIRs.

We now perform one more test concerning the space origin of the sub-ULF magnetic fluctuation before the M7.2 Chi-Chi EQ. Since 1) CIRs are a provoking agent of great EQs (Anagnostopoulos et al., 2021 and references therein), 2) CIRs-induced storms appear a characteristic ~ 27 -days periodicity in the late 1999 (Borovsky and Denton, 2006) and 3) the CIR-induced storms are characterized by sub-ULF wave activity on the ground (McPherron, 2005; Shi et al., 2020), we examine the hypothesis that ULF wave activity in Taiwan follows the solar $\sim 27/14$ days periodicity of the CIRs. A correlation of the ground pre-EQ sub-ULF activity with CIRs in the interplanetary

space would be an additional, very strong evidence of their space origin. The data in the interplanetary space were obtained by the ACE satellite (Figure 6).

For this reason, in Figure 7, we compare physical processes in interplanetary space, in the magnetosphere and on Earth (Taiwan) during a period of 7 weeks (from August 13 to September 30, 1999). The near Chi-Chi, Taiwan (adapted from Freund and Pilorz, 2012) from August 13 to September 30, 1999.

In particular, in Figure 7, we display, from top to bottom, 1) interplanetary space low and high energy proton flux

measurements from the EPAM instrument onboard the ACE spacecraft (panels A and B) 2) the space plasma proton speed measured by the Solar Wind Electron, Proton, and Alpha Monitor (SWEPAM) onboard the same spacecraft, (panel C), and 3) the 12-h running average difference of magnetic field values measured at the LY station minus those at the HL station in Taiwan. (adapted from Figures 15A,B of Freund and Pílorz (2012)). The 12-h running average difference of magnetic field values were used to emphasize the overall envelope. The energetic proton fluxes from channels P'1 (~47-68 keV), and P'7 (1060-1900 keV) were selected because of the general Sunward direction of the LEMS120/EPAM telescope (<http://sdwww.jhuapl.edu/ACE/EPAM/idf.html>), which allows investigation for particle streaming from the Sun.

When focusing on the time period before the Chi-Chi EQ (indicated by an arrow in panel E) we see a structure indicating an increased wave activity between days 12–19.9.1999 (ULF wave group marked IV), which correspond to the geomagnetic storm and the wave activity in Taiwan examined in the previous subsections (Figures 1–5; Tests 1–5). During this period the solar wind speed V (panel C) reached its highest values $V = \sim 800$ km/s that is ~ 2 times the normal value of solar wind speed.

Figure 7 also shows that, during days 12–20.9.1999, the enhanced solar wind speed values and the ULF wave group IV are also associated with enhanced proton fluxes showing two distinct peaks (panels A and B). These two flux peaks are related to the forward shock (FS) and the reverse shock (RS) of the CIR examined in Figure 4, and they reveal proton accelerating at the two edges of the CIR shocks (FS and RS). The coincidence of 1) the energetic particle flux enhancements (panels A and b), 2) the high solar wind speed structure (panel c), 3) the magnetic field profiles revealing the presence of a CIR (Figure 3) and (iv) the ULF wave group IV in Taiwan is in agreement with the CIR as a cause of the terrestrial magnetic field fluctuation at those times (Fraser, 2009; Richardson, 2018).

We examine now the hypothesis that the 27-days period corotating high solar wind speed streams/CIRs in late 1999 (Borovsky and Denton, 2006) may be related with the ULF wave activity in Taiwan. The observations in Figure 6 (panels A–E) clearly show that the ULF wave group II preceded the ULF group IV by ~ 28 days, that is a time almost equal to the solar rotation period. The data in Figure 7 also suggests the presence of: 1) a high speed solar wind stream (panel F) and 2) two peaks in energetic proton flux (panels a and b) associated with a FS and RS (data not shown here), during the ULF wave group II.

The time difference between ULF magnetic field wave groups II and IV and the appearance of a CIR structure at the times of the two wave groups II and IV suggest that the ULF wave groups II and group IV are related with the same CIR.

It is obvious that the two CIRs, which are associated in time with high solar wind speeds, strong magnetic storm activity and the ULF wave groups II and IV separated by a period of ~ 28 days, before the Chi-Chi EQ, strongly suggest that the two ULF magnetic field wave groups II and IV observed in Taiwan were caused by the incidence of a CIR on the Earth's

magnetosphere (Kivelson and Russell, 1995; Fraser, 2009; Richardson, 2018).

TEST 6. Solar Wind Speed and Taiwan Sub-ULF Magnetic Field Fluctuation

The sub-ULF magnetic field fluctuation (i.e. Pc 5 pulsations, in the frequency band 2–7 mHz; Jacobs et al., 1964) correlate well with solar wind speed (Engebretson et al., 1998; Kessel, 2008, Pahud et al., 2009; Hynönen et al., 2020). However, solar wind speed has been considered to have the largest effect on the ground ULF power compared to the solar wind ULF waves, the negative component B_z of the IMF and the presence of solar wind density perturbations (Bentley et al., 2018; Hynönen et al., 2020).

Based on the above space weather-terrestrial relations, we apply an additional test for the origin of the Taiwan sub-ULF wave activity before the Chi-Chi EQ (TEST 6). Since it is known that the sub-ULF wave activity is a normal result on Earth related with high solar wind speeds, we elaborate on the whole period examined in Figure 6, the possible relation of the changes of the sub-ULF wave activity before the Chi-Chi EQ with changes in the solar wind speed as observed by ACE in the interplanetary space.

In order to do that we name the four groups of the sub-ULF magnetic field fluctuation by numbering I, II, III, IV and the periods with absence or weak magnetic field activity by i, ii, iii, iv. The quiet periods i, ii, iii, iv, at times when the solar wind speed falls below the usual limit of 400 km/s, for more than 1 day, are marked by horizontal bars (panels D and E) to facilitate the solar wind speeds-Taiwan ULF EM waves comparison.

Such a comparison reveals that (A) during the four groups I, II, III and IV the solar wind speed V reaches maximum values between 600 and ~ 800 km/sec (blue horizontal line) and (B) during the four periods of weak or absence of magnetic field wave activity (intervals called i, ii, iii and iv), the solar wind speed reaches its lowest values, below the usual level of 400 km/s (blue bars in panels D and E).

This correlation between the solar wind speed values and the presence/absence of the magnetic fluctuation in Taiwan, along with the previous Test 5, confirms that an external agent controls the sub-ULF magnetic fluctuations in Taiwan during 7 months before the Chi-Chi 1999 earthquake. This finding is consistent with recent statistical results (Gulyaeva, 2014; Rekapali, 2014; Anagnostopoulos et al., 2021)

Furthermore, it worths noting that the analysis of polarization (the ratio of vertical magnetic field component Z to the horizontal component G), that the polarization (Z/G) showed a significant enhancement for 2 months before the Chi-Chi earthquake. Akinaga et al. (2001) pointed out that this temporal evolution of polarization seems to be associated with the Chi-Chi earthquake. These authors accepted as the generation mechanism of the sub-ULF (~ 0.01) Hz emissions the microfracturing model by Molchanov and Hayakawa (1995). However, the present study suggests that the temporal evolution of the polarization (Z/G) is related with the special space weather during the last 2 months before the Chi-Chi earthquake and most probably is the result of semi-continuous magnetic storm activity. However, this result should be further tested.

Test 7. Long Time ~14-days Periodicities in Space and in Taiwan

It is generally known that the ~27-days solar rotation controls many physical processes in the Earth's environment. The existence of a sole intense high speed solar wind stream emanating from the Sun causes ~27/28-days periodicities in various physical phenomena both in the near Earth environment and on the ground. The existence of more than one solar wind stream can produce additional periodicities. For instance a second high speed solar wind stream produces a ~13/14-days periodicity in the interplanetary space, in the Earth space and on Earth. Intense CIRs are observed as periodic (~27/28-days, ~13/14-days) phenomena even beyond the Earth's orbit, in the deep space (Burlaga, 1997; Anagnostopoulos et al., 2009).

The ~27/~13-days periodicity of high speed solar wind streams influence the Earth's magnetosphere in many ways. Among other phenomena, a power spectrum analysis recently revealed a ~27/13-days periodicity in the global seismic energy output, in particular during a quiet Sun (Anagnostopoulos et al., 2021).

The ~14 days-periodicity in sub-ULF activity is also seen in **Figure 6** in the ~14 days time separation of the four groups I, II, III and IV. This periodicity was also clear in the results of a Fourier Transform performed by Freund and Pírolz and (2012).

Since the four sub-ULF magnetic field wave groups I, II, III and IV are related with the arrival of the presence of high speed solar wind speed, we infer that the ~14 days-periodicity evaluated by Freund and Pírolz was of a clear space origin (and it is not due to the gravitational forces exerted by the moon and the Sun).

The space origin of the ~14 days-periodicity is also consistent with the fact that (both the onset and the maximum of) the four ULF groups I, II, III and IV earthquake reach earlier than the seismic energy E in all the four long lasting events before the Chi-Chi 1999 EQ.

The results from Tests 1–7 in a variety of observations in the interplanetary space and on the ground strongly suggest that the sub-ULF magnetic fluctuations in Taiwan during 7 months before the Chi-Chi 1999 earthquake are related with physical processes resulting from the interaction of high speed solar wind streams.

DISCUSSION

Great earthquakes as well as global seismic energy output have recently been confirmed as depending on solar activity and the subsequent space weather. Enhanced seismicity was found to be higher during times of a quiet Sun, when the sunspot number (SN) is low (but not in the deep minimum). Such solar conditions allow high solar wind speed streams to emanate from coronal holes and form structures rotating in the interplanetary space with the ~27-days period of solar rotation. Low SSN conditions and ~27-days corotating interaction regions (CIRs) are mostly observed in the decay phase throughout the ~11-years solar cycle, but also during the rising solar cycle phase as well as during short time intervals (some months) in the solar maximum phase. During such periods with small SN a ~27-days periodicity was revealed in seismic energy release at Earth (Anagnostopoulos et al., 2021). The seismic activity is in general anti-correlated to

the SSN. One of the results of our previous paper is the finding that all of the 16 giant ($M \geq 8.5$) EQs between 1900 and 2017 occurred during the decay and the rising phase of the solar cycle or at times of a strong SN reduction.

The question raised from the above Solar-terrestrial relationship is which physical mechanism mediates space weather (CIRs) with the lithosphere in order to provoke great earthquakes or high global seismic energy release.

In the present case study we tested the hypothesis whether the sub-ULF (<1 mHz) magnetic field activity before a great EQ may be of a space origin, and therefore, a possible final agent of the EQ itself. The sub-ULF (<1 mHz) magnetic field activity is a well known phenomenon in the space community resulting from CIR incidence on the Earth's magnetosphere, while it has been also accepted as an earthquake precursor resulted from lithospheric processes, as we reported in *Theoretical and Observational Framework*.

As a case study we selected to investigate the great (7.7 M_w) Taiwan September 20, 1999 earthquake, which has been shown to be preceded by a long time period of sub-ULF (<1 mHz) magnetic field activity. To this end, we performed seven observational tests. Furthermore, for the first time in earthquake prediction scientific literature, we compared simultaneous space observations in the interplanetary space and magnetic field waves on the ground.

The enhanced sub-ULF (<1 mHz) magnetic field wave activity in Taiwan was previously attributed to tidal loading and unloading of the Earth's crust, due to the gravitational forces exerted by the moon and the Sun. However, it was also noted that since the gravitational forces are relatively weak, the seemingly tight coupling between the Earth tides and both ULF emission and regional seismicity, comes as a surprise (Freund and Pírolz, 2012).

The concept of gravitational tidal triggering has been known for more than 110 years (Schuster, 1897; Emter, 1997). However, several studies have reported either no correlation between the Earth's tide and earthquake occurrence (Heaton, 1982; Vidale et al., 1998; Kennedy et al., 2004) or small positive correlations (Tanaka et al., 2002; Cochran et al., 2004) under several restrictions, as for instance, for a particular geographic region (Tolstoy et al., 2002; Kasahara, 2002), earthquake magnitude range (Wilcock, 2001; Tanaka et al., 2002; Kasahara, 2002) and increasing tidal stress levels. Métivier et al. (2009) found that small magnitude (less than magnitude 4.0) EQs are more easily triggered by tides.

Our data analysis during the period of 7 weeks before the Taiwan 1999 earthquake provides significant information concerning the origin of ~27/28 and ~13-days ULF wave periodicity found by Freund and Pírolz (2012). Our analysis strongly suggests that the ~14-days periodic detection of four groups of ULF wave activity in Taiwan was the result of four almost simultaneous events of high speed solar wind streams observed by ACE in the interplanetary space. More studies are needed to further check the origin of sub-ULF (<1 mHz) magnetic field waves before other great earthquakes.

However, preliminary examination of several great earthquakes suggests that the pre-EQ sub-ULF (<1 mHz) magnetic field wave activity seems to be in general CIR-induced geomagnetic phenomena.

The data examined in the present study provide strong evidence that four groups of enhanced sub-ULF (<1 mHz) magnetic field waves in Taiwan were related in time with four groups (Figure 6; groups I, II, III, IV) of high speed solar wind streams for 7 weeks before the great September 21, 1999 E. The relation of magnetic storm activity, its imprints on the ground and the associated subULF magnetic fluctuation in Taiwan with the high speed solar wind streams and sub-ULF Alfvén waves in the interplanetary space is consistent with space weather as the agent of ULF magnetic terrestrial fluctuation (Bentley et al., 2018; Hynönen et al., 2020) observed for 7 weeks before the Chi-Chi EQ.

Our study includes a more detailed data analysis for the fourth group of enhanced sub-ULF magnetic field activity (noted I Figure 6 as IV), which was observed between days 12–20.9.1999. At almost the same time a strong CIR produced a significant reduction in magnetic field magnitude, which was recorded by observatories in Taiwan. The Chi-Chi EQ occurred at the end of the CIR, on day 20.9.1999, whereas another earthquake in southern Taiwan (Chia-Yi) occurred after a solar rotation, at the end of the next arrival of the CIR preceding the Chi-Chi EQ.

Enhanced solar wind speed, sub-ULF Alfvén wave activity, magnetic pressure and southward IMF have been confirmed in space science to produce sub-ULF magnetic field activity at Earth (Fraser, 2009). In the time period we examined in this study, actually both enhanced solar wind speed (up to ~800 km/s) and intense sub-ULF Alfvén wave activity were observed by the spacecraft ACE, almost simultaneously with the enhanced magnetic field activity in Taiwan during the four groups. Some observational evidence on day 13.9.1999, 0–12UT, during the main phase of the CIR-induced storm, suggests that when the pattern of the IMF wave activity changed, the terrestrial magnetic field wave activity changed as well. This observation suggests a principal role of the IMF wave activity at least at that time (day 13.9.1999, 0–12UT).

Our present results from the study of the precursory physical conditions before the Taiwan 7.7 M_w EQ provide evidence that the pre-EQ sub-ULF (<1 min) magnetic wave activity may indicate a potential cause and not the result of tectonic stresses. This hypothesis is consistent with the fact that MHD generators have been used to activate local earthquakes (Pulinets and Boyarchuk, 2004; Sorokin et al., 2012; Novikov et al., 2017). The impact of electrical pulses of DC current injected through emitting dipole into the earth crust on the spatial and temporal distribution of weak seismicity has been confirmed (Tarasova et al., 2000; Tarasov and Tarasova, 2002, 2004; Chelidze et al., 2006). Furthermore, modern laboratory studies of electric triggering of macro events (laboratory “earthquakes”) were carried out at simplified slider system (Chelidze et al., 2002) and spring-block model simulated the seismogenic fault (Novikov et al., 2020).

The statistical results of Anagnostopoulos et al. (2021) and those of the present case study suggest that enhanced seismicity is preceded by CIRs and CIR-induced weak or moderate, but long lasting geomagnetic disturbances. In several cases examined, including the case of the present study (Taiwan 1999) some repeated CIRs, with a period of ~27 days, precede great EQs. We do believe that thereafter a good analysis of space weather should not be ignored in earthquake prediction research. In particular, a

weak geomagnetic activity may be misleading criterion concerning the origin of EQ EM precursory phenomena. Recently, Biswas et al. (2020) presented a paper, where they tried to separate the contamination in ionospheric parameters due to geomagnetic storm and acoustics parameters.

Although, the CME-driven storm is usually a strong phenomenon, it lasts for a short time period; from a few hours to a few days (Tsurutani et al., 2006). The HSSs/CIRs cause weaker magnetic disturbances in Earth’s magnetic field than the CMEs, but during a quiet Sun high speed solar wind streams corotate with the Sun’s 27-days period. Under such conditions several CIRs can affect the Earth’s magnetosphere semi-continuously for a long period of some months. During these long time periods, CIRs can transfer much more energy into the magnetosphere than a single CME (Tsurutani et al., 2006). For this reason high seismicity is well related with the presence of CIR-induced geomagnetic events around the minimum phase of the solar cycle (Gulyaeva, 2014; Rekapali, 2014; Anagnostopoulos et al., 2021). Other external sources, as for instance CME-driven events or Earth tides, possibly make some minor contribution to the preparation process of great earthquakes, but there is not such significant observational evidence.

We note that our understanding of the CIRs-induced sub-ULF electromagnetic radiation is a partner and not just a triggering agent of great earthquakes. This understanding comes, among other reasons, from the fact that all of the 16 giant ($M \geq 8.5$) EQs between 1900 and 2017 occurred during the decay, minimum and the rising phase of the solar cycle or at times of a strong reduction, that is under space weather conditions of a quiet Sun.

In concluding, our recent results suggest that the planet Earth should not be considered as an autonomous body in earthquake prediction research, but we should think about the lithosphere as a boundary between two different cosmic regions, the planet Earth and space. This fact implies that EQ prediction research can gain much from complementary space weather research.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication

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