Space Weather of the Heliosphere: Processes and Forecasts
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Space Weather in the Heliosphere

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Abstract. We live on a very special planet in a very special solar system. Our planet has a benign climate. Our star has several habitable planets and is not so active as to inhibit the exploration and future colonization of these planets. In this short paper we review how the solar wind interacts with the planets, what factors matter in this interaction, and how active is our star.

Keywords. Space weather, solar wind, magnetospheres, reconnection, solar out bursts

1. Introduction

The star we call 'the Sun' burns hydrogen producing helium and excess heat. This energy leaves the fusion zone in the interior of the Sun and is conducted, and convected to the photosphere where it is radiated into space. In the process of moving through the convection zone it generates a magnetic field that has an approximate 22-year cycle (Russell *et al.* 2010) in which the magnetic field forms flux ropes that are unstable to eruptions that produce energetic charged particles. At the current epoch this solar activity produces some hazards to the industrial activities on the surface of the populated, third planet that we call Earth. We refer to this solar energetic particle variability and its associated phenomena as space weather. In this brief treatise we discuss how space weather varies across the solar system and remark how space weather may also occur within the magnetic envelopes of some of the planets. We close with a discussion of the frequency of occurrences of extreme space weather events and their intensity.

2. Magnetic Reconnection in and with the Solar Wind

The most important process in a magnetized plasma is arguably magnetic reconnection. It can change magnetic energy into both thermal energy and directed flows. It can link moving plasmas and thereby transfer momentum. Space weather can be affected by reconnection in the solar wind and between the solar wind and planetary magnetospheres. An example of reconnection in the solar wind is the interaction regions of oppositely directed magnetic fields both rooted in the Sun and extending into space. An example of reconnection of a magnetosphere with the solar wind occurs when the flow of magnetized plasma from the Sun arrives at Earth and generates a magnetic storm. The former is affected by the beta value of the plasma (the ratio of the thermal energy density to the magnetic energy density) and the latter is affected by the magnetosonic Mach number of the solar wind flow relative to the planetary obstacle to that flow. The Mach number in turn controls the beta of the post-shock plasma that reaches the obstacle and therefore affects the reconnection rate at the boundary we call the magnetopause. High Mach numbers produce high beta in turn weakening reconnection (Scurry *et al.* 1994).

Figure 1 shows the expected heliocentric variation of the beta value (right hand scale) and the magnetosonic Mach number (M_{ms}) on the left-hand scale. The changes in B and

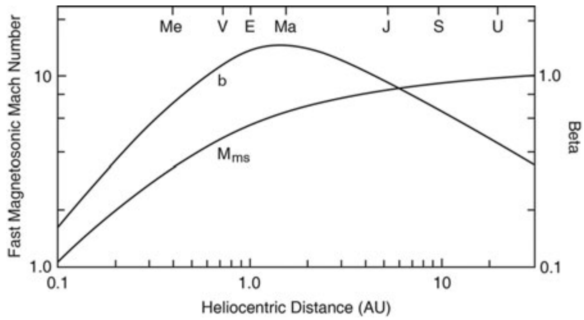

Figure 1. Expected values of plasma beta and solar wind Mach number versus heliocentric distance (Russell et al, 2016).

M_{ms} here reflect expected changes in the solar wind due to expansion and do not include any effects of the interaction with the local interstellar medium. Reconnection in the solar wind (governed by beta) should happen most rapidly near the Sun and far from the Sun. Reconnection between the interplanetary magnetic field and any planetary magnetic fields (governed by Mach number) should happen most readily at Mercury, Venus and Earth and less so at Jupiter, Saturn and Uranus. Flux transfer events (Russell and Elphic 1978) are small and occur rapidly at Mercury (Russell and Walker 1985), and they produce large infrequent events at Earth. They are seldom seen at Jupiter (Walker and Russell 1985) and almost never at Saturn (Lai *et al.* 2012). While no study has attempted to study sector boundary reconnection rates versus heliocentric distance, solar eruptions show that reconnection is very efficient and fast near the Sun.

3. The Role of Size

Size matters in the space weather of magnetospheres in two ways. Figure 2 illustrates the relative sizes of magnetospheres with each other and with their host planets. If the host planet (like Mercury) occupies a major fraction of the magnetosphere then a robust radiation belt will not form. Mercury has no radiation belt. Earth and Saturn have modest radiation belts and Jupiter has a particularly intense radiation belt. Part of energization of the jovian magnetosphere is the agitation of the inner magnetosphere by the material produced by Io's volcanoes. Uranus and Neptune appear to have very quiet magnetospheres and low trapped particle fluxes.

Size can also be judged relative to plasma scale lengths. Figure 3 uses a hybrid simulation to show the change in the disturbance in a flowing magnetized plasma in terms of the size of the obstacle as a function of the ion inertial length (the speed of light divided by the natural frequency of the ions) that is determined by the plasma density. The smallest sized obstacle produces a whistler wave (top pair of panels). A larger obstacle produces a standing compressional wave and a wake. A larger obstacle size produces a quasi-magnetosphere with a bow wave. At largest scales (bottom) the interaction has a bow wave, magnetosheath, and fully developed shock, a magnetopause and plasmas sheet with reconnection on the forward magnetopause and in the tail.

4. Momentum and Energy Transfer

J-W. Dungey (1961, 1963) was the first to understand how reconnection led to momentum transfer from the solar wind to the magnetosphere so that the plasma in the magnetosphere circulated. A moving magnetized plasma has an electric field in the frame of the

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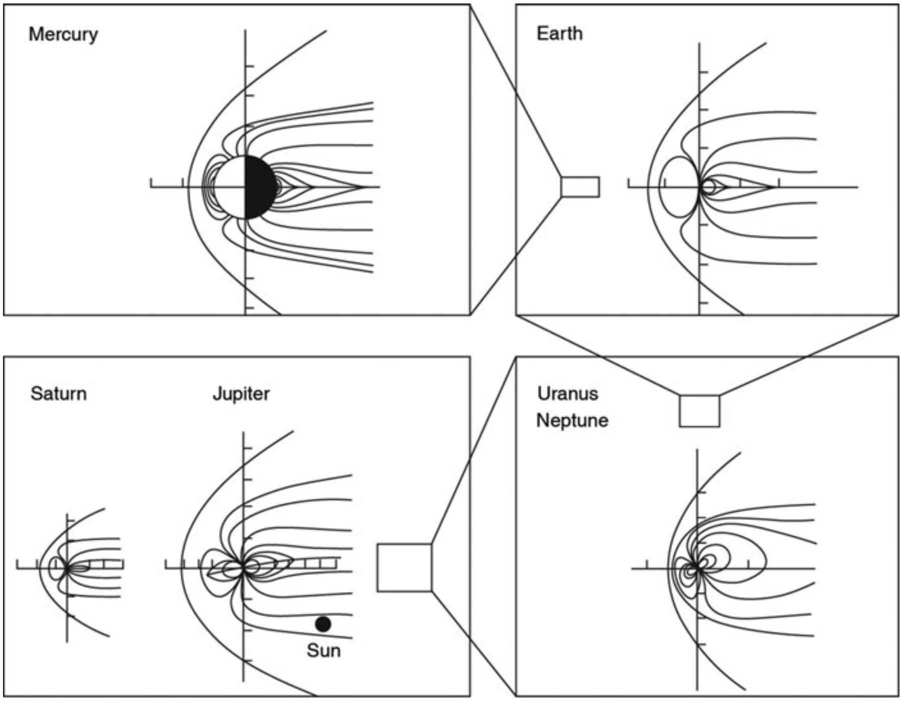

Figure 2. The relative size of the magnetospheres of the magnetized planets.

planet. This electric field affects the magnetosphere differently depending on the orientation of the planetary dipole field. Figure 4 shows the two key diagrams from Dungey's work. The top panel shows the situation for a northward magnetic field convected to the Earth. Antiparallel fields at the boundary allow for interconnection downstream from the magnetosphere. This can produce flows in the magnetosphere that move sunward at high latitudes and tailward at low latitudes.

If the magnetic field in the solar wind is southward, the reconnection can occur at noon and cause a circulation of plasma over the poles away from the Sun and back toward the Sun at low latitudes. Unsteadiness in the process leads to substorms. A strong steady flow will create a magnetic storm.

5. Space Weather in the Magnetospheres of Jupiter and Saturn

The volcanic moon Io, inside the jovian magnetosphere adds mass to that magnetosphere which becomes ionized by Jupiter's radiation belt particles. The rapid rotation of Jupiter spins up that plasma and it stretches the magnetized plasma until it "breaks" in the jovian magnetotail. Most of the plasma is then ejected down Jupiter's tail and the emptied flux tubes "float" inward against the outward flow to reach Io, be mass loaded again, and repeat their journey (Russell *et al.* 2000)). Enceladus, a moon at Saturn has a water plume that massloads Saturn's magnetosphere and reconnection in Saturn's tail allows the flux tube to return to Enceladus and be refilled (Lai *et al.* 2016)

6. Space Weather Events

The first extensively studied space weather event is the Carrington event of September 1, 1859 whose magnetogram is shown in Figure 5 (top panel). It is characterized by a very

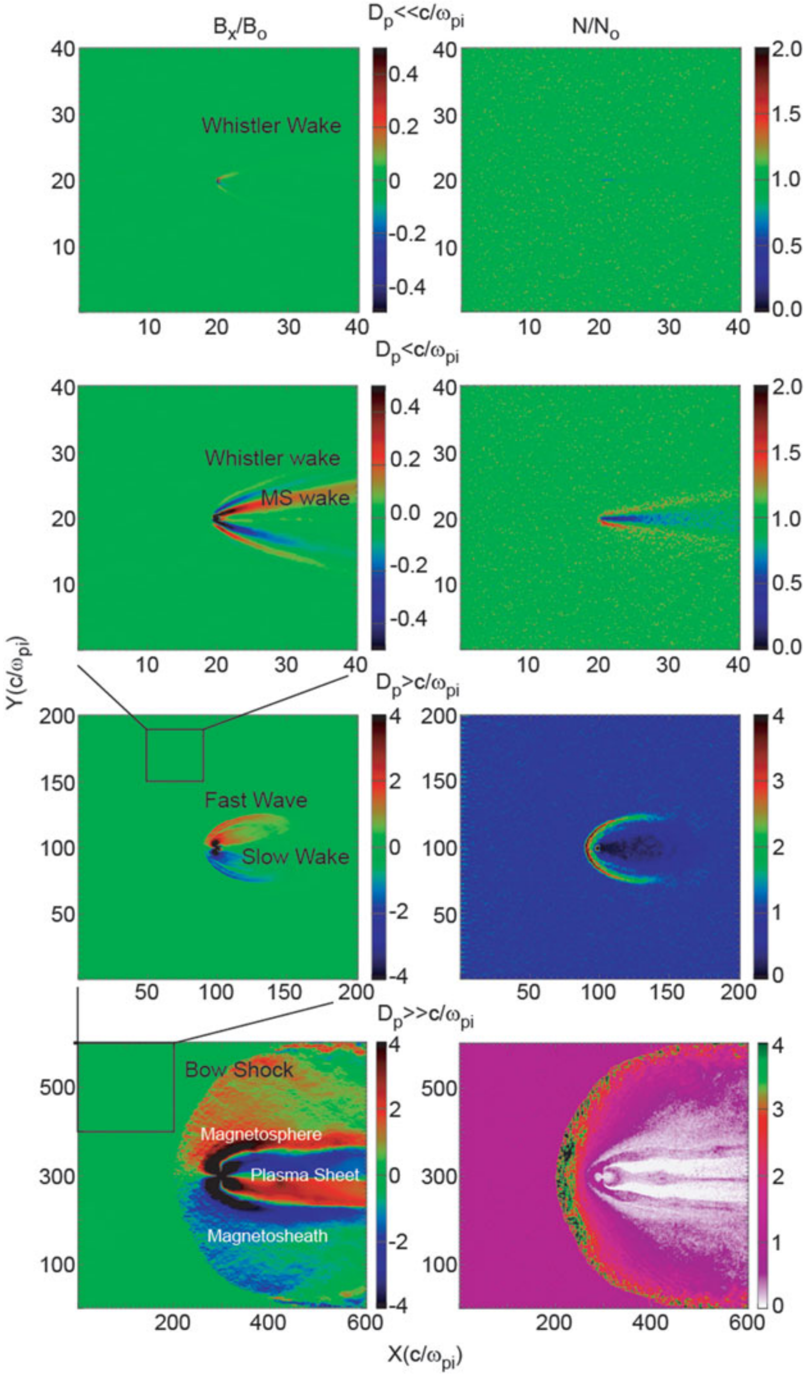

Figure 3. Magnetic field along the flow and the plasma density for four different hybrid simulations of increasing ratio of obstacle size to the ion inertial length. A hybrid simulation uses a particle code for ions and a massless fluid for electrons. The smallest obstacle produces only whistler mode waves when the largest obstacle deflects the flow and produces magnetosonic and Alfven waves (Blanco-Cano et al. 2004).

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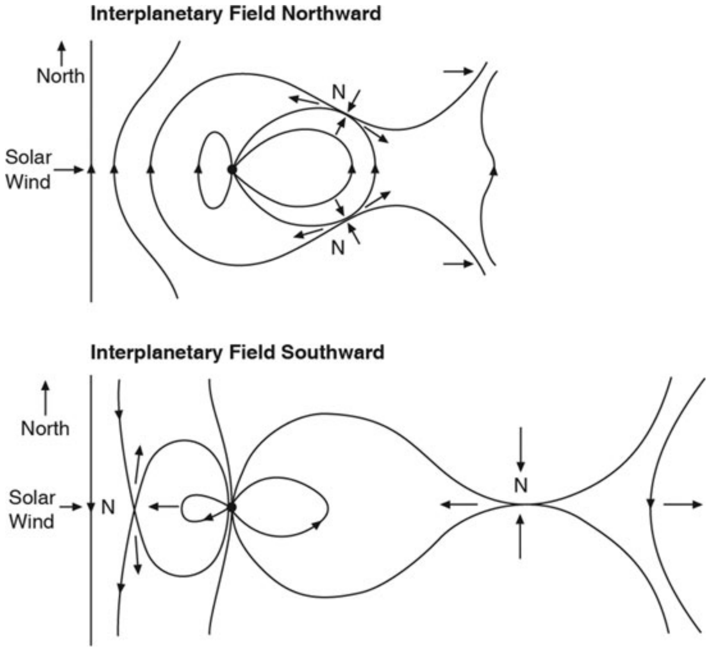

Figure 4. A magnetic reconnection of a due northward interplanetary magnetic field and a due southward magnetic field in the noon-midnight meridian (Dungey 1961; 1963).

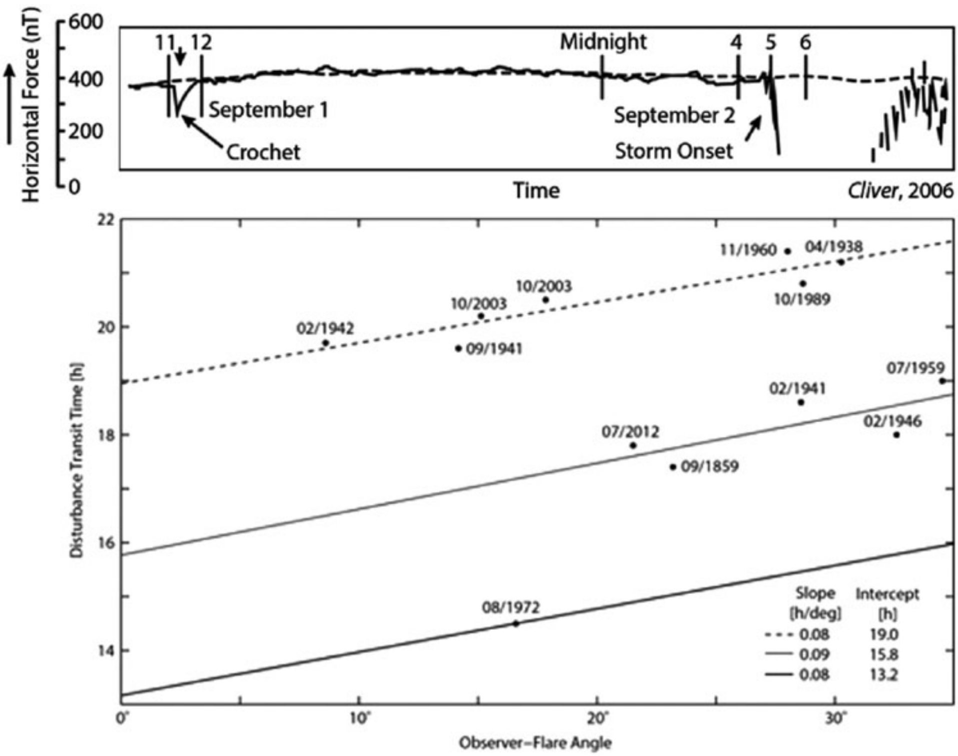

Figure 5. Magnetogram for the Sept 1, 1859 magnetic storm seen by Carrington together with the transition for 13 fastest solar outbursts (Freed and Russell 2014).

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short travel time from the Sun to the Earth. The time the event was released from the Sun is marked by the crochet produced when the x-rays produced on the Sun's surface, by the energetic particles that are shot downward on to the Sun, reach the Earth. The time the plasma accelerated by the solar event reaches the Earth is marked by the storm onset. Below this magnetogram are travel times for thirteen documented fastest events, plotted versus the angle of the observer away from the flare (release) site. These self-sort into three groups: one fastest event; five next fastest events including the Carrington event; seven next fastest events. The slope of these lines assumes that the disturbance fronts all have the same shape. The fastest event was the one with the record energetic particle flux. The next fastest set can be called Carrington-class events. The importance of this line is in part that it shows how often Carrington class events occur and that we have modern (space era) records of Carrington class events.

7. Conclusion

Space weather is manifested by many phenomena initiated by events on the Sun. These events can be quite deleterious to transmission and communication systems on Earth. We have examples of the largest events in our modern records and we know how to identify them. Waiting for more such events will eventually be successful but examining the ones that have already occurred may provide quicker answers to our questions.

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