CHAPTER 2.4

VARIABILITY AND EFFECTS BY SOLAR WIND

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1 Average structure of solar wind

A stream of charged particles, called the solar wind, continuously flows from the Sun into the interplanetary space. Solar wind carries with it the magnetic field of the Sun, which is called the interplanetary magnetic field (IMF) or the heliospheric magnetic field, reflecting the fact that the region of space dominated by the Sun via the solar wind and IMF is called the heliosphere (*helios* = Sun in Greek). While the solar wind is flowing radially away from the Sun, the magnetic field is turned to a spiral structure due to the rotation of the Sun, much in the same way as the water running out from a rotating garden hose.

The time of the solar wind to reach the Earth at its typical speed of about 400 km s^{-1} takes about 4 days. While expanding into open space, the solar wind gets diluted, and at the Earth, solar wind is already a very tenuous gas, containing only some of 5–10 particles per cubic centimeter. During this expansion, the solar wind cools down roughly by a factor of ten from the initial temperature of a couple of million degrees of the solar corona. The strength of the IMF also weakens from the Sun to the Earth to about 5 nanoTesla, which is only one in ten thousand when compared to the Earth's magnetic field on the ground. Most of solar wind energy is in the form of kinetic energy related to its anti-solar motion, with smaller contributions in thermal and magnetic energy.

The properties of the solar wind and IMF vary significantly, reflecting the nature of their coronal source. The solar wind can be roughly classified into two groups: the slow solar wind and the fast solar wind. The fast solar wind (faster than about 500 km s^{-1}) originates from large regions of solar corona that are seen as dark when viewed in normal light. Darkness is due to the low density of these regions. These rather empty regions of solar corona are called coronal holes. The low density results from the specific magnetic structure of these regions, which opens directly into space, having no magnetic loops that can contain high densities

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of plasma particles. Obviously, solar wind can better be accelerated to high speeds within the open field lines of large coronal holes. However, the reason to this preference is not yet very well understood and remains a topic of intense research. On the other hand, the slow solar wind originates from the proximity of solar active regions. Since these regions are fairly dense, slow solar wind is also denser than fast solar wind. The magnetic structure of those regions of solar corona emitting slow solar wind is rather complicated, and the field tends to experience non-radial expansion. The speed difference also affects the winding of the IMF spiral, which is more tight for slow solar wind.

The properties of the solar wind and IMF are continuously changing, from very short time scales below one second to intermediate scales of several hours to one solar rotation (about 27 days), and to long time scales of a solar cycle (about 10–11 years) up to a century and even beyond. The short time scale variations mainly develop during the interplanetary space, while the intermediate scales mainly reflect the momentary distribution of solar active regions on solar surface, and the longer time scales reflect the changes in solar dynamo during the solar cycle and longer. The daily averaged values of solar wind speed vary roughly by a factor of five from about 200 to 1000 km s^{-1}. All other solar wind parameters vary even more, especially the solar wind density and the IMF strength, which can vary by two orders of magnitude, reaching their highest values in interplanetary shocks.

2 Solar wind transients

On top of the average solar wind, various temporary phenomena and processes can significantly modify the properties of the solar wind. One can divide these phenomena in two groups: those that have their origin in the Sun and those that develop during the solar wind flow in the interplanetary space. Of the latter, the most important phenomena are the corotating interaction regions (CIR), which are interplanetary shocks that form as a result of the collision of fast and slow solar wind streams. When the fast solar wind stream attains the preceding slow solar wind, it cannot overtake it because the magnetic fields of these two regions strongly oppose mutual mixing. So, instead of a smooth change of solar wind parameters, the two regions form sharp boundaries over which the solar wind parameters vary dramatically. Since the two different solar wind streams often have opposite magnetic polarities, the CIR also typically includes an IMF sector boundary.

Since the source regions of IMF of opposite polarity are typically located rather far from each other on solar surface, the time difference between the fast and slow streams is several days, and the CIR is formed only rather far away from the Sun. Indeed, most CIRs develop beyond the Earth's orbit. The term corotating refers to the fact that the CIRs tend to appear repeatedly, once per solar rotation, as if the CIRs would rotate with the Sun. This repeating pattern takes place because the global solar magnetic field structure, which is produced by

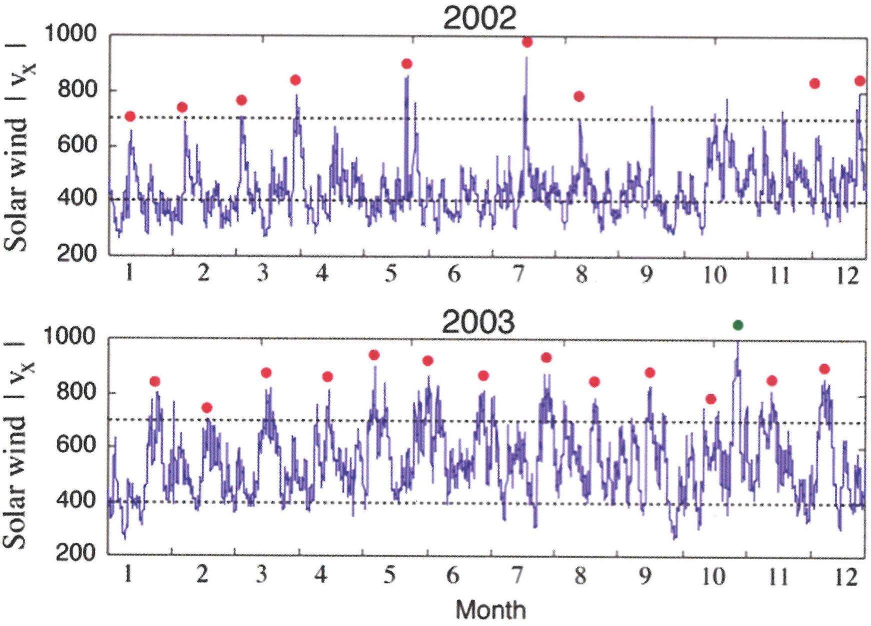

Fig. 1. Periodic high-speed streams from the solar coronal holes in 2002 and 2003. The same solar source region emits fast solar wind towards the Earth repeatedly at the 27-day rotation period of the Sun.

coronal holes and active regions, tends to remain roughly similar during several solar rotations. Figure 1 shows the repetition of high-speed solar wind streams at 27-day intervals during most of the years 2002 and 2003. CIRs are typically found to hit the Earth in the declining phase of the solar cycle, when the polar coronal holes are expanding and have an asymmetric structure in solar longitude. They often have an extension from the pole towards the equator, which can emit fast solar wind at low solar latitudes, thus reaching the Earth. When the production of new flux stops at the end of the cycle, the polar coronal holes become more symmetric and the high-speed streams become again more rare at the Earth. During sunspot maxima, there are active regions all over the solar surface, thus no large coronal holes exist.

The solar originated transients include, in particular, interplanetary coronal mass ejections (ICME) and solar flares. Solar flares can accelerate a fair amount of solar particles to very high energies, forming a burst of solar energetic particles (SEP), also called solar cosmic rays. However, the number of SEPs is rather small and, because of their high energy, they do not behave similarly as the solar wind particles. Therefore flares do not contribute much to the properties of the solar wind, and we will not discuss flares or SEPs in more details here.

Coronal mass ejections are large coronal loops with a huge amount of solar material, which burst into space typically during a few hours. These particles have roughly the same energy as solar wind particles, so they can become part of solar wind in the interplanetary space. Moreover, the ICMEs include so many particles that they can dominate over the background solar wind and thus determine its properties. ICMEs can be faster or slower than the ambient solar wind but, during the interplanetary travel, the ICME speed tends to approach closer to the speed of the backgound wind. Very fast and strong ICMEs, however, do exist and can reach the Earth even in less than one day, as during the famous Carrington storm in 1859.

Since the ICMEs are large loops of magnetic field, which can pertain their structure even in the interplanetary space, the magnetic field observed at the Earth's orbit during ICME passage can be very differently oriented than the background IMF structure. A typical core of a ICME is a magnetic cloud, a dense magnetic flux tube, where the field lines are twisted and tied to the Sun on one or both legs. Note also that fast ICMEs produce a leading shock ahead of them, which is followed by a sheath region of very turbulent field and solar wind until the ICME core arrives. Since ICMEs are related to sunspots and the appearance of new flux tubes on solar surface, they tend to maximise around the sunspot maximum.

3 Solar wind and the Earth

Solar wind affects the Earth's magnetic field, compressing the field on solar side and forming a comet-like tail in the nightside. Solar wind sustains a complicated and extremely variable system of electric fields and currents in this magnetic cavity, the Earth's magnetosphere, and in the ionosphere. The electric fields also accelerate magnetospheric particles (which partly come from the solar wind) and make some of them precipitate into the atmosphere. Overall, there is 10^{13} W power in the solar wind, of which about 10–20% is used to maintain the shape and basic convection of the magnetosphere. Accordingly, the solar wind power is much smaller than, e.g., the power of solar electromagnetic radiation, whereby its possible climatic effects were originally assumed to be minor.

The most important factor controlling the rate of energy input from the solar wind to the near-Earth space is the IMF orientation. Energy input increases as the IMF becomes increasingly antiparallel (southward IMF) to the equatorial geomagnetic field. Then, large scale merging or reconnection of magnetic field lines can take place, producing important electric fields and accelerating particles effectively. The energy input is enhanced by fast speed and high density of the solar wind, as well as by strong IMF. Moreover, the role of the ultra-low frequency (ULF) waves, also called Alfvén waves, in possibly enhancing the magnetic coupling, is under active study. Alfvén waves, which are more often found in the high-speed stream, may amplify the north-south IMF component and thereby the dayside reconnection electric field.

The charged particles precipitating into the atmosphere collide with the ambient neutral air at heights depending on their energy, the auroral particles at around 100 km and the more energetic particles down to about 50 km. The collisions ionise the atmosphere, thus contributing to the formation of the ionised layer called the ionosphere (which is mainly produced by solar EUV radiation). Most of the kinetic energy of the precipitating particles is converted to the thermal energy of the neutral air. Joule heating dissipates some 10^{15} J of energy during substorms, the majority of the energy available from the solar wind. In addition, the precipitating particles turn on the auroral lights. Most of this energy to all the three forms is dissipated by electrons while ions contribute less.

High-speed solar wind streams and CIRs are known to be particularly effective in accelerating magnetospheric particles. Therefore the declining phase of the solar cycle seems to be the most effective time interval for solar wind-related atmospheric effects, both to the ionised and to neutral air. Interestingly, there is increasing evidence that the high-speed solar wind streams, by accelerating and precipitating charged particles into the atmosphere, can produce significant chemical and dynamical changes in the atmosphere. In particular, they can produce NO_x and HO_x molecules which can descend into the middle atmosphere where they cause massive ozone destruction. This may further cause enhanced meridional circulation, creating a stronger polar vortex and a positive phase of the North Atlantic Oscillation. Indeed, recent studies show that the positive phase of the NAO prevails in the declining phase of the solar cycle and affects the arctic Winter temperatures strongly. These relations and effects are currently under active study.