Long-Term Solar-Terrestrial Data Sets and Their Value

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Synoptic, long-term observational programmes provide a wide diversity of information on the solar-terrestrial environment. Such data sets are particularly valuable in certain locations, on the ground, or in space. Further, such data sets are necessary for identifying the baseline from which anthropogenic changes may occur, for characterising transient events, for placing the results of short-term experiments in context, and also for carrying out statistical analyses. Results for all of these four examples can be interpreted according to present understanding of the physics of solar-terrestrial phenomena. Inadequacies are identified and understanding is thereby improved. New hypotheses are put forward and tested; new modelling schemes and new observational techniques are devised.

Some examples are presented, dealing with different physical parameters of solar, interplanetary, magnetospheric, ionospheric, thermospheric and geomagnetic phenomena. Considerations of mass, momentum and energy transfer across the magnetopause, and of energy dissipation in the polar, auroral and midlatitude upper atmosphere are emphasised, on time scales ranging from a few minutes to a century. Such studies are essential for the success of the Solar Terrestrial Energy Programme, STEP, the research aspects of which are underpinned by synoptic programmes. They will open the door to more successful predictions of the solar-terrestrial environment, an ever-developing requirement for mankind at the end of the twentieth century.

1. Introduction

This paper is concerned with some important physical parameters, measured either on the ground or in space, which are available to varying degrees from long-term data sets. These are listed in Table 1. The optimum observing locations are not considered here, neither are the optimum intervals between successive measurements.

2. The Sun

The source of energy for all phenomena occurring on the Earth’s surface, in the atmosphere and in the near-Earth space environment is the Sun. Visible radiation reaches the Earth’s surface and powers weather systems. Sunspots, i.e., dark, low temperature regions, absorb some of this photospheric radiation and bright, plage regions around sunspots produce a greater excess. The number and the latitudinal positions of sunspots vary over the eleven year solar cycle. In the ultraviolet, the sun is extremely spotty over all its surface. At X-ray wavelengths, very bright regions indicate hot, dense plasma on closed magnetic flux tubes.
Table 1. Important physical parameters measured on the ground or in space.

1. **Solar Activity**
   - Sunspots and solar magnetic field
   - Solar X-ray and UV flux
   - Solar irradiance
   - Solar 10.7 cm radio flux
   - Intensity of solar radiation at certain spectral lines

2. **Properties of the Interplanetary medium**
   - Solar wind plasma density, temperature and velocity
   - Interplanetary magnetic field (IMF) vector
   - Interplanetary electric field

3. **Properties of the Magnetosphere**
   - Mass, momentum and energy input
   - Location of the auroral oval and size of the polar cap
   - Current systems
   - Flux and spectrum of energetic charged particles

4. **Properties of the Ionosphere and Upper Atmosphere**
   - Ionospheric electron density profiles
   - Ionospheric plasma motions and electric current systems
   - Ionospheric absorption of cosmic radio noise
   - Thermospheric optical emissions and winds

5. **Geomagnetic Field**
   - Responses to changes of magnetospheric and ionospheric currents
   - Geomagnetic indices
     - \( \text{AE} \) - substorms and Joule heating in the auroral zone
     - \( \text{Dst} \) - magnetospheric ring current
     - \( \text{K} \) and its derivatives (\( \text{Kp} \), \( \text{Ap} \), etc.) - most commonly used indicator of geomagnetic activity

Extending into the corona. Dark regions, often of hemispheric extent, the so-called coronal holes, indicate low density plasma on diverging magnetic field lines which extend out into the interplanetary medium. UV- and X-radiation of different wavelengths is absorbed at different heights in the thermosphere to produce different layers of ionisation in the ionosphere.

The longest solar-terrestrial data set available is the time series of annual mean sunspot numbers. The National Academy Press report (1988) on Long-term solar-terrestrial observations shows (on p. 21) that the sunspot number exhibits an eleven year cycle of rather variable amplitude. Odd numbered solar cycles tend to have larger amplitudes—nearly 190 in 1957 and 155 in 1979, yet only 107 in 1969. From 1650 to 1700, during the Maunder minimum, the sunspot number was always less than 10. Between 1800 and 1820, the maximum sunspot number did not reach 50 and, in 1905, it was only 63. Thus the sunspot number varies with time in a far from simple harmonic manner, although there is an inherent period of approximately 11 years. Over that time, the Sun’s dipolar magnetic field reverses, so the fundamental periodicity is about 22 years. It is entirely evident that long-term data sets are required to determine long time scale fluctuations and trends.

Figure 1, from LEAN (1987), shows observations made over 50 years of the blocking effect of sunspots, at the bottom, then the area of faculae, a plage index, and the flux of 10.7
cm wavelength radio emission from the Sun’s chromosphere and corona, at the top. All four quantities exhibit the 11 year cycle, but with very considerable amplitude variations from month to month. TAPPING (1987) has presented monthly observations of the 10.7 cm solar flux which clearly show these irregular variations. Since the average solar rotation period is 27.3 days—but 25 days at the solar equator and 30 days near the poles—these results indicate that the corona evolves on a time scale of a week or so. DONNELLY (1988, 1989) has considered such matters further, including both ground-based and satellite observations.

3. The Interplanetary Medium and Magnetosphere

When considering the physics of solar-terrestrial relationships (RYCROFT, 1989), the interplanetary medium is crucial. This is because, as the solar wind plasma expands supersonically away from the Sun, it carries magnetic flux with it. That part of the solar magnetic flux reaching the Earth’s magnetosphere interacts with the Earth’s magnetic field. One important physical parameter for this interaction, and hence for the transfer of mass, momentum and energy from the interplanetary medium into the magnetosphere (see LUNDIN, 1988), is the electric field carried by the solar wind, $E$. In terms of the velocity of the solar wind, $v$, and of the interplanetary magnetic field (IMF), $B$, $E$ equals $-v \times B$ in regions where dissipation is not taking place.
Thus detailed, in situ observations of $v$ and $B$ in the upstream interplanetary medium (SLAVIN et al., 1986; ALLEN, 1990) and synoptic (daily) maps of $v$ derived from ground-based radioastronomy observations of interplanetary scintillations (TAPPIN, 1987) are invaluable. SLAVIN et al. (1986) have averaged, over four solar rotations, the sunspot number, the total solar magnetic flux deduced from Mount Wilson magnetograph data, and $\log B$ (since the IMF follows a log-normal distribution). Figure 2, from SLAVIN et al. (1986), shows annual averages, in the upper panel, of $B$ (log averaged, as diamonds), and the moduli of $B_x$ (radial component from Sun, triangles), $B_y$ (dawn-to-dusk component, open circles), $B_z$ (North-South component, perpendicular to the ecliptic plane, squares), and the root mean square of the $x$ and $y$ components, $(B_z^2 + B_y^2)^{1/2}$ (solid circles). Average $B$ values, which almost doubled from solar minimum (in 1976) to 1982, are rather better correlated with the total solar magnetic flux than with the sunspot number. Generally $B_y$ slightly exceeds $B_x$; the explanation for this is that the angle between the spiral interplanetary magnetic field line and the radial vector from the Sun slightly exceeds 45°. For an average radial solar wind velocity of 400 kms$^{-1}$, the spiral angle is 48°. From 1973 to 1975, and in 1984 and 1985, the higher solar wind velocities associated with high speed streams caused the spiral angle to be reduced,
and hence $B_x$ to exceed $B_y$. The ratio between the IMF components perpendicular to and parallel to the ecliptic plane (middle panel) varies almost sinusoidally with time, with smaller values occurring in the decreasing phase of a solar cycle when high speed streams are more prevalent. These emanate from coronal holes at low solar latitudes. The auroral electrojet (AE) index (bottom panel) of ionospheric currents enhanced by auroral substorm activity tends to be greater then. Both lesser substorm activity and smaller $B$ values were recorded in 1980 when the polarity of the Sun’s magnetic field reversed. In 1982, greater substorm activity could be linked with higher values of $B$.

Geomagnetic activity indices are derived from over 180 magnetometer observatories situated around the world. The most severe disturbance which is recorded by these observatories is called the geomagnetic storm. This often has a sudden commencement (SC).

HIRMAN et al. (1988) have shown that geomagnetic storms are most likely during the declining phase of a solar cycle. LEGRAND and SIMON (1989) have shown that they preferentially occur near the equinoxes, when geomagnetic activity tends to be higher anyway (RUSSELL and MCPHERRON, 1979; GREEN, 1984). Energetic solar proton events also exhibit two maxima per solar cycle, whereas the number of solar flares, observed at optical wavelengths, closely follows the sunspot number variation (HIRMAN et al., 1988). It should be noted that this research group considers a proton event to have the flux of $>10$ MeV protons exceeding $10$ particles per cm$^2$ sec steradian. Other authors use other criteria for defining a proton event.

4. The Magnetosphere and Ionosphere

Attention is now focused on time scales of a few days or less. GONZALEZ and TSURUTANI (1987) have presented the variation of the solar wind density, velocity and temperature, and the variation of the North-South component of the IMF and its orientation for four days in April 1979, together with the AE index and Dst index of the ring current in the magnetosphere (see WRENN, 1989). With no change of the other parameters, a southward turning of the IMF triggers a substorm (see EASTMAN et al., 1988), enhancing AE, after an hour or so; thereafter the ring current builds up. However, a shock front, exhibited as a sharp increase in solar wind velocity, temperature and density, and a predominantly northward, rather than southward, IMF has rather minor effects on the magnetosphere. At almost all times, the physical parameters of the interplanetary medium are changing appreciably on a time scale of minutes to hours. Thus, the interplanetary medium is never in steady state conditions.

As shown in Fig. 3, ALLEN et al. (1989) have presented the horizontal component of the geomagnetic field variation at Boulder, Colorado, which shows an SC at 01.28 UT on 13 March 1989. They also presented the approximately North-South component of the magnetic field observed by the GOES7 geostationary satellite; negative values observed after 14.16 UT on 13 March 1989 mean that the magnetopause was on the earthward side of the geostationary orbit at 6.6 Rs (earth radii). From late on March 13 and into March 14, the eastward auroral electrojet was at unusually low latitudes, over the central U.S.A. The flux of 4.2 to 8.7 MeV protons at geostationary orbit was up to $10^4$ times greater than normal (i.e., from $10^{-2}$ to $10^{-1}$ count/cm$^2$ sec sr MeV). Also there were several X-ray flares on the Sun during these two days, and these severely disrupted radio communications via the ionosphere. A variety of monitoring instruments operating routinely on the ground and in space are therefore necessary to detect these unusual transient events.
Fig. 3. Observations made on March 13 and 14, 1989 (from Allen et al., 1909) of the flux of X-rays (at wavelengths between 1 and 8 Å) at geostationary orbit (top panel), the flux of protons (with energies between 4.2 and 8.7 MeV) at geostationary orbit, the North-South component of the magnetic field observed at geostationary orbit (showing a magnetopause crossing at 14.16 UT on March 13, 1989), the horizontal component of the geomagnetic field at Boulder, Colorado (showing a Sudden Commencement at 01.28 UT on March 13, 1989), and the Deep River neutron monitor departure from the mean value (bottom panel). During this very disturbed period, the space shuttle Discovery was launched.

On time scales of minutes and seconds, monitoring instruments also provide useful data. For example, Lanzerotti et al. (1987) have presented geomagnetic fluctuations in three components that are simultaneous with transient riometer (relative ionospheric opacity meter) events. Resembling a relaxation oscillator signal, these are interpreted as being caused by excess D-region ionisation produced by a burst of precipitating electrons of more than 50 keV, possibly due to a wave-particle interaction in the magnetosphere (Rycroft, 1990); the excess ionisation then recombines. The aurora is a magnificent and dynamic (on ~1 s time scale) spectacle when observed in detail from the ground. It is a visible manifestation of the effects of ~1 keV electrons precipitating from the magnetotail as they bombard the upper atmosphere at 110 km altitude (Rees, 1989). From the vantage point of space, the overall, global structure of the auroral oval is evident, and its evolution on a time scale of ~0.2 hours is well studied from successive images observed by the Dynamics Explorer 1 satellite (Frank and Craven, 1988).

In a steady-state situation, and with the IMF having a southward component, the quantity of magnetic flux emanating from the southern polar cap is equal to the amount
entering the interplanetary medium through the southern part of the magnetotail. Similarly, the amount entering the northern magnetotail from the interplanetary medium is equal to the flux into the northern polar cap. As Rycroft (1987) showed, the application of the law of the conservation of magnetic flux relates \( B \) to the dimensions of the bounded region, both near the Earth and in the magnetotail.

Further, the application of Faraday’s law of electromagnetic induction to the magnetic flux carried downstream by the solar wind plasma relates the electric field, \( E, \sim 10 \text{ kV}/R_E \), across the magnetotail to the electric field across the polar cap ionosphere; this drives the noon-to-midnight convection of \( F \)-region plasma. Studies of the auroral and polar cap ionospheres in North and South rely to a great extent on various synoptic measurements. They are essential for putting the results of experiments conducted on a campaign basis, say, using satellite overpasses (see Opgenoorth and Kirkwood, 1989), rockets or the EISCAT (see Kirkwood et al., 1988; Lockwood et al., 1989) or PACE (see Baker et al., 1988), radars, into context.

At midlatitudes, \( F \)-region peak densitites, \( N \), for some days following an SC geomagnetic storm vary in complex ways with location, season and local time. Rodger et al. (1989) have used synoptic ionosonde data to illustrate the variation of \( \ln (N/N_0) \), where \( N_0 \) is the quiet time, reference, peak density. \( N \) may either exceed \( N_0 \) (a positive storm effect) or be reduced (the more usual, negative storm effect). Rodger et al. (1989) conclude that energy has to be put into the ionosphere to account for the observations, and suggest that this is via the precipitation of ring current oxygen ions and via the electric field across the magnetotail penetrating to unusually low latitudes during storms. Changes of thermospheric composition and effects due to thermospheric winds are also considered to be important. Smith and King (1981) have presented evidence showing that the relationship between \( N \) and the sunspot number has changed on a decadal time scale. They interpreted this as indicating the importance of faculae as a source of ionising radiation.

5. The Future

Solar-terrestrial physics is a complicated, and important, subject. It is complicated because several different regions of space are involved, because several physical processes couple mass, momentum and energy from one region to another, across plasma boundaries, and because the real situation is time varying, and not in the steady state which is more amenable to theoretical treatment. The International Solar Terrestrial Physics (ISTP) programme (see National Academy Press, 1985), and the Global Geospace Science (GGS) program of the U.S. NASA, plus ESA, Japanese and Intercosmos satellites to be launched during the 1990s will attack such problems, as will the ICSU-approved Solar Terrestrial Energy Programme (STEP, 1990). Synoptic observations play significant roles in both these programmes.

The subject is important because mankind now relies upon technological services whose performance can be upset by unusual solar-terrestrial events. Some examples are:
- the failure of satellites, or their instruments or microchip components, in geostationary orbit due to plasma-spacecraft interactions,
- the destabilisation of polar orbiting satellites due to thermospheric density and geomagnetic field changes,
- the disruption of radio communications and navigation systems by the disturbed ionosphere,
the disruption of electricity grid systems, and the perturbation of other long
conductors, by large induced electromotive forces,
the disruption of aeromagnetic surveys by enhanced geomagnetic activity,
radiation dangers to crew and passengers of high flying aircraft, and to astronauts,
due to energetic charged particles.
Although nothing can be done to prevent such disturbances, their consequences can
sometimes be avoided if sufficient warning is given. Appropriate synoptic observations (see
RISHBETH et al., 1989), both on the ground and in space, are essential for understanding such
phenomena. That understanding is a prerequisite for making predictions of their occurrence
and for appraising their consequences for mankind.

REFERENCES

LEPPING, PACE observations of IMF dependent changes in ionospheric convection near the cusp,
DONNELLY, R. F., The solar electromagnetic radiation flux study (SERFS), STP Newsletter, 88-1, 34–36,
EASTMAN, T. E., G. ROSTOKER, L. A. FRANK, C. Y. HUANG, and D. G. MITCHELL, Boundary layer dynamics in
FRANK, L. A. and J. D. CRAVEN, Imaging Results from Dynamics Explorer 1, Rev. Geophys., 26, 249–283,
GONZALEZ, W. D. and B. T. TSURUTANI, Criteria of interplanetary parameters causing intense magnetic
HIRMAN, J. W., G. R. HECKMAN, M. S. GREER, and J. B. SMITH, Solar and geomagnetic activity during cycle
KIRKWOOD, S., H. OPGENOORTH, and J. S. MURPHREE, Ionospheric conductivities, electric fields and currents
associated with auroral substorms measured by the EISCAT radar, Planet. Space Sci., 36, 1359–1380,
LANZEROTTI, L. J. and T. J. ROSENBERG, Impulsive particle precipitation and concurrent magnetic field
The contributions to geomagnetic activity of shock waves and of the solar wind, Ann. Geophys., 7,
LOCKWOOD, M., P. E. SANDHOLT, and S. W. H. COWLEY, Dayside auroral activity and magnetic flux transfer
LUNDIN, R., On the magnetospheric boundary layer and solar wind energy transfer into the magnetosphere,
NATIONAL ACADEMY OF SCIENCES, An implementation plan for priorities in solar-system space
NATIONAL ACADEMY OF SCIENCES, Long-term solar-terrestrial observations, 72 pp., National Academy
OPGENOORTH, H. J. and S. KIRKWOOD, Ground-based observations coordinated with Viking satellite


