LONG-TERM VARIATIONS OF THE SOLAR WIND*

J. C. Brandt

Laboratory for Solar Physics and Astrophysics,
NASA-Goddard Space Flight Center,
Greenbelt, Maryland 20771, *U.S.A.*

The earth is in the outermost part of the solar atmosphere called the solar wind which consists of an ionized gas flowing nearly radially past the earth at an average speed (w) of 400 km/sec. The other average properties at earth are an electron (N_e) and proton density of 6 per cm^3, a proton temperature of 8×10^4 °K, an electron temperature of 1.5×10^5 °K and an alpha particle fraction by number of 0.04. This flow is a consequence of the high temperature of the solar corona (2×10^6 °K) and a supersonic flow results from an interaction of the high temperature gas with the sun's gravitational field. Local conditions in the corona, such as the magnetic field configuration, can strongly influence the flow. The solar-wind magnetic field at earth is drawn out by the flow into a spiral and is divided into sectors of opposite polarity. There are normally 4 or 2 sectors, and within them, the velocity, density, and magnetic field show regular, repeating patterns.

Solar-cycle dependences of geomagnetic activity and galactic cosmic ray modulation have been known for years and are well-established. Variations in the solar wind would seem to be an obvious way of carrying out the solar-cycle effects. For example, it seemed clear that variations in the bulk properties of the solar wind, specifically in the average speed, were responsible for the modulation of galactic cosmic rays. Pathak and Sarabhai (1970) found that a variation of solar-wind speed of 320 km/sec between solar maximum and solar minimum would be needed on the basis of their models in the sense of a faster speed at solar maximum.

Recently, the possibility that the solar wind may influence the weather and climate has received considerable impetus from the discovery of a correlation between weather patterns and the passage of sector boundaries in the solar wind (see *Possible Relationships Between Solar Activity and Meteorological Phenomena*, 1975, NASA SP-366). Hence, long-term variations in the solar wind might influence climate as well as cosmic rays and geomagnetism.

Direct measurements of the solar wind exist for approximately one solar cycle covering the solar minimum in 1964 and the solar maximum in 1969. Variations in solar-wind properties by less than 10 to 15% are considered insignificant for the purpose of this paper.

*Presented at the AAAS Symposium entitled "The Magnetically Varying Sun and Its Effects on Terrestrial Climate," held at Boston, Massachusetts on February 22, 1976.

A major conclusion of this review is that the expected variations are not evident in the solar-wind experimental data. Recently, Vasyliunas (1975) wrote in this regard :

> "The average bulk speed of the solar wind does not show any major systematic variation with solar cycle (see, e.g., Gosling et al. 1971; Hundhausen 1972; Diodato et al. 1974; review by Neugebauer 1975). In view of the well-established solar cycle modulation of cosmic-ray intensity and of geomagnetic activity, this result has been somewhat surprising and has stimulated a search for more subtle solar wind properties that might show a dependence on the solar cycle."

The statistical search for subtle effects in a large body of inhomogeneous data is a process fraught with difficulties.

If the bulk speed doesn't vary, could some other property of the distribution of speeds vary ? A possibility might be the frequency of high-speed streams as suggested by Intriligator (1974). However, Vasyliunas (1975) has shown that the original result was spurious. We return to the question of stream structure below.

Hirshberg (1973) has suggested that the high field part of the distribution of magnetic field values might be enhanced at solar maximum and thus provide the solar-cycle variation. This has been challenged by Mariani et al. (1976) who wrote :

> "Although temporal fluctuations are observed on field components and magnitudes, no clear solar cycle variation is found. The same conclusion holds for the statistical distribution and variances of these parameters."

The fraction by number of alpha particles in the solar wind could vary in the solar cycle. A change from 0.035 at solar minimum to 0.045 at solar maximum has been reported by Ogilvie and Hirshberg (1974) . While the authors feel that the variation is real, their data is consistent with no variation.

There is general agreement that no variation has been measured in the proton temperature. The electron temperature is very insensitive to the solar-wind conditions and no solar cycle variation is expected.

The average density in the solar wind may vary, as reported by Diodato et al. (1974), in the sense of a *smaller* density at solar maximum than at solar minimum. This variation should be challenged because it involves questions of the absolute calibration of different instruments, of reduction procedures, and of possible biases in the data. The change in average density is approximately 40%, corresponding to a decrease from (say) 8 electrons per cm^3 to 5 electrons per cm^3. Density measurements made by two electrostatic analyzers in orbit at the same time have shown worse-case differences of 40%. Faraday cup experiments are better in this respect and differences between two experiments would be roughly 10%. But the absolute comparison of dissimilar experiments is more difficult and involves the details of reduction procedures, method of correcting for alpha particles, etc. Moreover, even if the experimental procedures are perfect, there can still be biases in the data. Solar-wind measurements can only be made outside of the earth's magnetic field, and orbits traversing the boundary are often used. If the orbital period is commensurate with the solar rotation period, the sample could be biased because of the solar-wind sector structure.

Hence, the density measurements by themselves are not convincing, even though they are very suggestive. However, independent evidence appears to argue for a variation in density even if the amplitude is uncertain. The position of the earth's bow shock and magnetopause appears to vary in a way consistent with the density decrease. The position of these features is determined by the dynamic pressure in the solar wind (proportional to $N_e w^2$) and they occur at larger distances from the earth at solar maximum. The density variation, therefore, is probably real.

The one certain solar-cycle variation in the solar wind is the variation of high-speed stream structure.

> "Large amplitude high speed solar wind streams and streams with maximum speeds in excess of 700 km s^{-1} are far more common in years of declining and minimum solar activity than near solar maximum. Further, the broadest solar wind streams observed directly with space probes during the years 1962-1974 occurred near solar minimum in 1974......"

according to Bame et al. (1976). These are apparently the quasirepetitive streams detected years ago on the basis of geomagnetic variations and the same general variation was noted (Bartels 1932). There are roughly 5 such streams per year at solar maximum and roughly 20 such streams per year at solar minimum. This variation could produce a small increase in the average solar-wind speed at solar minimum (see below).

A summary of possible solar-wind variations based on direct measurements is given in Table 1. The author has discussed these variations with representatives of the experimental groups at the Goddard Space Flight Center, Jet Propulsion Laboratory, Los Alamos Scientific Laboratory, and Massachusetts Institute of Technology in an effort to verify their reasonableness. Note that the most likely variations (frequency of large amplitude streams, density) are in a sense of an *increase* from solar maximum to solar minimum. There is probably even a small increase (~10%) of the solar-wind average speed from solar maximum to solar minimum. Curiously, this result was obtained long ago from the comet data and discarded as spurious (Brandt 1967).

It is unlikely that *any* bulk property of the solar wind is responsible for the modulation of galactic cosmic rays or variations in the frequency of sudden commencements.* These phenomena appear to result from more subtle variations in the solar wind. Hedgecock (1975) has suggested that enhanced directional fluctuations in the magnetic field could be responsible for the cosmic-ray modulation and this suggestion is illustrative of the class of variations that seem to be required.

Variations in solar-wind parameters can be extended back in time through the use of the orientations of ionic comet tails and through geomagnetic indices. The comet-tail data extends back into the 1880s and no major change in the bulk velocity is apparent. Geomagnetic variations have been used to map the solar-wind sector structure back to 1926 with no apparent long-term changes.

Table 1

Possible Solar-Cycle Variations of the Solar Wind

Property	
o Average Bulk Speed	Definitely Does *Not* Vary
o Average Proton Temperature	
o Frequency of High-Speed Streams	
o Magnetic Fields	*Might* Vary
o Fraction of Alpha Particles	
o Average Density	*Probably* Varies
o Frequency of High-Speed Streams with Speeds greater than 700 km/sec (apparently same as M-region streams)	*Definitely* Varies

Nothing in the results presented so far prepares us for the possibilities brought to mind by the changes in the solar corona associated with the Maunder minimum (Eddy 1976). Unfortunately there is insufficient data to say much about possible solar-wind variations. Cometary data are of no use because accurate measurements are needed to derive solar-wind speeds. The appearance of comets holds little data either because the visual impression is dominated by the emission of dust. This effect was

*However, the probable variations in average density coupled with the variations in frequency of M-region streams are not inconsistent with the observation that the maximum of geomagnetic activity as reflected in the planetary index K_p occurs several years after solar maximum.

dramatically illustrated by the appearance of Comet West (1975n) in the morning sky in early March 1976. The visual effect was dominated by the fan-shaped dust tail. The perihelion passage of a comet, such as the comet of 1680 (used by Newton in the *Principia*) or Halley's comet in 1682, with no solar wind at all would probably present a reasonably "normal" appearance. The only hope of probing the state of the solar wind during the Maunder minimum is the historical records of auroras.

Nothing in our present knowledge of the solar wind and its variations emerges as the candidate parameter for a good correlation with changes in climate. This statement is made in the context of direct observations over one solar cycle only. Other solar cycles may be quite different. There is evidence for variations on the scale of millions or billions of years. These can be obtained from the studies of lunar rocks, meteorites, and the rotation rates of solar-type stars. A more active solar wind with higher densities, higher magnetic fields, and a faster (solar) rotation rate is probable. Perhaps these variations can produce some interesting very long-term changes in climate.

References :

Bame, S. J., Asbridge, J. R., Feldman, W.C. and Gosling, J. T. 1976, *Ap. J.* (August 1 issue).

Bartels, J. 1932, *J. Terrestrial Mag. and Atmos. Electricity*, **37**, 1.

Brandt, J. C. 1967, *Ap. J.*, **147**, 201.

Diodato, L., Moreno, G., Signorini, C. and Ogilvie, K. W. 1974, *J. Geophys. Res.*, **79**, 5095.

Eddy, J. A. 1976, *Science* (in press).

Gosling, J. T., Hansen, R. T. and Bame, S. J. 1971, *J. Geophys. Res.*, **76**, 1811.

Hedgecock, P.C. 1975, *Solar Phys.*, **42**, 497.

Hirshberg, J. 1973, *Astrophys. Space Sci.*, **20**, 473.

Hundhausen, A. J. 1972, *Coronal Expansion and Solar Wind* (Berlin-Heidelberg: Springer-Verlag), p. 164.

Intriligator, D. S. 1974, *Ap. J.* (Letters), **188**, L23.

Mariani, Diodato, L. and Moreno, G. 1976 (Preprint).

Neugebauer, M. 1975 *Space Sci. Rev.*, **17**, 221.

Ogilvie, K. W. and Hirshberg, J. 1974, *J. Geophys. Res.*, **79**, 4595.

Pathak, P. N. and Sarabhai, V. 1970, *Planet. Space Sci.* **18**, 81.

Vasyliunas, V. M. 1975, *Ap. J.* (*Letters*), **202**, L159.
