Polar Coronal Holes and Cosmic-Ray Modulation

Abstract. *A comparison of the size of polar coronal holes with the cosmic-ray intensity observed during the most recent sunspot cycle shows close correspondence. This lends support to recent suggestions that the well-known sunspot-cycle modulation of cosmic rays is a three-dimensional effect, probably related to the global character of the interplanetary magnetic field.*

Coronal holes in the polar regions of the sun have been observed at the Mauna Loa Observatory since 1965, or during the most recent sunspot cycle. The instrument used is the K-coronameter, which measures coronal radiation while occulting the sun with a disk. The temporal variations in the size of the "polar holes" correspond to those in the cosmic-ray intensity observed at Earth. In particular, the rapid reappearance of the polar holes between late 1970 and early 1971 (following their disappearance in the sunspot maximum epoch) matched the similarly abrupt, ~ 10 percent rise in cosmic-ray intensity from the low level observed at sunspot maximum to the higher level characteristic of sunspot minimum; smaller fluctuations in the polar hole area during the period from 1972 to 1975 were followed by 3 to 5 percent variations in cosmic-ray intensity with time lags of only ~ 3 months. This correspondence lends support to recent suggestions that the changing three-dimensional structure of the interplanetary magnetic field plays an important role in the modulation of cosmic rays entering the solar system.

Coronal holes (*1–3*) are regions of low density in radiation emitted from or scattered by coronal material. They are associated with magnetic field lines that "open" into interplanetary space and have been identified as the source of the major streams of fast solar wind in interplanetary space. Coronal holes also play a key role in determining the spatial structure of the interplanetary magnetic field. The open field lines in any particular hole tend to be of a given polarity; that is, they point predominantly toward or away from the sun. This organization of the magnetic field is extended into the interplanetary region as the expanding solar wind carries frozen-in solar magnetic fields outward from the sun. Thus the global pattern of coronal holes and their magnetic polarity is mapped into a spatial structure of the interplanetary field that rotates with the sun and gives rise to the pattern of alternating magnetic sectors well known from spacecraft observations in the ecliptic plane (*4, 5*).

The existence of a general, dipolar solar magnetic field at some phases of the sunspot cycle (*6*) suggests a particularly simple structure at these times, with coronal holes in the northern and southern hemispheres of the sun having opposite magnetic polarities. The resulting interplanetary magnetic field would then consist of two "hemispheres" of opposite polarity, separated by a neutral (or current) "sheet." This neutral sheet should lie near but not at the solar equator, having been displaced from that ideal position by the complex and irregular features known to exist in the real solar magnetic field (*7–10*). Indeed, the observed pattern of coronal holes does at times suggest such a simple configuration; they are often observed to surround the poles of the sun (defined by its rotation axis), and coronal holes at lower latitudes tend to "connect" to these semipermanent polar holes. A hypothetical neutral sheet can be drawn through the brightest portions of the corona, separating holes of opposite magnetic polarity to give a magnetic polarity structure consistent with the sector pattern observed in the ecliptic (*11*). Finally, the excursion of the Pioneer 10 spacecraft to 16° solar latitude in 1976 revealed a change in the sector pattern consistent with an approach to such a neutral sheet (*12*). Thus there is growing evidence for this type of interplanetary magnetic structure related to the general magnetic field of the sun and to polar coronal holes.

The existence of an 11-year variation in the intensity of cosmic-rays observed at the earth and its relation to the sunspot cycle were recognized in the 1950's by Forbush (*13*). The implied connection between cosmic-ray intensity and solar activity has recently been used (*14*) to infer long-term variations in the level of solar activity from terrestrial records of ^{14}C (produced in the atmosphere by incoming cosmic rays). The solar-cycle modulation of the propagation of cosmic rays entering the solar system from interstellar space has been widely attributed to their interaction with a solar wind that varies with solar activity. A detailed theory of such effects of scattering of cosmic rays by irregularities in the magnetic field convected along by the solar wind has been developed (*15, 16*). Models of the diffusion of "galactic" cosmic-rays into a spherically symmetric solar wind with this scattering would lead to an 11-year cycle if solar wind characteristics were assumed to vary in reasonable ways through the sunspot cycle. However, solar wind observations have not revealed the assumed variations in the ecliptic plane (*17, 18*), and spacecraft probing the outer solar system have failed to find the higher cosmic-ray intensities consistent with the early diffusion models. Thus recent work has involved three-dimensional (or nonspherically symmetric) effects, including the entry (*19*) and drift (*20–23*) of cosmic rays in a two-hemisphere interplanetary magnetic structure similar to that described above.

No definitive test of the influence of the three-dimensional interplanetary magnetic structure on cosmic-ray propagation is possible as long as observations are limited to the ecliptic plane. However, the relation of coronal holes to the interplanetary magnetic structure suggests a test that, although less than defin-

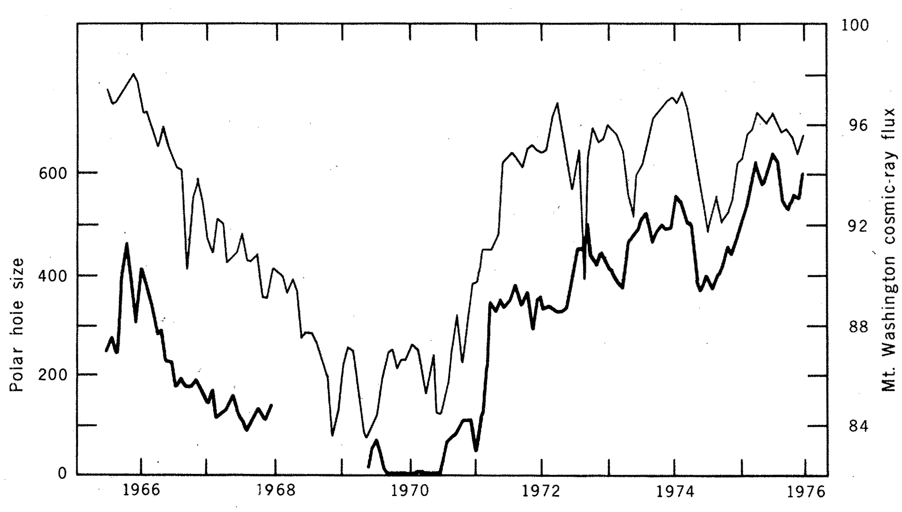

Fig. 1. Size of the polar coronal holes (thick line) in units of 75 square degrees (5° in latitude by 15° in longitude) and the Mount Washington monthly average counting rates (thin lines), 1965 to 1976. Counting rates normalized to 100 = 2506.

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itive, is both informative and possible with existing data. If polar holes do have a crucial effect on the three-dimensional magnetic structure, the demonstration of a relation between these coronal features and the cosmic-ray intensity would be important evidence in favor of three-dimensional effects in general and the global magnetic field in particular.

Except for a single long break in 1968, the coronal hole observations at the Mauna Loa Observatory observations have been carried out on a daily basis (weather permitting). A sequence of daily measurements of the coronal polarization brightness, *pB*, as a function of solar latitude at some distance above the limb of the sun, can be displayed as a map of *pB* as a function of latitude and longitude in a coordinate system rotating with the sun. The quantity *pB* is basically a measure of the integral of coronal electron density along the line of sight; one might expect coronal holes to appear as regions of low *pB* on these maps. This expectation is confirmed by direct comparison with other identifications of holes (*11, 24, 25*), and the K-coronameter data has been used in numerous studies of these features. The polar holes are usually well defined on the K-coronal maps as regions of low *pB* sharply bounded by steep brightness gradients. This data set is well suited to the study of long-term evolution of coronal holes and especially the polar holes, and reveals (*26*) a simple pattern of evolution over the most recent sunspot cycle (sunspot cycle 20, 1964 to 1976).

The size of the polar holes can be estimated from the K-coronal maps by finding the area of the map enclosed by a circumpolar contour of constant *pB* falling on the steep brightness gradient bounding such a hole. This value will depend on the *pB* level chosen [but not strongly if the brightness gradient is steep (*27*)]. We have chosen to use an area in square degrees of solar latitude and longitude (measured in units of 75 square degrees corresponding to our resolution of 15° in longitude and 5° in latitude); this quantity weights the polar regions more heavily than those at low latitudes and is thus suitable for studying the effects of polar holes. To avoid confusion with the true area, we will refer to this index as the size of the polar holes. Figure 1 shows the combined size of the two polar holes (north and south), based on observations made at half a solar radius above the photosphere for each rotation of the sun from 1965 to 1976 (excluding, of course, the 1968 interval in which no observations were made). There is a strong variation in this parameter with phase of the sunspot cycle, reflecting the qualitative behavior obvious (*24*) from examination of the maps: (i) shrinkage of the polar holes as sunspot number increased from 1965 to 1967; (ii) absence (or at least indetectability) of polar holes in 1969 and early 1970, or at sunspot maximum; (iii) rapid rebirth of polar holes in late 1970 (southern hemisphere) and early 1971 (northern hemisphere); (iv) slower average growth of the polar holes during the descending phase of the sunspot cycle.

The temporal variation in size shown in Fig. 1 resembles the general pattern found by Broussard *et al.* (*28*) from a much less complete set of x-ray and extreme ultraviolet images. The true areas of polar holes determined from K-coronameter data are larger than those obtained from x-ray or extreme ultraviolet data (*25, 28*) because they are determined at a greater height in the corona; the angular sizes of coronal holes increase with height in association with the rapid divergence of open magnetic field lines.

Figure 1 also shows the monthly average counting rates of the Mount Washington neutron monitor (*29*) for the same 1965–1976 period. The sunspot cycle modulation of the ~ 5-GeV cosmic rays recorded by this instrument is evident in the decrease in counting rates from 1965 to 1968, the low values in 1968 to 1969 (sunspot maximum), and the increase in counting rates from 1970 to 1976. However, the latter increase was poorly correlated with sunspot number (*30, 31*). The cosmic-ray counting rates increased virtually all of the way from the sunspot maximum to sunspot minimum levels in late 1970 and early 1971. In contrast, the number of sunspots required the entire 1970 to 1975 period to reach the level characteristic of sunspot minimum. The abrupt rise in counting rates does correspond well to the rapid rebirth of the polar holes and the major increase in their areas that occurred in late 1970 and 1971. The smaller fluctuations in polar hole size (superposed on a continuous but gradual increase), with minima in early 1972, early 1973, and mid-1974 seem also to be reflected in 3 to 5 percent fluctuations in the Mount Washington counting rate, with minima occurring in mid-1972, mid-1973, and mid-to-late 1974. The time lags between these polar hole and cosmic-ray variations appear, as judged by the timing of the minima, to be only 2 or 3 months. There is, however, no long-term rise in cosmic-ray intensity corresponding to the gradual increase in polar hole size from 1972 through 1976.

We believe that this close correspondence between the polar size and cosmic-ray intensity variations strongly suggests the influence of a three-dimensional interplanetary structure on the propagation of cosmic rays through the solar system to the orbit of Earth. The correspondence is particularly interesting in light of the apparent "breaking" of the relation with solar activity as measured by sunspot number (*29*). Although this brief study is inadequate to isolate a physical mechanism or offer detailed confirmation of a particular model, the widely accepted connection between holes and interplanetary magnetic structures brings to mind mechanisms and models involving cosmic-ray propagation in a large-scale magnetic structure (*20–23*). The rebirth of polar coronal holes in 1970–1971 would be expected to produce a rapid restructuring of the interplanetary magnetic field, with the simple two-hemisphere polarity structure invoked in these models replacing the more complex structures that should prevail near sunspot maximum. The short time lags implied in Fig. 1 certainly point to a mechanism involving distances no more than 10 to 15 AU from the sun (the distance the solar wind travels in 2 to 3 months) as having a primary influence on the particles that reach Earth.

We should emphasize that a study of correspondence or correlation between two parameters may suggest a physical connection and is a common and valid basis for suggesting such a connection when a reasonable mechanism, as in this case, can be proposed. However, such studies fall short of proving that connection, especially when, as on the sun, many indices of behavior are correlated with a variety of phases or lag times. Only further study will reveal whether the correspondence shown here leads to a better understanding of the relations among coronal structure, interplanetary structure, and cosmic rays in the solar system.

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Oxidative Transformations of Polycyclic Aromatic Hydrocarbons Adsorbed on Coal Fly Ash

Abstract. *Polycyclic aromatic hydrocarbons adsorbed onto coal fly ash were found to be stabilized against photochemical decomposition. However, a number of adsorbed polycyclic aromatic hydrocarbons will spontaneously oxidize in the absence of light, with those compounds containing a benzylic carbon being particularly susceptible. The decomposition rate appears to be fly ash–dependent.*

Recently it has been reported (*1*) that fly ash emitted from coal-fired power plants contains compounds that are mutagenic as indicated by the Ames test (*2*). Although the identities of these compounds have not been firmly established, present indications (*1, 3*) are that most are either polycyclic aromatic hydrocarbons (PAH's) or derivations and heteroatom analogs thereof. Such compounds are known to be adsorbed onto the surface of emitted fly ash (*4, 5*), and several have been shown to be both mutagenic and carcinogenic (*3, 6, 7*). Since emitted fly ash may contribute significantly to the atmospheric aerosol, it is important to establish the ways in which associated toxic and carcinogenic compounds may change prior to inhalation by human beings.

Information about the fate of particulate PAH's released to the atmosphere is at present fragmentary and unclear. It is generally assumed, however, that photochemical oxidation processes play an important role (*3*). There is ample evidence that most PAH's will undergo photooxidation in solution, as the pure solid, and when adsorbed onto certain solid substrates such as alumina (*3*). It has been inferred that similar processes take place when the compounds are adsorbed on airborne particulates (*3, 8*). Indeed, it has been suggested that the half-lives of such PAH's in the presence of sunlight may be "only hours or days" (*3*, p. 60).

Contrary to this expectation, we now report that the rate and extent of photodecomposition of PAH's may be decreased substantially by adsorption onto coal fly ash particles. Certain PAH's, however, undergo rapid oxidation in the dark when adsorbed onto fly ash.

In our studies we used a model system in which individual PAH's were adsorbed onto the surface of fly ash collected from the electrostatic precipitators of several coal-fired power plants. Known gas-phase concentrations of individual PAH's were generated in either pure air or pure nitrogen by use of a simple diffusion cell (*5, 9*) and passed through an expanded bed (*5, 10*) of fly ash. By regulating the bed temperature and the time of exposure, we were able to control the amount of a PAH adsorbed. All fly ash samples were size-fractionated by sieving; we used particles in the size range from 44 to 74 μm on the assumption that the surface chemistry of particles in this size range is similar to that of the small fly ash particles (< 5 μm) likely to be emitted to the atmosphere. This assumption is supported by the results of extensive surface analyses of several fly ashes (*11*). Exhaustive preextraction with several solvents (cyclohexane, benzene, and methanol) showed that none of the fly ashes used contained more than 50 ng per gram of total PAH. The PAH's were thereafter adsorbed onto raw unextracted fly ash to avoid the possibility that the preextraction procedure might modify the fly ash surface.

We believe that this model system for adsorbed PAH on fly ash is closely reminiscent of the real situation, that is, fly ash collected from within the power plant stack system is used as an adsorbent just as occurs in practice. On the other hand, aged fly ash has different amounts of carbonates, hydroxides, and hydration water from freshly generated fly ash, and so the model system we used could conceivably exhibit different surface chemical behavior and extraction characteristics. No indications of such differences have been observed.

We carried out the sample irradiation in both pure air and pure nitrogen, using outdoor sunlight and several artificial light sources [150-W xenon arc lamp, 275-W commercial sunlamp, and "quartz line" lamps (General Electric model 5-OT3/Cl), all unfiltered]. The fly ash was revolved slowly in a quartz container to provide equal exposure of all surfaces, and radiant fluxes were estimated to be equal to or greater than that of midday summer sunlight (45°N) over the wavelength range 300 to 800 nm. Selected fly ashes were analyzed by electron spectroscopy for chemical analysis

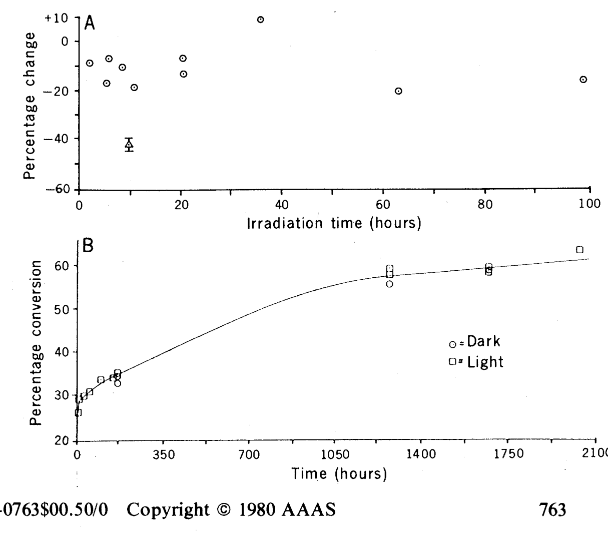

Fig. 1. (A) Percentage conversion of benzo[*a*]pyrene adsorbed onto coal fly ash. Each point surrounded by a circle represents a different fly ash sample, and several light sources are also represented. The point surrounded by a triangle indicates the percent decomposition of benzo[*a*]-pyrene dissolved directly in methanol. (B) Percentage conversion of fluorene adsorbed on coal fly ash as a function of time.