A BRIEF HISTORY OF RECURRENT SOLAR MODULATION OF THE GALACTIC COSMIC RAYS (1937–1990)

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Abstract. This brief review of the pre-Ulysses era begins with the first measurements by ionization chambers in 1937 of a cosmic ray 27-day intensity variation that was believed to have its origin in recurrent variations of the geomagnetic field. However, with the introduction of neutron monitor analysis of the nucleonic component, it was shown in the 1940s and 1950s that this cosmic ray intensity variation arose from interplanetary dynamical phenomena. Beginning in the 1960s direct spacecraft investigations in the heliosphere with Pioneer-10, Pioneer-11, Voyager-1 and Voyager-2 proved that Corotating Interaction Regions were not only the source of the cosmic ray recurrent intensity modulation, but also the source of charged particles accelerated in corotating forward and reverse shocks associated with the corotating interaction regions.

These early investigations, confined to low latitudes, have contributed to the understanding of solar phenomena, interplanetary dynamics, charge particle acceleration and the Sun-Earth convection.

The experimental and theoretical investigations on the origin of the 26-day recurrent cosmic ray intensity variations have made vital contributions to solar physics, to the discovery of many dynamical processes in the heliosphere and to the Sun-Earth connection.

This is a brief history extending from the discovery of the 27-day variation to the time prior to the Ulysses mission cosmic ray modulation investigations at high heliospheric latitudes in the inner solar system. The references and the larger literature quoted therein are intended as guides for the reader to the development of early experimental and theoretical findings and the evolution in our understanding of this phenomenon.

Forbush (1938) reported the first conclusive evidence for the existence of a 27-day cosmic ray intensity variation based on measurements with the world-wide network of Compton-C ionization chambers (Compton, Wollan and Bennett, 1934) established in the late 1930s. Since the amplitudes of the 27-day "waves" were much less than a one percent effect in ionization chambers – whether at sea level or mountain altitude – Forbush had to apply elegant statistical analysis methods. He showed that the existence of this world-wide variation was inversely correlated with 27-day variations of the geomagnetic field, as shown in Figure 1.

Based on this inverse correlation of ion chamber and geomagnetic field intensities, he concluded that the geomagnetic field variations produced the cosmic ray intensity variations by means of recurrent changes in the geomagnetic cut-off for cosmic rays. He and others suggested that the Bartels recurring M regions on the

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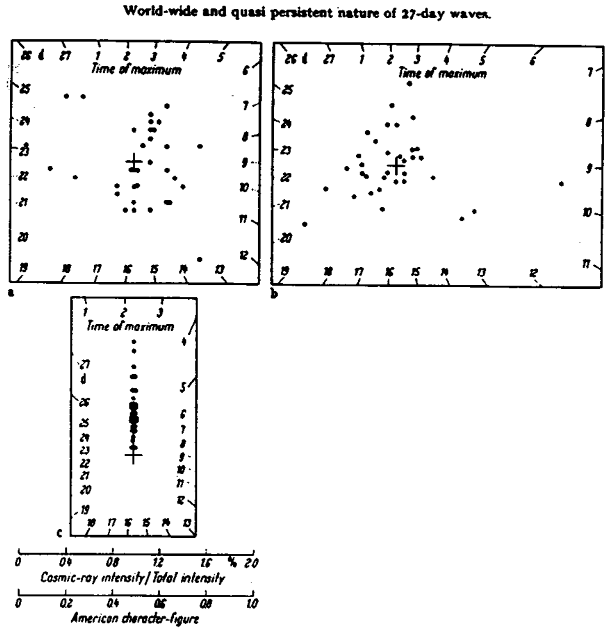

Figure 1. Harmonic dials for the departure of individual 27-day waves from the average 27-day wave: a) For magnetic character figures (0.0 very quiet to 2.0 intense storm); b) For cosmic ray intensity at Huancayo (equator) - percent of total intensity is shown to scale; c) Validity test. For details see Forbush (1938) or pages 362–363 in The Works of S.E. Forbush.

Sun (Bartels, 1940) were the source of the geomagnetic synodic 27-day recurrence. Thus, the concept generally accepted in the 1940s assumed that persistent M regions on the Sun emitted streams of ionized matter (ion streams) traveling in an interplanetary vacuum and interacting with the geomagnetic field. On the other hand, Alfvén (1949) proposed that energetic particles crossing these recurrent streams would be accelerated by cross-beam electric field to produce the observed intensity variations. However, in the reference frame of the cosmic ray charged particle no electric field exists.

The discovery of the nucleonic component large scale latitude effect (Simpson, 1948) in the atmosphere and the development of the neutron monitor pile (Simpson, Fonger and Treiman, 1953) – which was sensitive to the primary nucleonic component down to a geomagnetic rigidity of $\sim$ 2 GV deep in the atmosphere-made it possible to prove that the origin of the 27-day cosmic ray intensity variations was due to dynamical phenomena in the interplanetary medium. The amplitude of these nucleonic component 27-day variations was a factor approximately five times greater than for ion chambers (Figure 2) and increased in amplitude from the geomagnetic equator to high latitudes (Fonger, 1953). These and other investigations proved that 27-day changes in the geomagnetic cutoff did not produce the cosmic ray intensity variations – they were interplanetary in origin and correlated

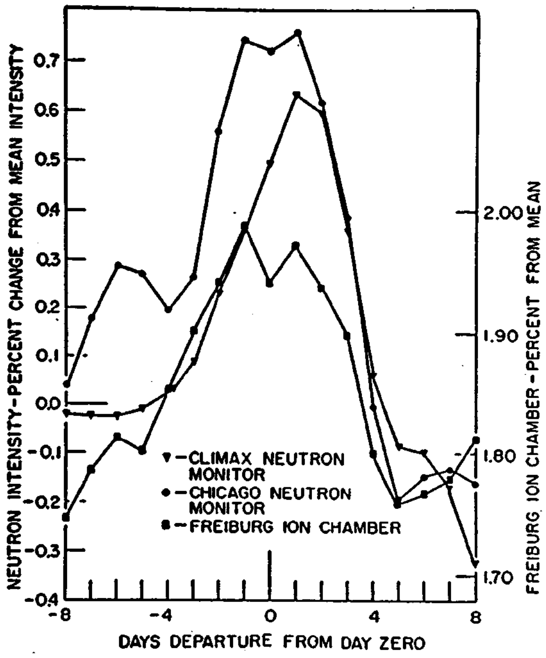

Figure 2. The dates of central meridian passages of the UM region (shown in Figs. 3A and 3B) for 7 consecutive rotations were called day "0". The percent change of neutron intensity from the mean intensity of the period studied was recorded for each day "0" and for ±8 days. The average percent change of intensity for the 7 rotations is shown. Each rotation was indexed by a peak of cosmic-ray intensity, followed about 4 days later by modulation. A similar process was followed for the Freiburg ionization chamber data. (A. Sittkus in the "Sonnen-Zirkular" of the Fraunhofer Institute, Freiburg im Breisgau, Germany.) Note that the amplitude of the ionization chamber data has been multiplied by the factor 5.

with recurring coronal active regions (Simpson, 1954). By 1951–1952 the mechanism in the interplanetary medium appeared to be a modulation of the cosmic ray spectrum, but whether by acceleration or deceleration could not yet be decided.

The development by H.W. Babcock (1953) of instrumentation utilizing the longitudinal Zeeman effect led to their discovery of recurrent "unipolar" weak magnetic field regions on the Sun (Figure 3). Based on seven consecutive solar rotations in 1953 it was then discovered (Simpson, Babcock and Babcock, 1955) that these "unipolar" magnetic regions were correlated within three to four days by means of recurrent interplanetary streams with both the increase of cosmic ray 27-day modulation, as shown in Figure 2 and a recurrent series of geomagnetic storms. In 1972 Skylab investigators renamed these unipolar regions "coronal holes" (see Coronal Holes and High Speed Wind Streams, 1977). Research in the period 1955–1958 provided further evidence that both the 27-day recurrent intensity variations and the approximately 11-year change of cosmic ray intensity had their origins in interplanetary processes modulating the galactic cosmic ray

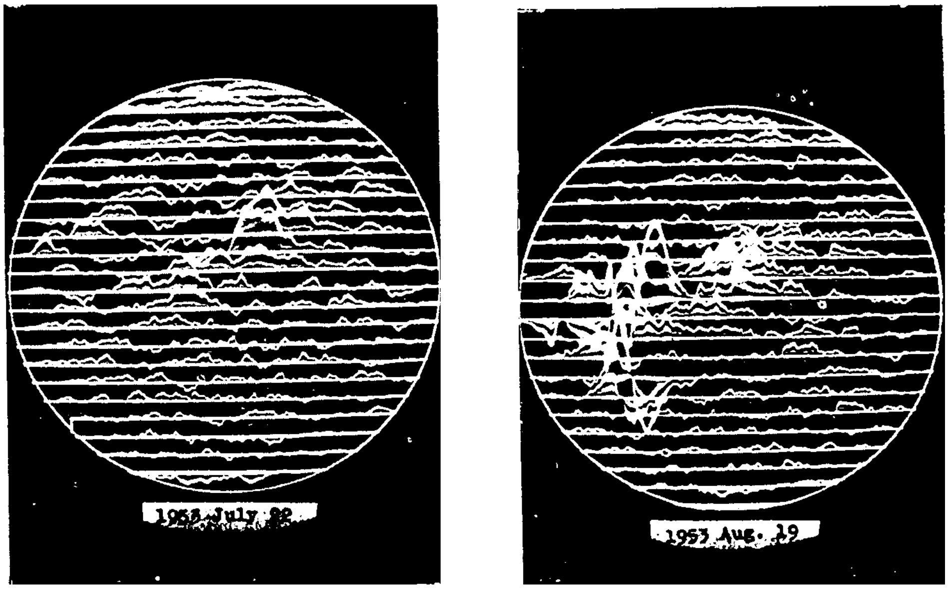

Figure 3. (a): The presence of a weak magnetic field predominantly of one sign (deflections positive upwards) is shown for July 22, 1953 by this conformal mapping of the solar disk. The sense of solar rotation is from right to left. (b): The conformal mapping of the solar disk for August 19, 1953. In both 3A and 3B the north pole is shown vertically upward (from Simpson, Babcock and Babcock, 1955).

spectrum. The discovery of a dynamical heliosphere (Meyer, Parker and Simpson, 1956) and the development of a theory for the solar wind (Parker, 1963) greatly expanded the scale and understanding of these time-dependent intensity changes.

The first evidence from experiments in space concerning the origin of the 27-day modulation was reported by Bryant, Cline, Desai and McDonald (1963) (Figure 4). Multi-spacecraft observations showed (Figure 5) that CIR sources of particle acceleration extended over a large radial range (McDonald *et al.*, 1975). Smith and Wolfe (1976) and Hundhausen and Gosling (1976) found from solar wind and magnetic field observations that the recurrent streams formed corotating interaction regions (CIRs) bounded by forward and reverse shocks. Barnes and Simpson (1976) then found that these forward and reverse shocks were the source of the acceleration for low energy ($\sim 1-20$ MeV nucleon^{-1}) particles in the CIRs (Figure 6) extending over a wide radial range (Figure 7).

The experimental searches have been accompanied by extensive theoretical and model investigations that have expanded our understanding of the physical processes of charged particle acceleration and propagation (see, for example, the references in Hundhausen and Gosling, 1976; Fisk and Lee, 1980; Burlaga *et al.*, 1985; Pizzo, 1989; and Intriligator and Siscoe, 1995).

Investigations were confined in latitude to $\sim 16°$ (that is, above the prevailing latitude range of the heliospheric current sheet), by *Pioneer-11*, (post-Saturn

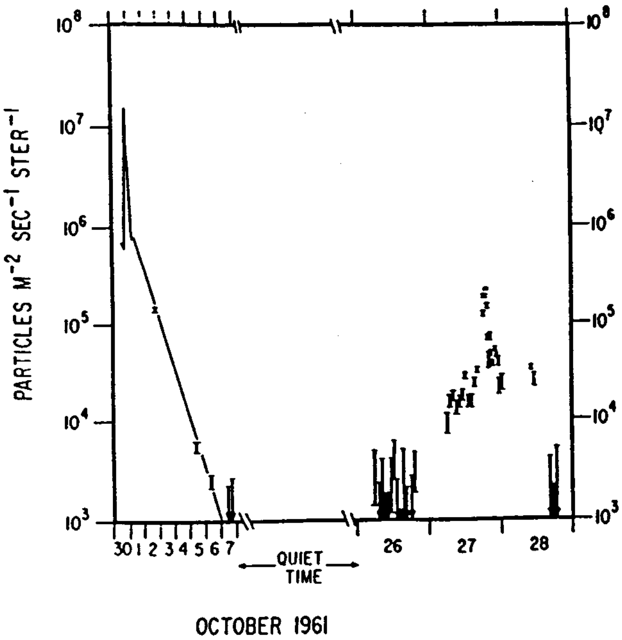

Figure 4. Intensity of > 3 MeV protons between 30 September and 28 October 1961. (Note that the time scales before and after the period during which the intensity remained at a quiet-time value are different.) (From Bryant *et al.*, 1963.)

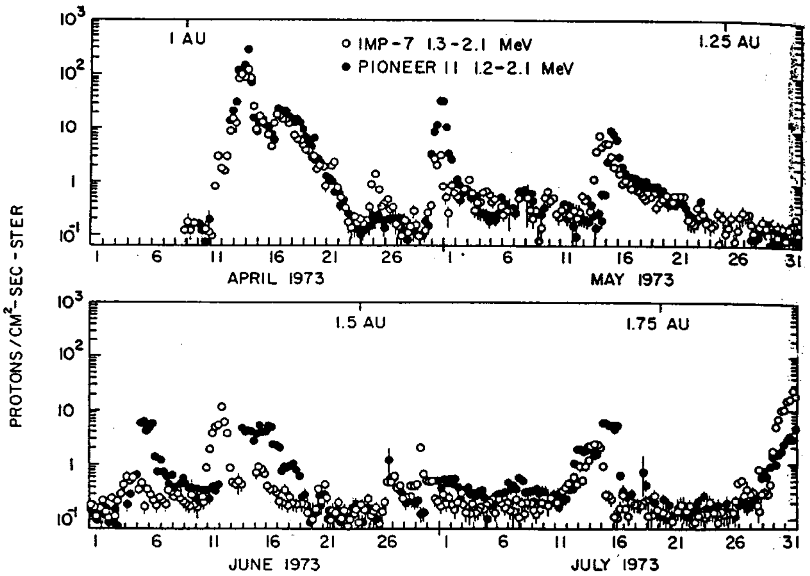

Figure 5. IMP-7 and *Pioneer-11* flux values for 1.2–2.1 MeV protons (and 0.3–2.1 MeV alphas). Data have been averaged over 6-hour periods. The corotation times range from one day in early June to two days in July with IMP-7 leading *Pioneer-11*. (McDonald *et al.*, 1975).

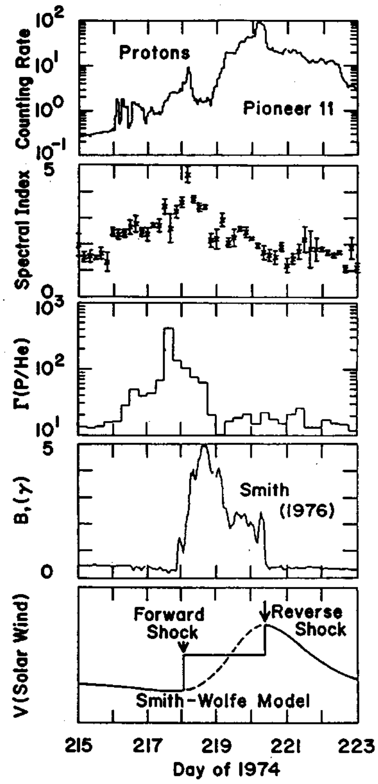

Figure 6. Typical recurring proton events. Plotted are 0.5–1.8 MeV proton counting rate, spectral index γ for a fit of the differential energy spectrum $\mu E^{-\gamma}$, the ratio of protons to helium of equal kinetic energy per nucleon and the magnetic field strength and solar wind velocity (see Smith and Wolfe, 1976). *Pioneer-11*, at about 4.4 AU (Barnes and Simpson, 1976)

encounter (Simpson, Smith and Tsurutani, 1986) until the 1990s when the two Voyager spacecraft were deflected to higher latitudes by planetary encounters (Neptune and Uranus) in the distant heliosphere and, the *Ulysses* spacecraft carried experiments from solar pole-to-pole in the inner solar system (Smith and Marsden, 1995). These Voyager and Ulysses missions into the third dimension continue to provide new insights for not only the origin of the recurrent modulation of galactic cosmic rays and the anomalous nuclear component, but also for the recurrent interplanetary acceleration of elections and pickup ions.

This brief historical report has attempted to provide the reader with a guide to the literature of other important research on this subject.

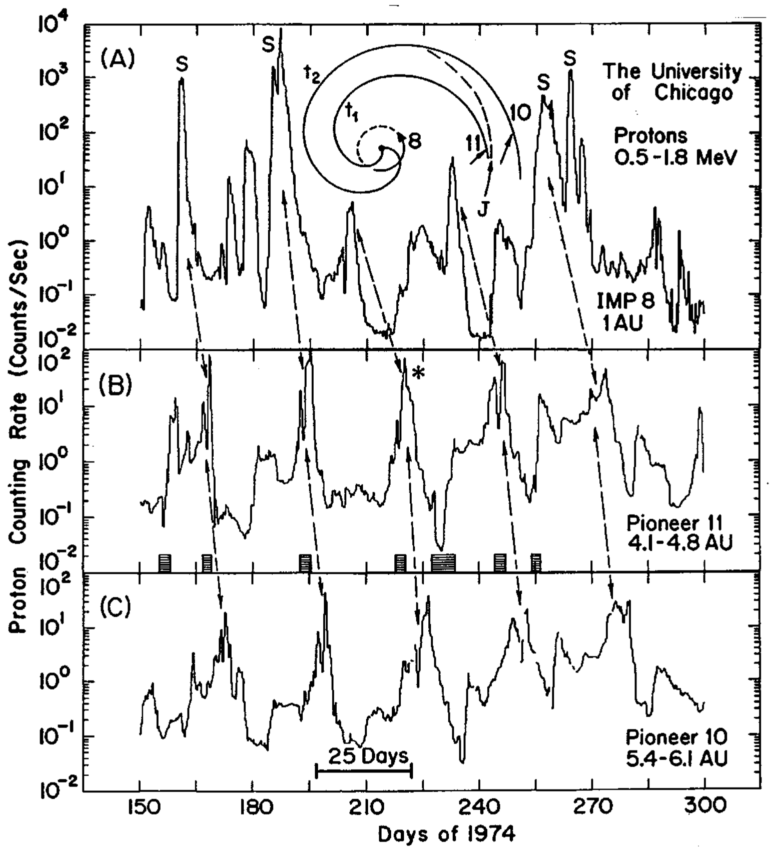

Figure 7. Proton counting rates from identical charged particle telescopes on IMP-8, *Pioneer-10* and *Pioneer-11* are plotted for 150 days during 1974. The horizontally hatched areas are CIRs up to Day 265. The inset at top shows the trajectories of IMP-8, *Pioneer-10*, *Pioneer-11*, and Jupiter from Day 150 (tail of respective arrow) to Day 300 (point of arrows). Typical proton peaks which corotate from one spacecraft to another are connected by dashed lines (Barnes and Simpson, 1976).

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