THE SUN, SPACE, COSMIC RAYS, AND CLIMATE

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THE STRUCTURE OF THE SUN

The spherical form of the Sun (M_O=$2x10^{33}$ gm) is enforced by the gravitational field, with g = $2.8x10^4$ cm/sec^2 at the visible surface (R_O = $7x10^{10}$ cm)

At the center, density = 100 gm/cm^3, temperature = $15x10^6$ K.

Outward pressure opposed by gravitation.

Nuclear burning in central core,

$R < 0.25\ R_O$, $9x10^6 K < T < 15x10^6 K$.

Present age of the Sun $4.6x10^9$ years

Red giant phase at age $10x10^9$ years

Solar luminosity, $L_O = 4x10^{33}$ ergs/sec, representing a mass loss rate,

$$L_O/c^2 = 4x10^{12} \text{ gm/sec},$$

in the core.

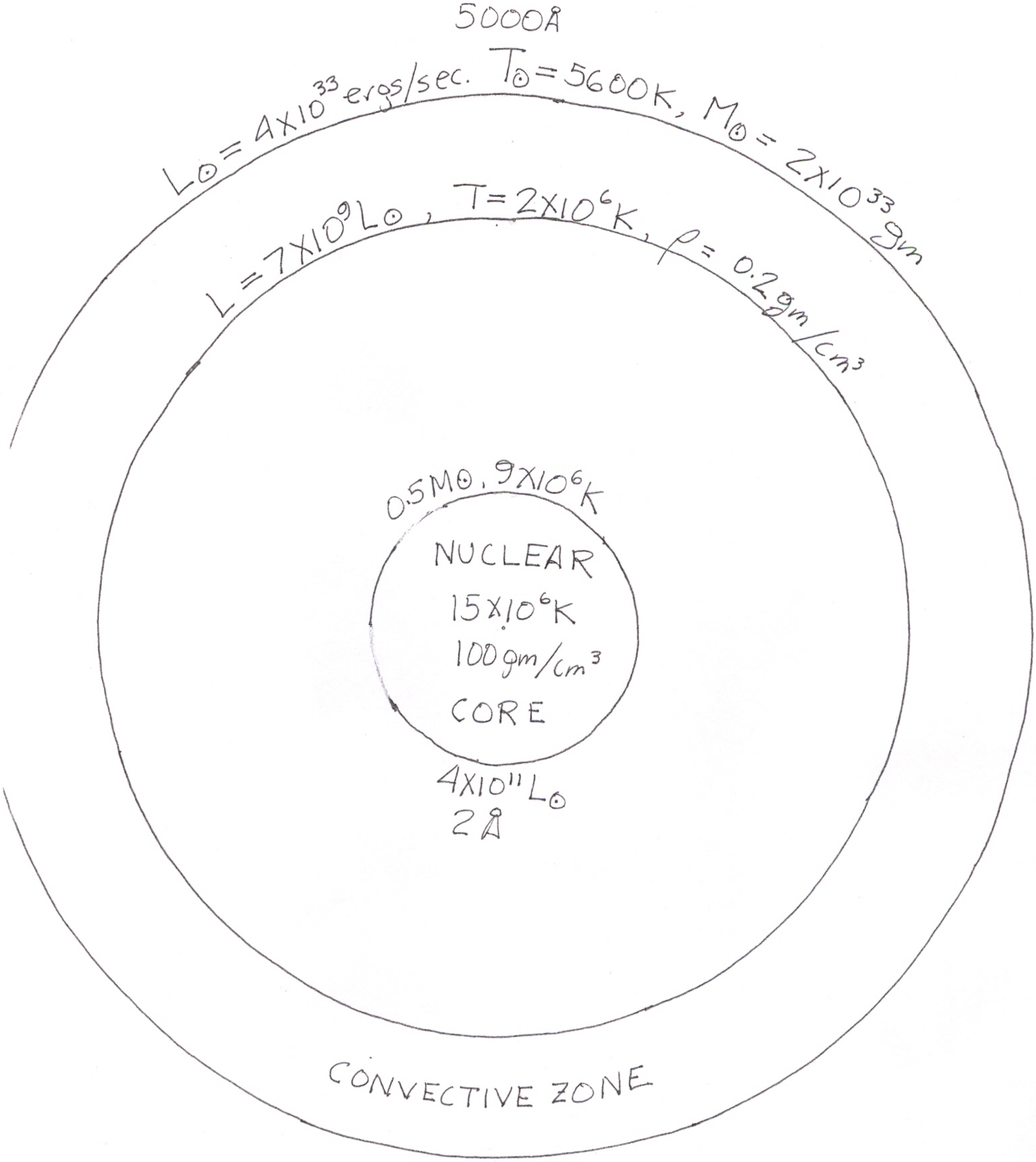
Four times the mass loss in the solar wind!

The visible Sun is just an opaque shroud around the nuclear core, with core luminosity

$$L_{core} = 4x10^{11} L_O.$$

Outward heat flow through shroud is thermal radiation,

X-rays around 3 A.


5000Å
L⊙ = 4X10^33 ergs/sec. T⊙ = 5600K, M⊙ = 2X10^33 gm
L = 7X10^9 L⊙ , T = 2X10^6 K, ρ = 0.2gm/cm^3
0.5M⊙, 9X10^6 K
NUCLEAR
15X10^6 K
100gm/cm^3
CORE
4X10^11 L⊙
2Å
CONVECTIVE ZONE

Thanks to helioseismology and to the theoretical work of John Bahcall and others, the theoretical model of the solar interior is accurate to within 1/500 of the actual conditions.

The solar neutrino emission, measured by Ray Davis, was the first evidence of the nonzero rest mass of the neutrino.

The story of the Sun would end here, were it not for the convective zone (CZ) in the outer 2/7 of R_O.

Below $2x10^6$ K the thermal radiation is not sufficient to transport the heat. So the temperature gradient exceeds the adiabatic gradient.

The convection:

1. Introduces meridional circulation.

2. Causes the Sun to rotate nonuniformly,

   25 days at the equator, >30days at the poles.

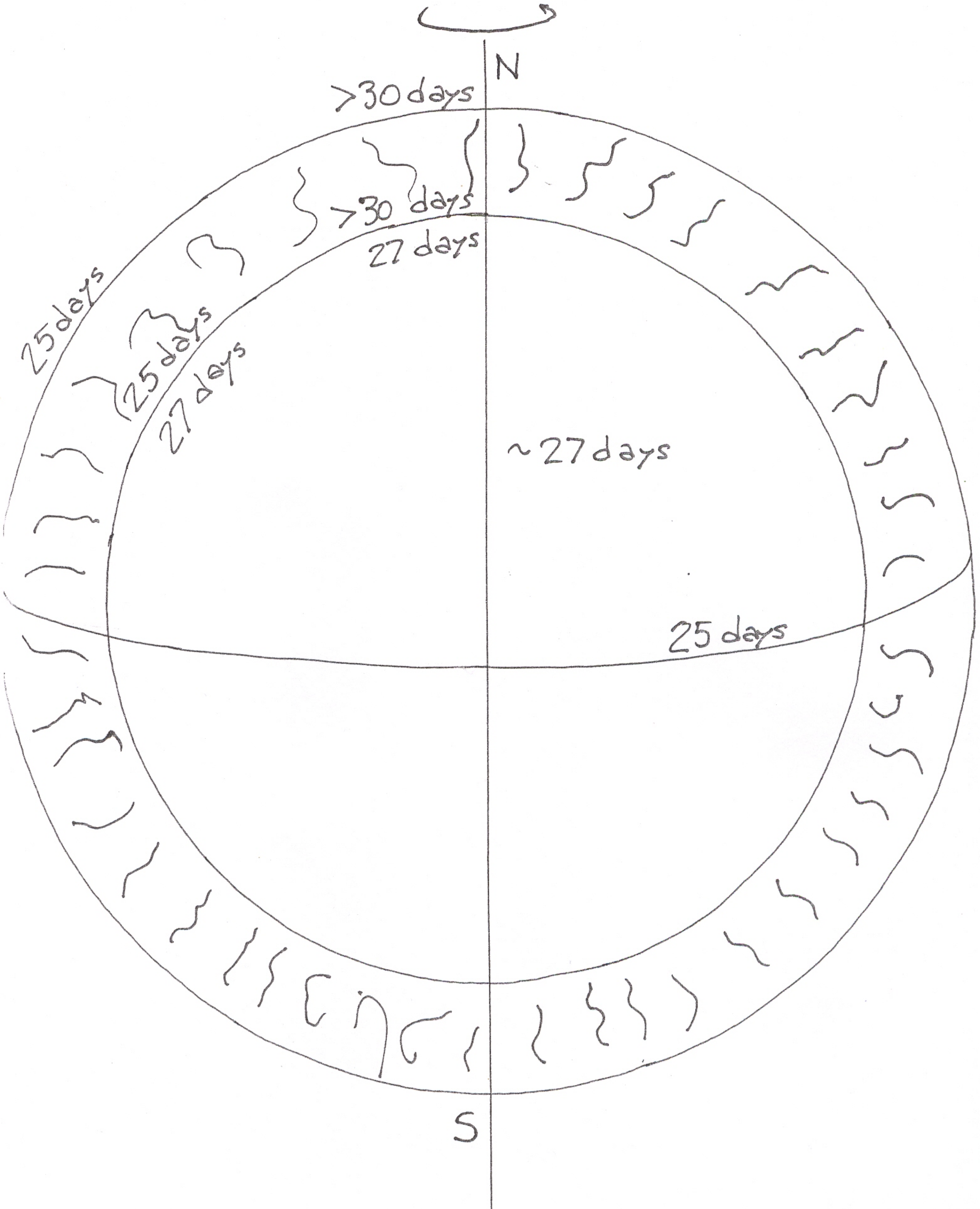
3. Generates magnetic fields.

Helioseismology shows that:

1. The radiative zone, inside the CZ, rotates approximately rigidly.

2. The rotation in the CZ is approximately independent of depth, producing a strong shear at the boundary between radiation and convection.

Theoretical hydrodynamics has so far been unable to reproduce the nonuniform rotation.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The combined nonuniform rotation, cyclonic convection, and "turbulent diffusion" generate magnetic fields.

The magnetic fields are carried bodily with the streaming ionized gas of the Sun.

A magnetic field exerts pressure and tension and contains energy.

The bipolar magnetic regions appearing at the visible surface indicate a strong azimuthal magnetic field deep in the CZ.

The buoyancy of the magnetic field and the overall convective instability cause Ω-loops to bulge upward through the visible surface, forming the bipolar magnetic regions.

Fe IX/X
(~1 MK)


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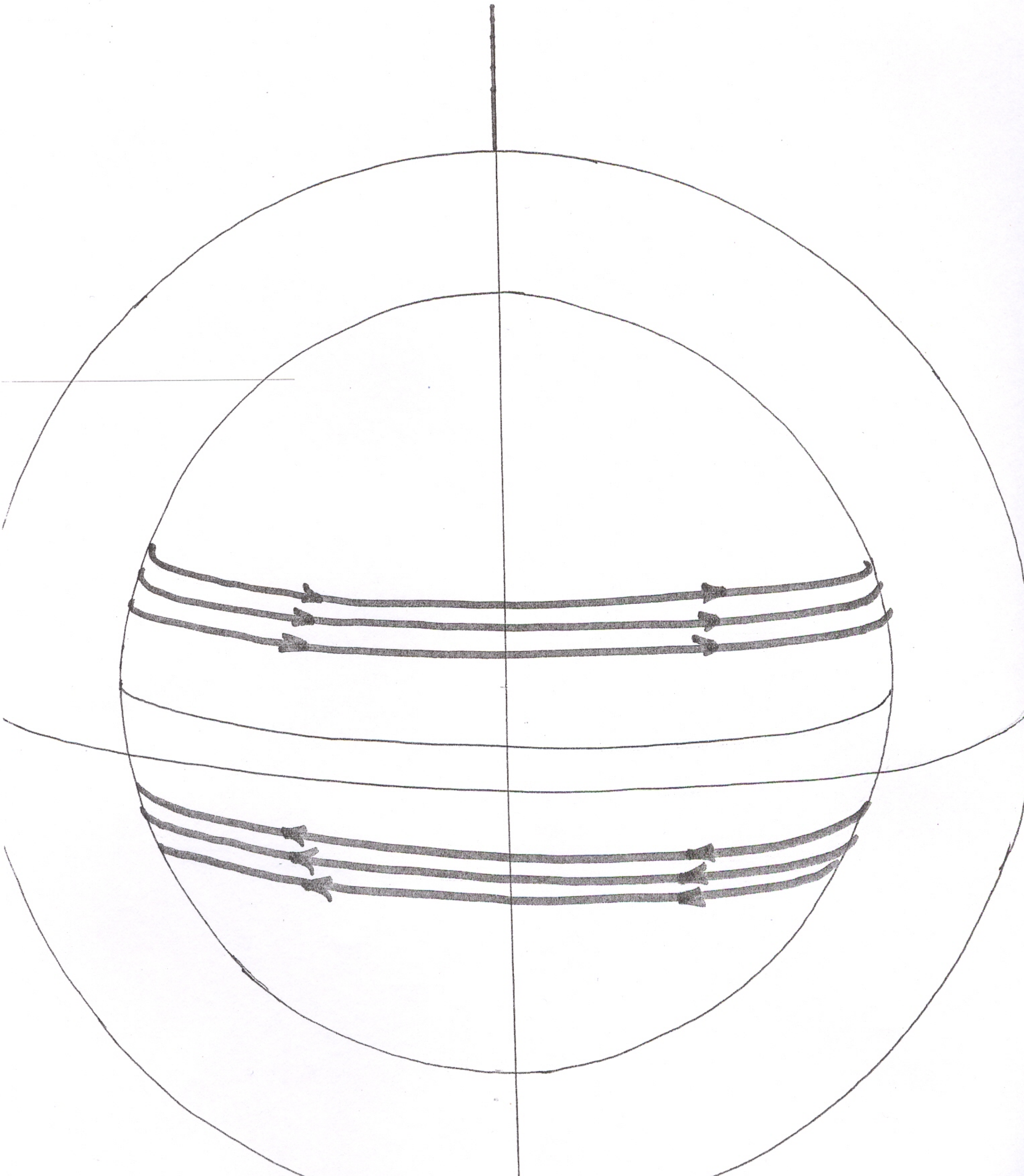


The bands of azimuthal magnetic field migrate toward the equator, and successive bands have opposite sign, so that the overall field reverses on a 9 – 14 year basis – the familiar 11-year magnetic cycle.

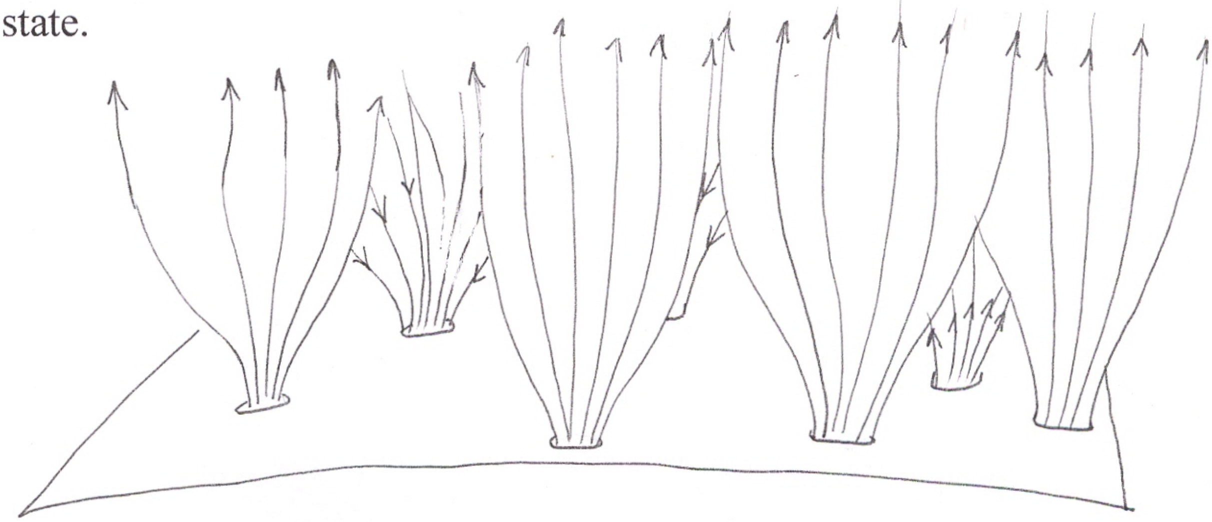
This convective generation of magnetic field exhibits the curious property of waxing and waning over periods of decades.

The Maunder Minimum 1645 – 1715 is the best known example of a protracted deep minimum of solar magnetic activity.

Another serious puzzle is the effect of meridional circulation, recently investigated by A. R. Choudhuri and others.

Then there is the question of how the convection can provide the essential “turbulent diffusion” of the strong (10^5 Gauss) magnetic fields inferred to exist in the low CZ.

The magnetic field at the surface of the Sun is in a curious fibril state.



The motions of these active magnetic fibrils provide a very complex and dynamic field structure, with myriads of points of explosive dissipation of magnetic energy.

These small, and occasionally large, flare events are believed to be the principal energy source responsible for heating the quiet corona to $1 - 2 \times 10^6$ K.

There is much physics that has yet to be figured out for the generation of magnetic fields in the Sun.

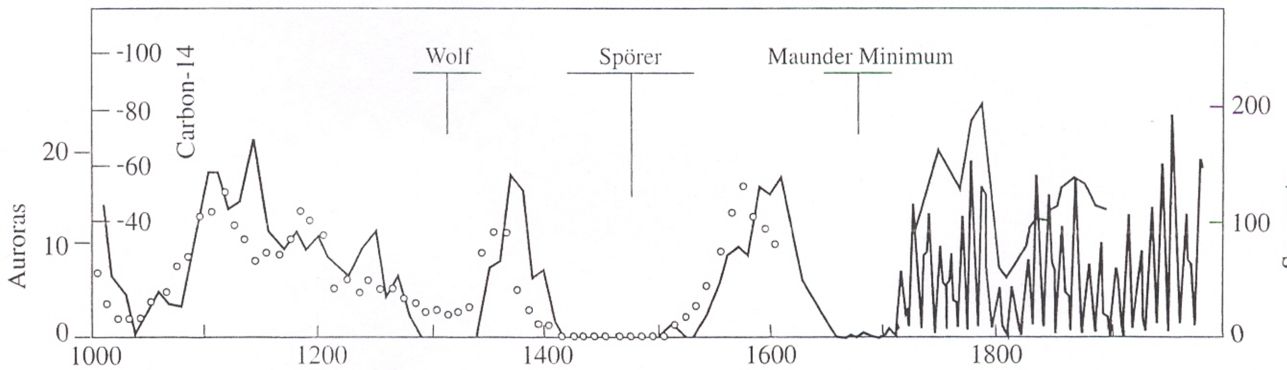
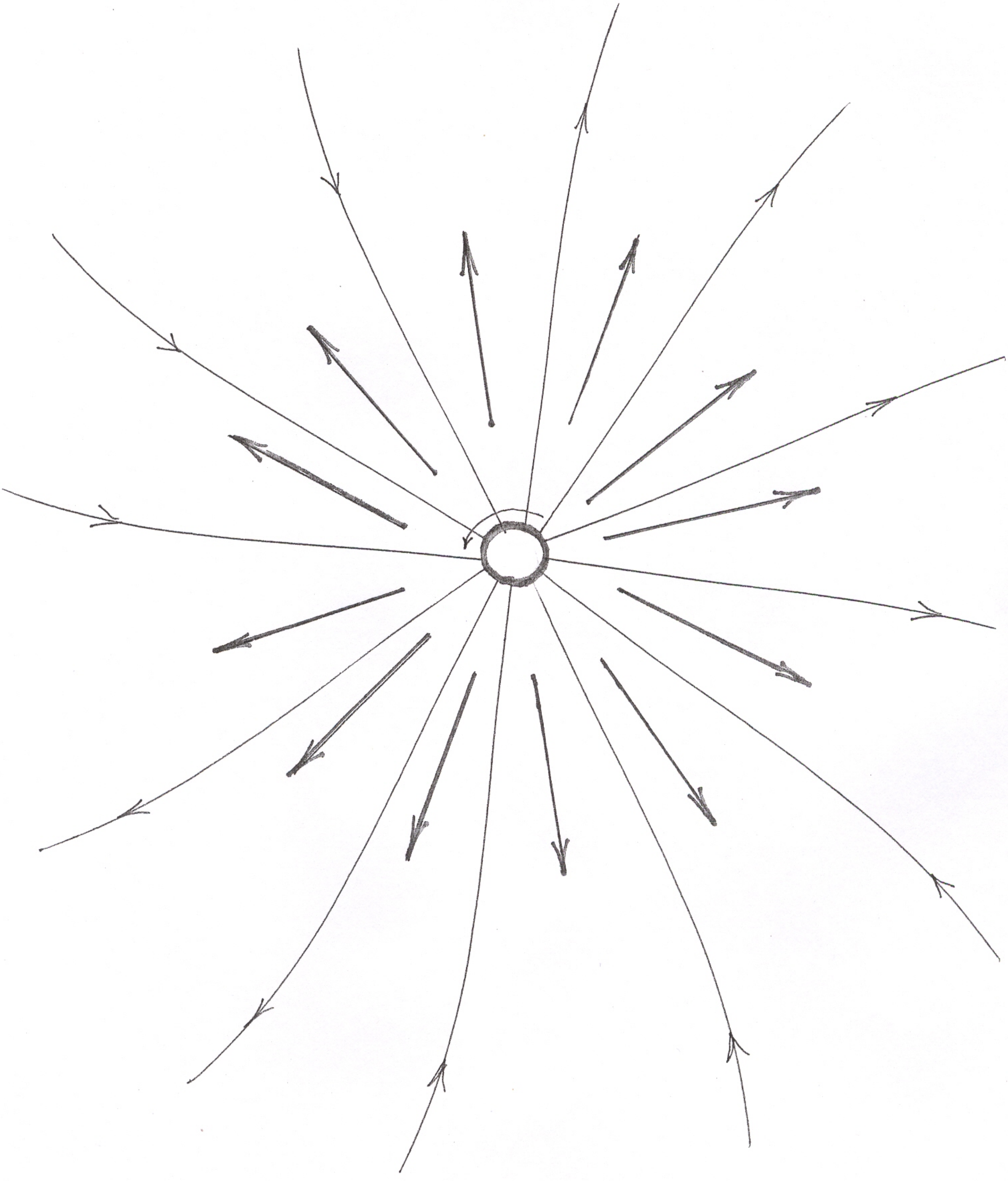


Fig. 8.25 **Long periods of solar inactivity** Three independent indices demonstrate the existence of prolonged decreases in the level of solar activity, such as the Maunder and Spörer minima. The observed annual mean sunspot numbers (*scale at right*) also follows the 11-year solar activity cycle after 1700. The curve extending from A.D. 1000 to 1900 is a proxy sunspot number index derived from measurements of carbon-14 in tree rings. Increased carbon-14 is plotted downward (*scale at left-inside*), so increased solar activity and larger proxy sunspot numbers correspond to reduced amounts of radiocarbon in the Earth's atmosphere. Open circles are an index of the numbers of auroras occuring in the Northern Hemisphere (*scale at left-outside*). (Courtesy of John A. Eddy.)

The continued hydrodynamic expansion of the million degree solar corona provides the supersonic solar wind, creating the heliosphere.

The expanding corona carries the local magnetic fields along with it, stretching the solar field out through the heliosphere to distances beyond 100 AU.

On scales of 10^3 - 10^5 km the extended field is strongly irregular, but on the large scale of 10^6 km and more the field is well ordered, starting out radially near the Sun and becoming strongly spiraled beyond the orbit of Earth.



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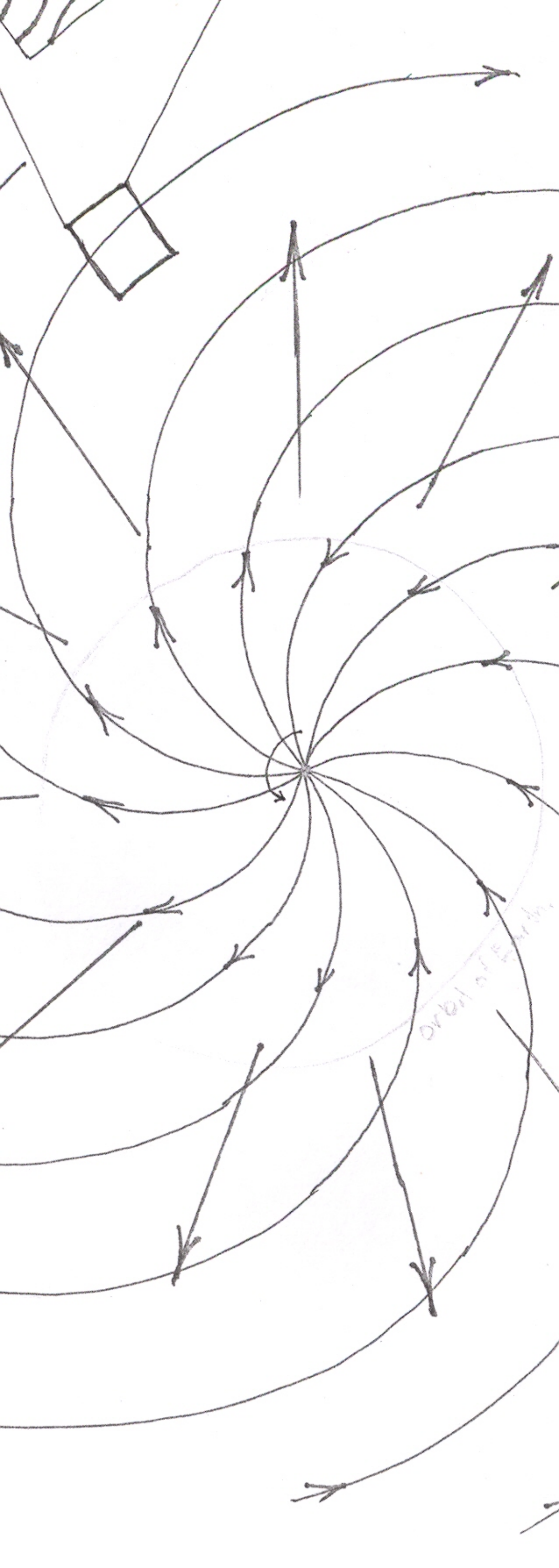

Orbit of Earth

GALACTIC COSMIC RAYS

The galactic "cosmic rays" are mostly protons with smaller numbers of heavier nuclei, all accelerated to relativistic velocities, presumably in association with supernovae.

On a galactic scale the cosmic rays represent a gas that is relativistically hot, inflating the magnetic fields that lie along the spiral arms of the Galaxy.

The cosmic ray intensity at Earth varies as the Sun orbits around the Galaxy and oscillates across the galactic plane.

The outward sweep of the magnetic fields in the solar wind substantially reduces the cosmic ray intensity at Earth, the reduction increasing with the level of magnetic activity.

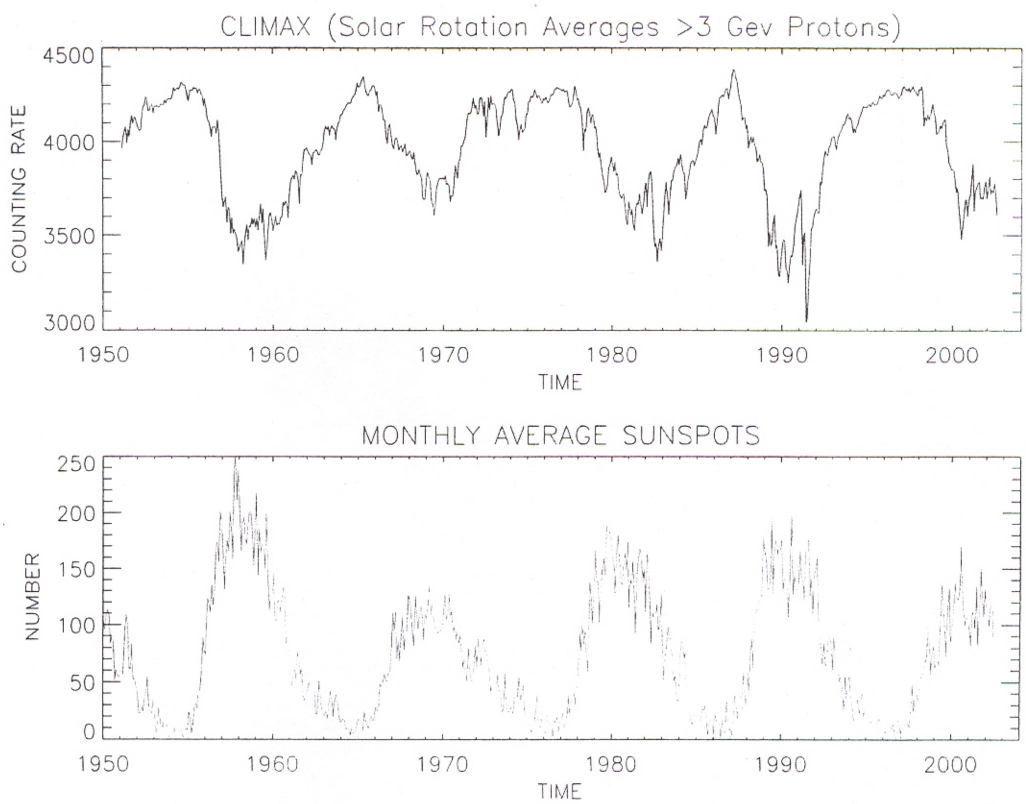
So the cosmic ray intensity varies with:

(a) Solar activity;

(b) Radius of the heliosphere;

(c) Local galactic cosmic ray intensity;

(d) Waxing and waning geomagnetic field.



A comparison of galactic cosmic ray intensity, as determined from counting rates at the University of Chicago's neutron monitor in Climax, Colorado (top panel) and monthly average sunspot numbers (bottom panel). The data, which cover a period of more than five decades, from the declining phase of solar cycle 18 through the peak of solar cycle 23, clearly illustrate the anticorrelation between galactic cosmic ray intensity and solar activity. Courtesy of J.R. Jokipii (University of Arizona), the University of Chicago, the National Science Foundation, and the World Data Center for the Sunspot Index (Brussels, Belgium).

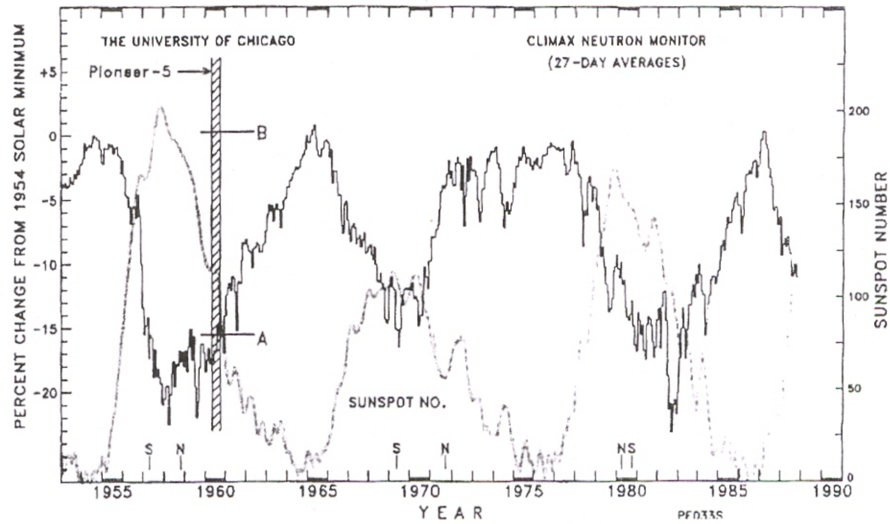


Fig. 3.5. Changes in the nucleonic component integral flux above ~ 3 GV (**solid line**). The solar activity is represented by the sunspot numbers (**dashed line**). From Simpson (1989 [492])

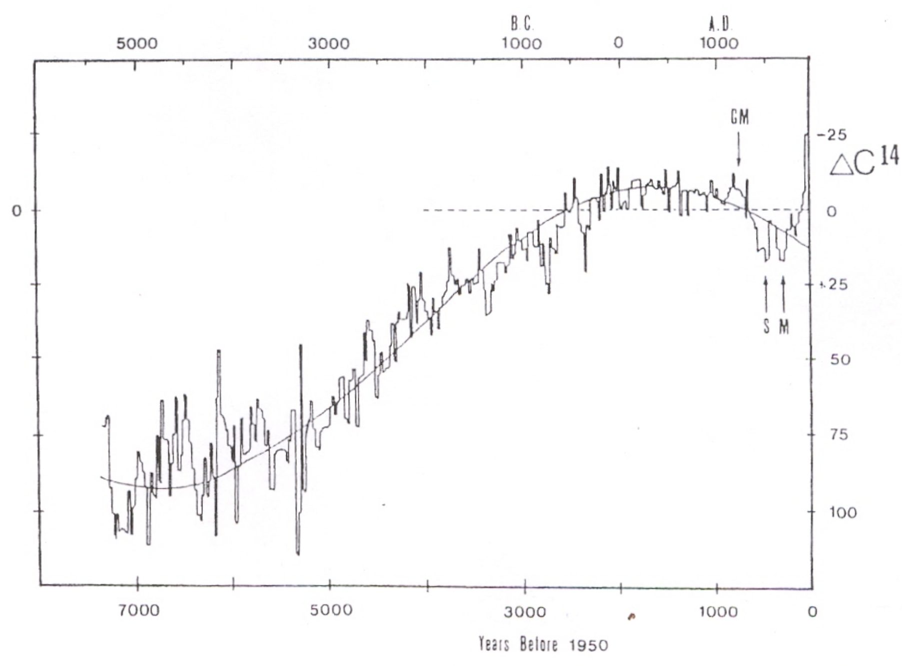
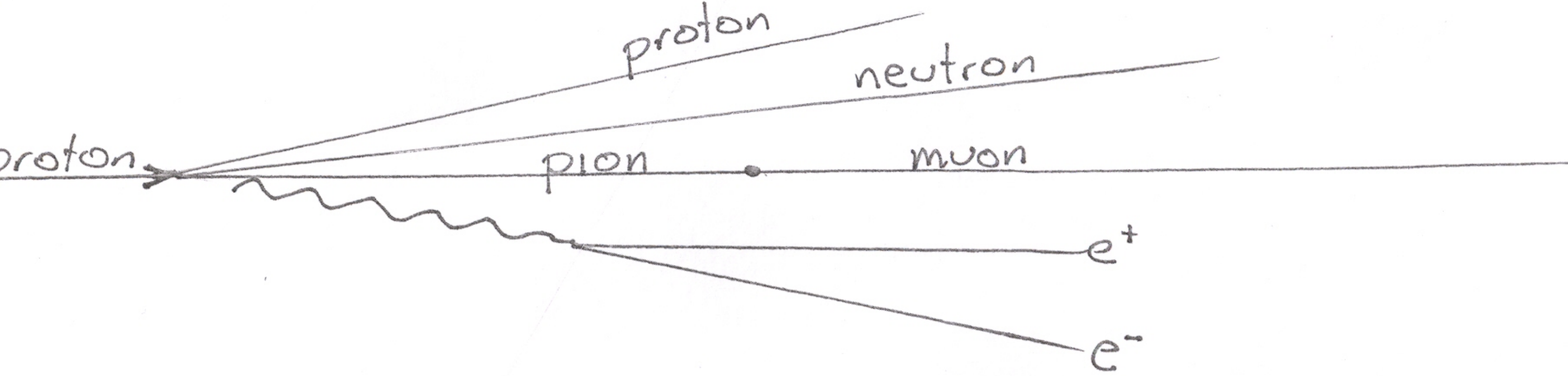


Fig. 5. History of relative radiocarbon concentration from tree ring analysis. S is for Spörer, and M is for Maunder, and both these dips mean more ^{14}C (relative to ^{12}C, in units of per mille or parts per thousand in concentration) to what was manufactured in the atmosphere, showing up in trees sensitive to moisture. Note that Eddy displayed more ^{14}C downward. In contrast GM (Grand or Great Maximum) denotes times of reduced ^{14}C production occurred during the Medieval Maximum. Note that the highly diluted ^{14}C level in modern times, say since the 1900s, is a result of fossil-fuel and coal burnings (the so-called Suess effect). The smooth sinusoidal curve ("making the ski-slope") overlaid on the ^{14}C data could be tied to the effects caused by a gradual variation of the Earth's magnetic dipole field intensity. (After John A. Eddy, 1980)


proton
neutron
proton
pion
muon
e+
e-

TERRESTRIAL CLIMATE

1976 Eddy pointed out the close correlation between Mean Annual Temperature in the northern hemisphere and the level of sunspot activity, i.e. magnetic activity.

The Maunder Minimum 1645-1715 was the outstanding example, associated with cold climate.

Extending the data back to 1100, showing the cold spells associated with the

Dalton Minimum 1870-1890,

Sporer Minimum 1450-1550.

Warm climate associated with the

Medieval maximum 1350-1430.

1978-1990 JPL measurement of solar luminosity variation.

Solar luminosity varies by about one part in 1000 through the 11-year solar magnetic cycle.

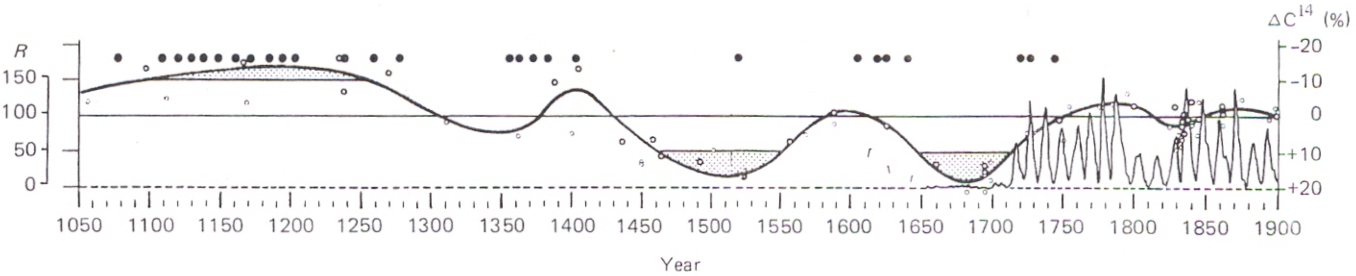


Figure 2.3. Historical sunspot variability as deduced by Eddy (1976). The heavy solid line is variation in C^{14} concentration in tree rings and the thin curve is Wolf sunspot numbers (R). Solid circles are from historical Oriental sunspot records; open circles are from tree ring analysis. Shaded portions of the C^{14} curve are the Spörer and Maunder sunspot minimums.

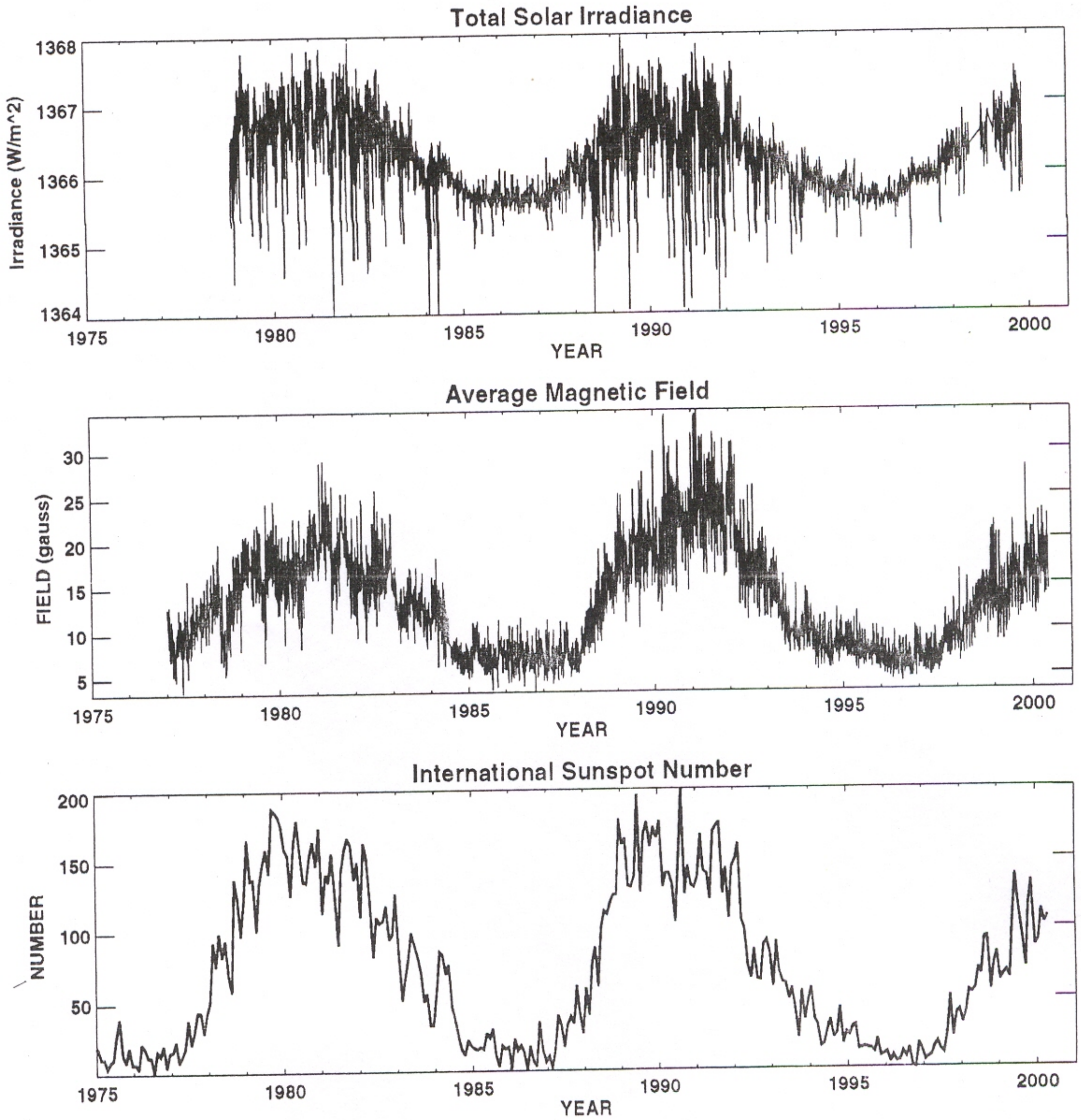


Figure 2. The 11-year Schwabe Cycle in Total Solar Irradiance (upper), Average Solar Magnetic Field (middle), and Average International Sunspot Number (lower).

Luminosity variation is enough to account for perhaps one quarter of the thermal response of terrestrial climate.

There must be some other, more powerful, effect operating as well.

TERRESTRIAL CLIMATE

Some years ago Henrik Svensmark pointed out that the ions created by the cosmic rays in the terrestrial atmosphere are essential for cloud formation, and therefore cloud cover varies with the solar magnetic cycle.

Cloud cover is the principal valve controlling the flow of solar heat into the greenhouse atmosphere of ours.

During the enhanced cosmic ray intensity at minimum solar activity, the climate is cooler. High solar activity reduces the cosmic ray intensity, reducing the cloud cover and providing a warmer climate.

Variation in worldwide cloud cover, and climate, is expected over geological time scales with the variation of the galactic cosmic ray intensity at the position of the heliosphere and Sun.

In the early days of Earth, when the Sun was substantially fainter than at present, the presumed strong solar magnetic activity greatly reduced the cosmic ray intensity at the orbit of Earth, thereby providing clear skies and enhance solar heat input.

It must be appreciated that our understanding of the Cosmic Ray-Climate effect is not yet fully quantitative.

The cosmic ray variations are known, but the direct influence on the rate of cloud formation has not yet been precisely measured.

A forthcoming experiment at CERN will give precise rates.

The basic statement is that our climate is strongly influenced by the cosmic ray intensity at the orbit of Earth. That cosmic ray intensity is determined

(a) by the cosmic ray intensity at the position of the Sun in the Galaxy
(b) by the degree to which the magnetic activity in the CZ of the Sun admits the cosmic rays to the position of Earth in the heliosphere.

Needless to say, the climate is also influenced by changes in the greenhouse gases in the atmosphere, and by the relative geographic positions of the continents and the associated winds and ocean. currents.

For the complete picture see the forthcoming book THE CHILLING STARS by Svensmark and Calder.

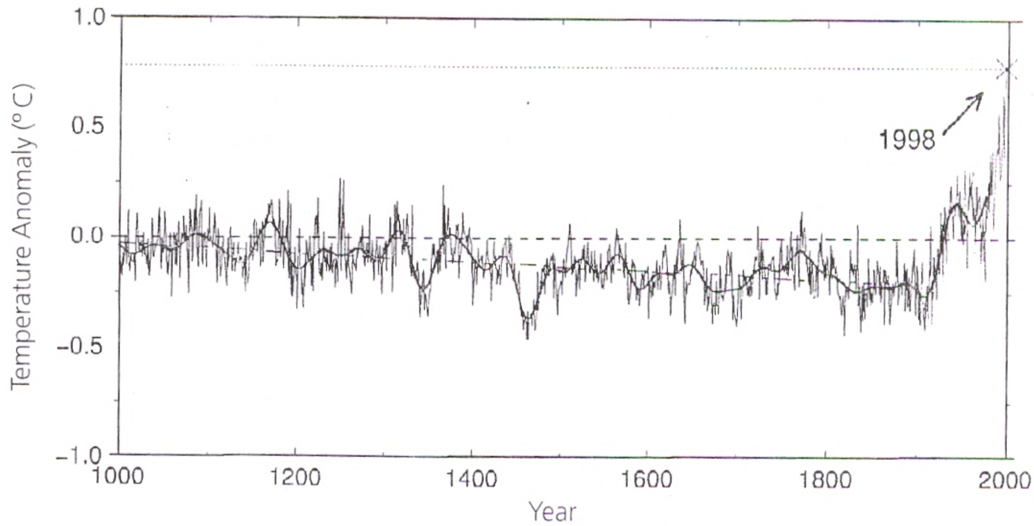


Fig. 8.24 **Unusual heat** This reconstruction of the hemisphere temperature record suggests that the Northern Hemisphere has been warmer in the 20th century than in any other century of the last thousand years. The sharp upward jump in the temperature during the last 100 years was recorded by thermometers at and near the Earth's surface. Earlier fluctuations were reconstructed from "proxy" evidence of climatic change contained in tree rings, lake and ocean sediments, and ancient ice and coral reefs. The heavy solid line is the reconstruction smoothed over 40-year intervals; the long dashes depict the linear trend from A.D. 1000 to 1850, and the short dashes provide the reference zero level, at the mean for the calibration period 1902 to 1980. The farther back in time the reconstruction is carried, the larger the range of possible error, denoted by the yellow shading. (Courtesy of Michael E. Mann.)

It appears that the warming since the short Dalton Solar Minimum, around 1890, was driven by the increasing level of solar activity and the decreasing cosmic ray intensity.

After about 1950, solar activity ceased to increase, and so did the temperature here at Earth.

Around 1970 the temperature began again to rise, while solar activity did not. The average cosmic ray intensity has not been declining

That rise continues today at an accelerating rate, and can be attributed only to the accumulating greenhouse gases.

So we live under the thumb of solar activity and the distant supernovae, while we grapple with our excessive burning of fossil fuels.

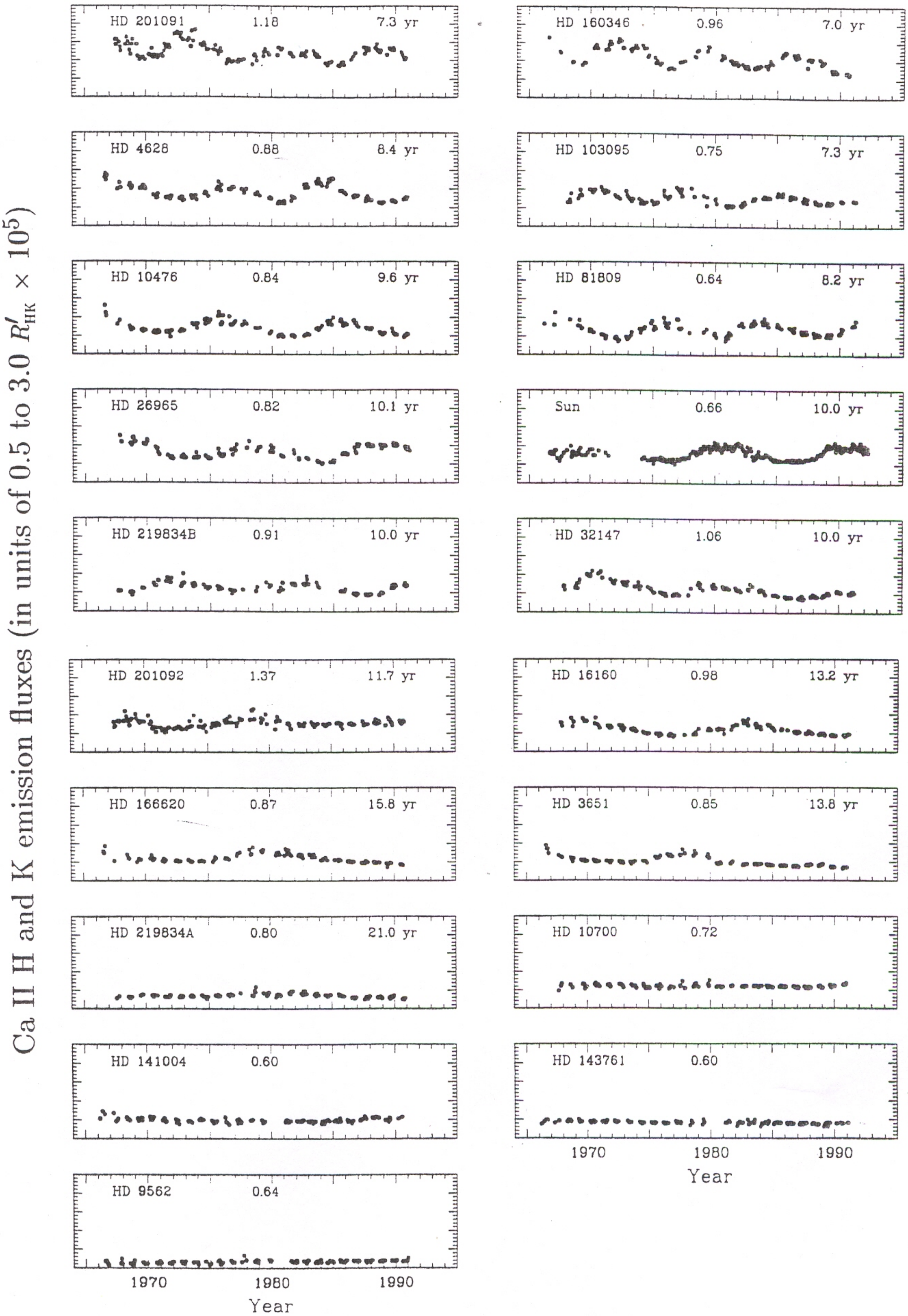

Ca II H and K emission fluxes (in units of 0.5 to 3.0 R'_{HK} × 10^5)
HD 201091 1.18 7.3 yr
HD 160346 0.96 7.0 yr
HD 4628 0.88 8.4 yr
HD 103095 0.75 7.3 yr
HD 10476 0.84 9.6 yr
HD 81809 0.64 8.2 yr
HD 26965 0.82 10.1 yr
Sun 0.66 10.0 yr
HD 219834B 0.91 10.0 yr
HD 32147 1.06 10.0 yr
HD 201092 1.37 11.7 yr
HD 16160 0.98 13.2 yr
HD 166620 0.87 15.8 yr
HD 3651 0.85 13.8 yr
HD 219834A 0.80 21.0 yr
HD 10700 0.72
HD 141004 0.60
HD 143761 0.60
HD 9562 0.64
1970
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Figure 2

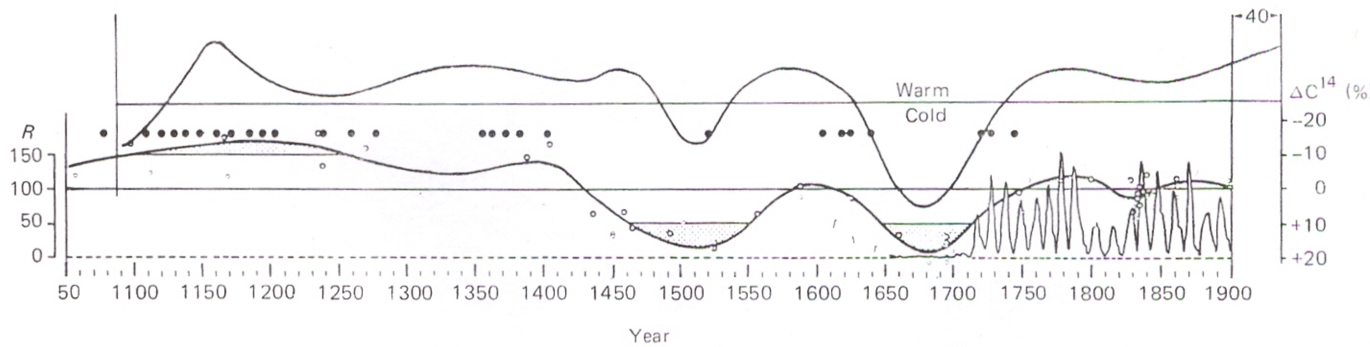

Figure 3.9. Relationship between winter severity in Paris and London (top curve) and long-term sunspot variations as reproduced from figure 2.3. The winter severity index is shifted 40 yr to the right to allow for cosmic-ray-produced C^{14} assimilation into tree rings (see p. 18). From Eddy (1976, 1977).