THE SOLAR CYCLE CONUNDRUM

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A CONUNDRUM?

- **SCHWABE (1843)**: SUNSPOTS VARY ON AN 11-YEAR PERIOD

- **HALE (1908)**: SUNSPOTS ARE MAGNETIC

- A DYNAMO DEEP INSIDE THE SUN MODULATED BY CYCLIC PROCESSES

- PREDICTION OF TIMING AND AMPLITUDE OF UPCOMING CYCLE
THREE POSSIBILITIES ...

• CONCEPT IS COMPLETELY WRONG

• THE BASIC CONCEPT IS CORRECT, BUT THERE IS SOMETHING MISSING

• THE SOLAR CYCLE CAN NEVER BE PREDICTED
TALK OUTLINE

THE SUN AS A MAGNETIC VARIABLE STAR

SOLAR CYCLE MODELS & THEIR ABILITY TO FORECAST

A DIFFERENT APPROACH NEEDED?

REQUIREMENTS FOR PROGRESS
400 YEARS OF SUNSPOT DATA

X ..... DATA INTERMITTENT AND LOWER QUALITY

| ..... DATA MORE COMPLETE AND RELIABLE
11-YEAR MODULATION OF SUNSPOTS NUMBERS

... BUT THE PERIOD IS NOT EXACTLY 11 YEARS RANGING FROM 8 TO 14 YEARS
THE AMPLITUDE OF THE CYCLES VARIES...

... RANGING FROM <50 TO >200
A LONG PERIOD WITHOUT MANY SPOTS APPEARING

A HARD TEST FOR ANY SOLAR CYCLE MODEL
HOW TO START A EXTENDED MINIMUM
HOW TO GET OUT OF IT
THE MAGNETIC CYCLE IS 22 YEARS

1. NORTHERN & SOUTHERN REGIONS HAVE OPPOSITE POLARITY
2. MAGNETIC POLARITY REVERSES FROM SOLAR CYCLE TO CYCLE
3. POLAR MAGNETIC FIELD REVERSAL IN MIDDLE OF SOLAR CYCLE
PART 2:

SOLAR CYCLE MODELS & THEIR ABILITY TO FORECAST
AN EMPIRICAL MODEL

AVERAGE CYCLE PROFILE

SMOOTHED SUNSPOT NUMBER

RISE PHASE

MAXIMUM

DECAY PHASE

MINIMUM

YEARS

0  2  4  6  8  10  12
... BUT GIVES LOTS OF FALSE RESULTS
PHYSICS-BASED MODELS
ROTATION IS A CLUE TO THE NATURE OF THE SOLAR DYNAMO

BOHM-VITENSE (2007)
WINDING UP

RADIATIVE ZONE

CORE
INSTABILITY SETS IN

- WINDING UP CREATES STRONGER MAGNETIC FIELDS
- MAGNETIC PRESSURE EXCEEDS GAS PRESSURE
- MAGNETIC FLUX ROPES EXPAND AND BECOME BUOYANT
- RISE TO THE SURFACE TO APPEAR AS SUNSPOTS
AND THEN IT GETS COMPLICATED

STARTING POINT

CANCELLATION

TRANSPORT

EROSION
AND THEN IT GETS COMPLICATED

ZERO POLES

REVERSAL

MINIMUM

NEW CYCLE
BUT ALL WAS NOT WELL ...

• THE EARLY MODELS REQUIRED SHEAR THROUGHOUT THE CONVECTIVE ZONE
  
  — HELIOSEISMOLOGY SHOWS SHEAR AT THE BASE OF THE CONVECTION ZONE AND NEAR THE SURFACE

• PREDICTED CYCLES TOO SHORT (ONLY 2 YEARS!)

• MOST MODELS ASSUME N-S MAGNETIC SYMMETRY

• A DEEP MERIDIONAL FLOW?
THE DIKPATI MODEL

Sunspot Cycles: Past and Future

Sunspot Number

1940 1960 1980 2000 2020

18 19 20 21 22 23 24 25
HOW WELL DID WE DO?

Data Tabulated by D. Pesnell (GSFC)
THE EXPERTS ARE FALLING IN LINE?

International sunspot number R$_i$: last 13 years and forecasts

- Daily
- Monthly
- Monthly smoothed
- SC Predictions
- CM Predictions

SILSO graphics (http://sidc.be) Royal Observatory of Belgium 16/07/2013
PART 3:
A DIFFERENT APPROACH ...
OUR NEW APPROACH

• DITCH SUNSPOT NUMBER
  – AT SOLAR MINIMUM B FIELD PRESENT BUT FEW OR NO SPOTS

• USE NEW DATA SOURCES
  – DIRECT MEASUREMENTS OF SOLAR MAGNETIC FIELDS
  – CORONAL X-RAY EMISSIONS

• FIND WHAT THE SUN WILL ALLOW US TO FORECAST (IF ANYTHING)
TIMING IS KEY

• SOLAR CYCLES MEASURED WRT SOLAR MAX OR SOLAR MINIMUM DATES
  – 13-MONTH SMOOTHED SUNSPOT NUMBER
  – UNCERTAIN
  – DON’T KNOW UNTIL A YEAR HAS PASSED

• DEFINED A NEW TIMING REFERENCE: THE “ONSET”
The Onset is a **Global** Burst of Activity

BEFORE
Carrington Rotation 1924

AFTER
Carrington Rotation 1927
The B Ratio: A PERFECT FIDUCIAL

\[
B \text{-RATIO} = \frac{(x + z)}{y}
\]

Tune x, y, and z boundaries and B threshold to show different aspects of a solar cycle.
THE B RATIO CAN BE USED TO PREDICT THE ONSET

Cycle 21
Cycle 22
Cycle 23

THE BEGINNING OF CYCLE 24
A SERIES OF BURSTS

FULL SUN NSO SYNOPTIC CHARTS
THE SOUTHERN HEMISPHERE
(10S – 60S; B > 50G)

Normalized Magnetic Flux

Carrington Rotation Number

2070 2080 2090 2100 2110 2120 2130 2140
ONSET OF SC24
SOUTH; B>50; dt = 8.3 (.4) solar rotations

Diagram showing relative amplitude of peaks against Carrington rotation number.
AVERAGE LENGTH OF BURST THROUGH ONSET PHASE OF CYCLES 22-24
SOMETHING HAS CHANGED

• LOWEST SOLAR CYCLE IN 100 YEARS (SO FAR)

• SOLAR CYCLES GETTING LONGER?
  • SC21: 10.3 YEARS
  • SC22: 10.6 YEARS
  • SC23: 12.6 YEARS
  • SC24: ????? YEARS

• PROBLEM: HOW CAN THIS HAPPEN?
HINTS

• NORTHERN & SOUTHERN HEMISPHERES INTERACTING

• CYCLE TO CYCLE INTERACTIONS

• MULTIPLE CYCLES PRESENT SIMULTANEOUSLY
A NEW MODEL

- RESONANCE OSCILLATORS
OR A COMPOUND OSCILLATOR?
PART 4:

WHAT NEEDS TO BE DONE?
THE BASIC PROBLEM

• WE SEE LESS THAN 35% OF THE SOLAR SURFACE MAGNETIC FIELD FROM EARTH

• NEVER GET A CLEAR VIEW OF THE POLAR REGIONS

NEED TO BUILD ON THE SUCCESS OF STEREO
THE $4\pi$ CONCEPT

• MULTIPLE SPACECRAFT ORBITING THE SUN IN THE ECLIPTIC PLANE AND OVER THE POLES

• INSTRUMENTS
  – MAGNETOGRAPH/HELIOSEISMMOMETER
  – CORONAL IMAGER
  – CORONAGRAPH
  – PARTICLES AND FIELDS MONITORS
4π SCIENCE

• CONTINUOUS OBSERVATIONS OF THE SOLAR GLOBAL MAGNETIC FIELD AND SOLAR WIND

• MEASUREMENTS OF GLOBAL OSCILLATIONS TO PROBE DEEPER AND MORE BROADLY THE INTERNAL DYNAMIC OF THE SUN

• FOLLOW THE EVOLUTION IN 3D OF ALL SUNSPOT REGIONS, FLARES AND CMES

• DETERMINE THE ROLE OF LARGESCALE CORONAL FIELDS IN THE EVOLUTION OF THE SOLAR CYCLE
CONCLUSIONS

• CURRENT SOLAR CYCLE MODELS ARE INADEQUATE FOR PREDICTION OF THE SOLAR CYCLE

• SC24 WILL LIKELY BE THE LOWEST CYCLE IN 100 YEARS
  — LENGTHENING OF THE CYCLE
  — LOW % OF LARGE (M & X) FLARES
  — EXTENDED SOLAR MINIMUM

• SOMETHING HAS SLOWED?

• SUGGESTED IMPROVEMENTS TO THE MODELS
  — USE THE MAGNETIC FIELD, NOT THE SMOOTHED SUNSPOT NUMBER
  — NEED BETTER TIME FIDUCIAL
  — INCLUDE ASYMMETRY IN N-S HEMISPHERES
  — CYCLE NOT SMOOTH BUT A SERIES OF BURST OF MAGNETIC ACTIVITY

• A WAY FORWARD: THE $4\pi$ CONCEPT
THANKS

YOUTUBE: drkstrong
WHY IS FORECASTING THE SOLAR CYCLE IMPORTANT?

• OUR EXISTENCE DEPENDS ON THE SUN’S VARIABILITY BEING BENIGN

• A TEST OF HOW WELL WE UNDERSTAND STARS

• SOCIETAL IMPACTS

• SOLAR SYSTEM EXPLORATION