

Physical Interpretation of TSI Variations

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Most stars have a *variable brightness* at some level

They vary as a consequence of two mechanisms:

1) surface features (usually big starspots) rotating into and out of view on the stellar disk

MAGNETIC STARS, LOW-MASS STARS

2) because of structural readjustments that affect the subphotospheric rate of energy output (luminosity)

CEPHEIDS

MIRA VARIABLES

ETC.

THE SUN CAN VARY IN *BOTH* WAYS:

STRUCTURAL (INTERNAL)- ALL GLOBAL PARAMETERS
CHANGE

e.g. **EVOLUTION**

ROTATION OF SURFACE FEATURES:

e.g. **ACTIVE REGIONS, NETWORK**, etc.

WHICH TYPE OF VARIATION DOMINATES DEPENDS
ON THE *TIMESCALES* INVOLVED..

The mechanisms currently proposed for **solar effects on climate** are:

DIRECT: variations of the Total Solar Irradiance (TSI)

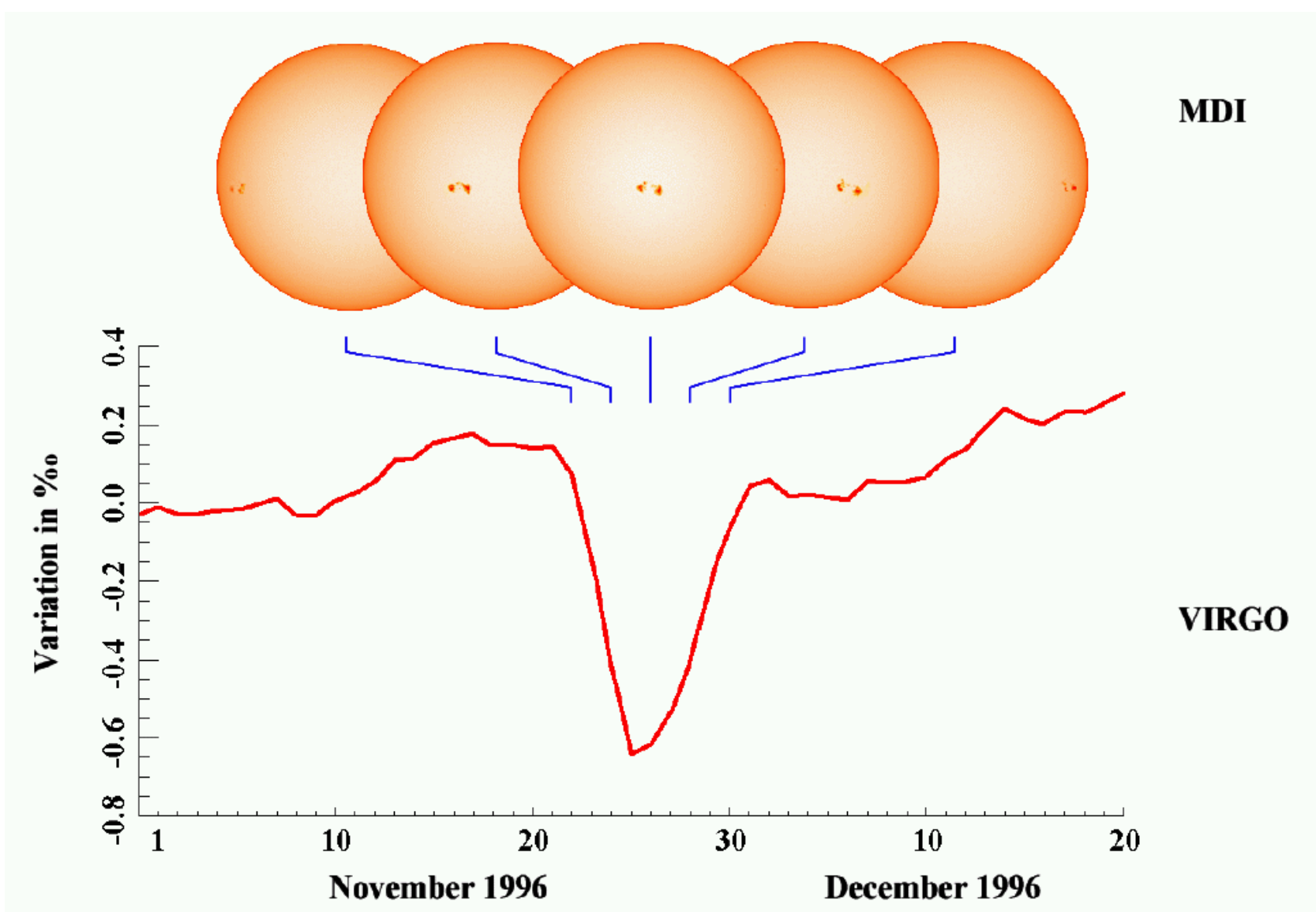
INDIRECT: Trigger mechanisms- Variations of EUV-UV that affect the structure and dynamics of the upper atmosphere; Cosmic Rays that may affect cloud formation, etc.

Our work concentrates on the **TSI variations**.

SHORT TIMESCALE VARIATIONS OF THE TSI

Since the early 1980S, it has been known that the *TSI* varies on timescales of MINUTES TO MONTHS, and most of the variation can be attributed to *THE PASSAGE OF ACTIVE REGIONS (SPOTS AND FACULAE)* on the solar disk

SURFACE PHENOMENA



For VERY LONG TIMESCALES, variability is clearly

Dominated by INTERNAL CHANGES

---this can be inferred from THEORY OF VARIATIONS

--- and from ENERGY REQUIREMENTS

QUESTION:

WHERE DO BOTH MECHANISMS CROSS OVER?

IN PARTICULAR,

WHAT FRACTION OF THE 11 YEAR CYCLE IS DUE TO SURFACE MODULATION?

WHAT FRACTION IS DUE TO INTERNAL PROCESSES?

Many recent studies have dismissed the idea that the 11 year Cycle might have an internal component because of a **MYTH**

“INTERNAL PROPERTIES OF THE SUN CANNOT VARY ON TIMESCALES SHORTER THAN THE THERMAL TIMESCALE OF THE BASE OF THE CONVECTION ZONE”

10⁵ YEARS

demonstrated wrong by

OTHER STARS, e.g. MIRA variables

RECENT RESULTS FROM HELIOSEISMOLOGY

PROPERTIES OF STRUCTURAL VARIATIONS

BECAUSE THEY INVOLVE THE ENTIRE CONVECTION
ZONE (LOTS OF ENERGY), *THEY CAN HAVE LONG
TIMESCALE COMPONENTS FOR CLIMATE CHANGE*

LONG TIMESCALE COMPONENTS ARE *DIFFICULT TO
DIFFERENTIATE FROM INSTRUMENT DEGRADATION*
IN ENERGY FLUX-TYPE MEASUREMENTS

IF WELL UNDERSTOOD, THEY PROVIDE PHYSICAL
MECHANISM RESPONSIBLE FOR CHANGE

PREDICTABILITY

We assume that the internal variability is dominated by the magnetic field generated by a dynamo mechanism.

The solar dynamo produces in the two toroidally shaped magnetic fields of variable intensity.

A variable magnetic field contributes to pressure, internal energy, and modifies energy transfer both by convection and radiation, and flow-dynamics.

IT AFFECTS THE STRUCTURE

CONVENTIONAL STELLAR MODELS ARE INADEQUATE

1. Sensitivity
2. Timescales
3. Inadequacy of standard mixing length theory of convection
4. Do not include magnetic fields, turbulence, rotation, etc.

- In standard stellar model calculations there are four stellar structure equations, since there are four variables. They are
 - Mass Conservation
 - Momentum Conservation
 - Energy Conservation
 - Energy Transport

When *magnetic fields* are present, we have to introduce two new *magnetic variables* and two new *turbulence variables*

Stellar structure equations with magnetic fields and turbulence

Modified stellar structure equation

EQUATION	STANDARD	MODIFIED	RELATIONSHIP
MASS	$\frac{\partial r}{\partial M} = \frac{1}{4\pi r^2 \rho_0}$	$\frac{\partial r}{\partial M} = \frac{1}{4\pi r^2 \rho}$	$\rho = \rho_0 / [1 + \frac{(\gamma-1)\chi \rho_0}{P}]$
MOMENTUM	$\frac{\partial P_0}{\partial M} = \frac{GM}{4\pi r^4}$	$\frac{\partial P}{\partial M} = \frac{GM}{4\pi r^4}$	$P = P_0 + (\gamma - 1)\chi \rho$
ENERGY	$\frac{\partial L}{\partial M} = \epsilon - T \frac{dS_0}{dt}$	$\frac{\partial L}{\partial M} = \epsilon - T \frac{dS}{dt}$	$TdS = TdS_0 + d\chi$
RADIATION	$\frac{\partial T}{\partial M} = -\frac{3}{64\pi^2 ac} \frac{\kappa_0 L}{r^4 T^3}$	$\frac{\partial T}{\partial M} = -\frac{3}{64\pi^2 ac} \frac{\kappa L}{r^4 T^3}$	$\kappa = \kappa_0 - \kappa_e \frac{(\gamma-1)\tau_e^2 \Omega_e^2}{4+(\gamma-1)\tau_e^2 \Omega_e^2}$
CONVECTION	$\frac{\partial T}{\partial M} = -\frac{T}{P_0} \frac{GM}{4\pi r^4} \nabla_0$	$\frac{\partial T}{\partial M} = -\frac{T}{P} \frac{GM}{4\pi r^4} \nabla$	see Table 2

Stellar structure equations with magnetic fields and turbulence

STANDARD	MODIFIED
$\nabla_0 = \nabla_{\text{ad}} + (y/V \gamma_0^2 C)(1 + y/V)$	$\nabla = \nabla'_{\text{ad}} + (y'/V' \gamma_0^2 C)(1 + y'/V')$
$2Ay^3 + Vy^2 + V^2y - V = 0$	$2Ay'^3 + V'y'^2 + V'^2y' - V' = 0$
$V = [\gamma_0 C^{1/2} (\nabla_{\text{rad}} - \nabla_{\text{ad}})^{1/2}]^{-1}$	$V' = [\gamma_0 C^{1/2} (\nabla_{\text{rad}} - \nabla'_{\text{ad}})^{1/2}]^{-1}$
$\gamma_0 = (c_p \rho) / (2\alpha c T^3) (3 + \omega^2) / (3\omega)$	$\nabla'_{\text{ad}} = [1 - f(\nu \nabla_\chi + \nu' \nabla_\gamma) / \mu] \nabla_{\text{ad}}$
$C = (g/l^2 \delta) / (8H_p)$	$f=3$ for magnetic fields
$A = (g/8)\omega^2 / (3 + \omega^2)$	$f=1$ for turbulence

χ and γ are magnetic, turbulent, or combined magnetic and turbulent variables,

$$\nu = -(\partial \ln \rho / \partial \ln \chi)_{T,P,\gamma}, \quad \nabla_\chi = \partial \ln \chi / \partial \ln P$$

$$\nu' = -(\partial \ln \rho / \partial \ln \gamma)_{T,P,\chi}, \quad \nabla_\gamma = \partial \ln \gamma / \partial \ln P$$

μ and δ are the compressibility and expansion coefficient at constant temperature and constant magnetic field, respectively.

Definition of magnetic and turbulent variables

Three magnetic variables	Two turbulent variables
$\chi_m \equiv B^2 / (8\pi\rho)$	$\chi_t \equiv \frac{1}{2}(v'')^2$
$\gamma_m \equiv 1 + (B_\theta^2 + B_\phi^2) / B^2$	$\gamma_t \equiv 1 + 2(v_r'' / v'')^2$
$\vartheta_m \equiv 1 + (B_\phi^2 + B_r^2) / B^2$	Here v'' , v_r'' : turbulent velocities

Variable	Meaning
χ_m	The magnetic energy per unit mass
γ_m^{-1}	The ratio of the magnetic pressure in the radial direction to the magnetic energy density
ϑ_m^{-1}	The ratio of the magnetic pressure in the co-latitude direction to the magnetic energy density
χ_t	The turbulent kinetic energy per unit mass
γ_t	The effective ratio of specific heats due to turbulence

Results of Early (1D) Calculations

- A dynamo type magnetic field does indeed affect the solar structure and dynamics, and as a consequence, all of the global parameters (R, T_{eff} , L).
- *The specific properties of the effects (the relationships between the variations of all the parameter pairs) depend on the **currently unknown** details of the magnetic field (magnitude, depth, shape, etc.), and of the interaction between the magnetic field and turbulence.*

FOR EXAMPLE:

A DEEPER MAGNETIC FIELD NEEDS TO BE LARGER TO PRODUCE A GIVEN LUMINOSITY CHANGE

THE DEEPER FIELD CAUSES A LARGER RADIUS CHANGE

A DEEPER FIELD HAS SMALLER EFFECTS ON HIGH- l OSCILLATIONS, ETC.

Hence,

To verify the model of the solar variations it is necessary to observe, simultaneously, all of the global parameters, plus the oscillations.

PICARD WILL MEASURE:

- solar diameter, limb shape, asphericity in the photosphere

-total solar irradiance

-oscillation modes

-Temperature variations in the photosphere

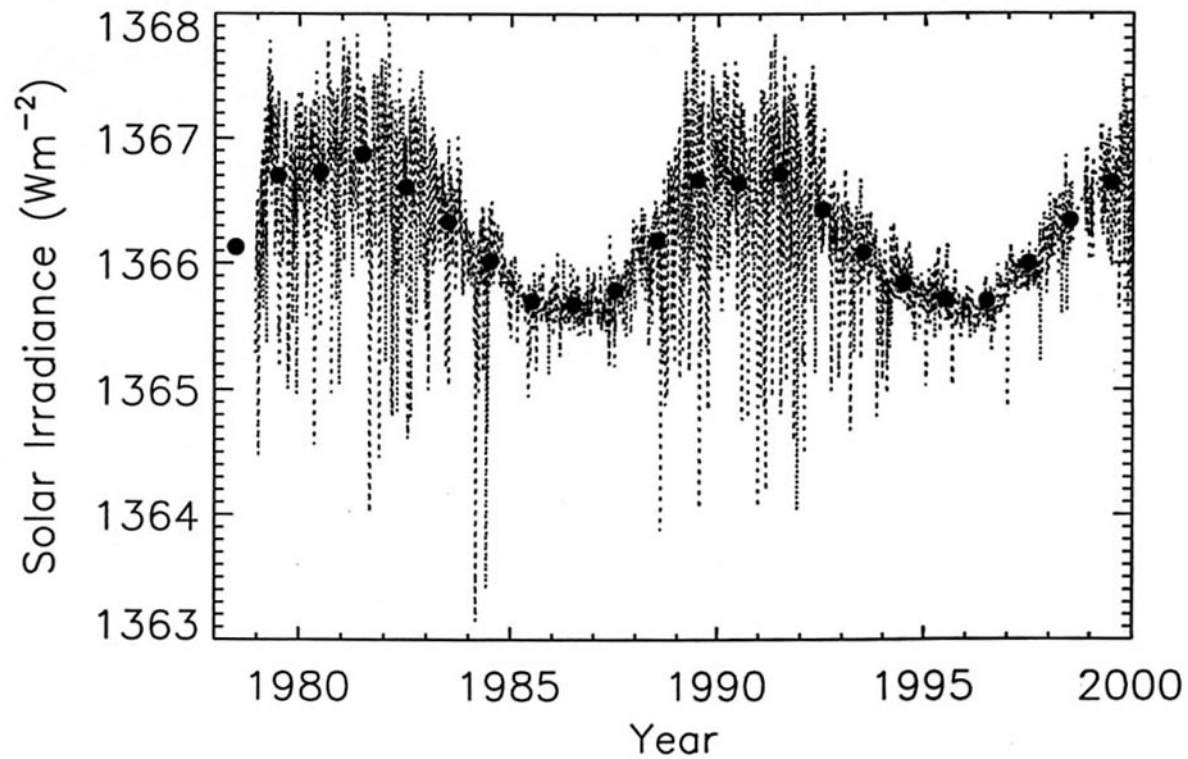
AT A PHASE INTERVAL OF THE ACTIVITY CYCLE THAT
MAXIMIZES THE VARIATIONS

PRIOR TO PICARD

At the present time, we do not have available all the simultaneous observations required to test the models.

WE HAVE MADE DO WITH WHAT WE HAVE

We assume that the average TSI variation observed over the last 20 years is due to structural changes



A REDUNDANT SET OF DATA TO SEPARATE VARIATIONS OF THE SUB-PHOTOSPHERIC LUMINOSITY FROM THE EFFECTS OF SURFACE FEATURES IS THE *TEMPERATURE OF THE UNDISTURBED PHOTOSPHERE*.

Attempts to do it in the past from **ground-based** observations have yielded controversial results

PICARD WILL BE ABLE TO DETERMINE PHOTOSPHERIC TEMPERATURE VARIATIONS IN A VERY DIRECT WAY, WITHOUT THE NEED OF CALIBRATIONS THAT CAUSED THE CURRENT UNCERTAINTY

Radius Variations

Radius is a powerful diagnostic of internal processes not fully exploitable until now. In our simulations we only assumed that the radius variations are in antiphase with the activity cycle, but of unknown amplitude.

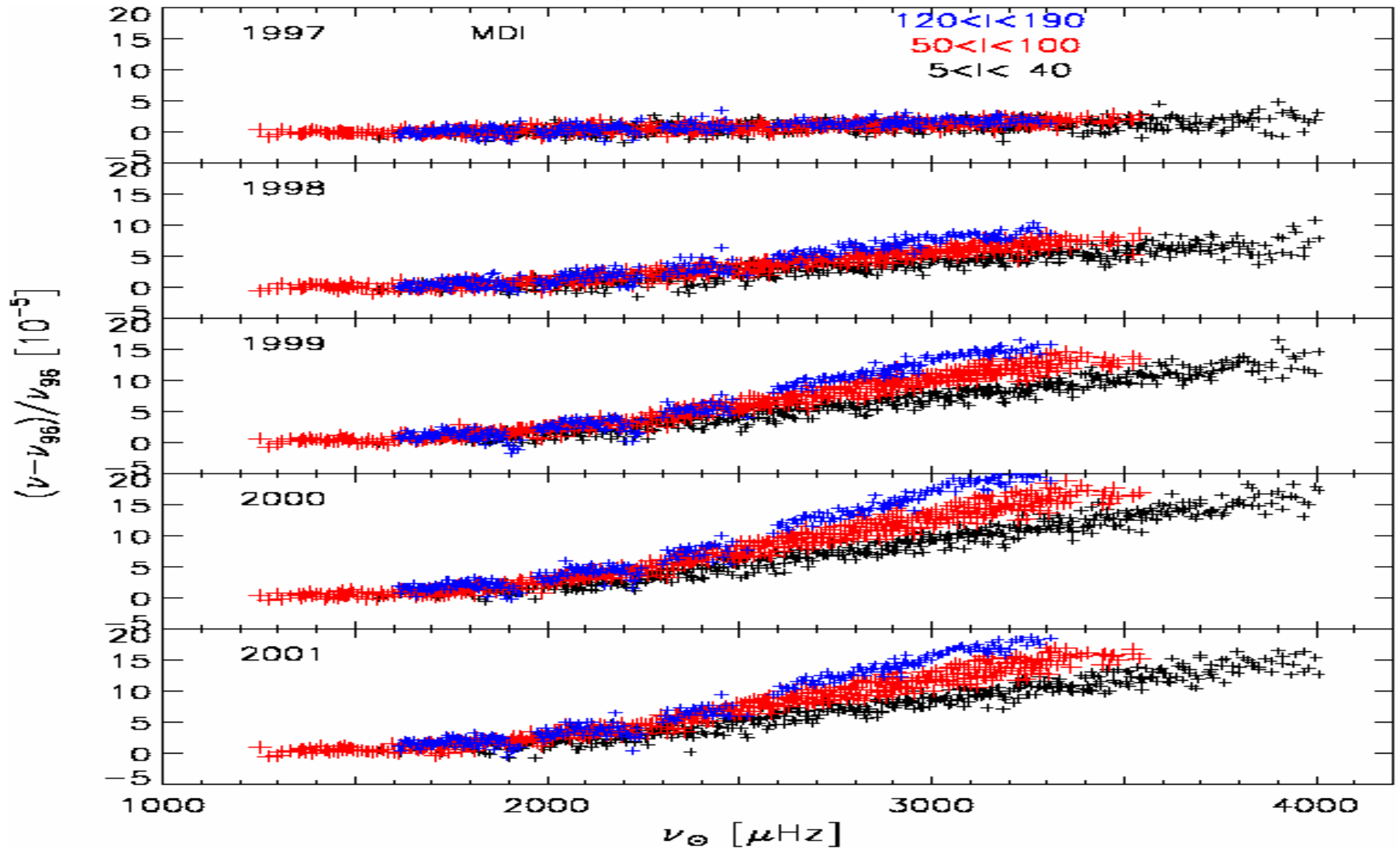
BECAUSE A MAGNETIC FIELD CAN ONLY PRODUCE A POSITIVE PRESSURE, IT ALONE CANNOT LEAD TO RADIUS CHANGES IN ANTIPHASE WITH THE ACTIVITY CYCLE

THIS LED US TO INCLUDE THE EFFECT OF A MAGNETICALLY MODULATED TURBULENCE IN THE SIMULATIONS

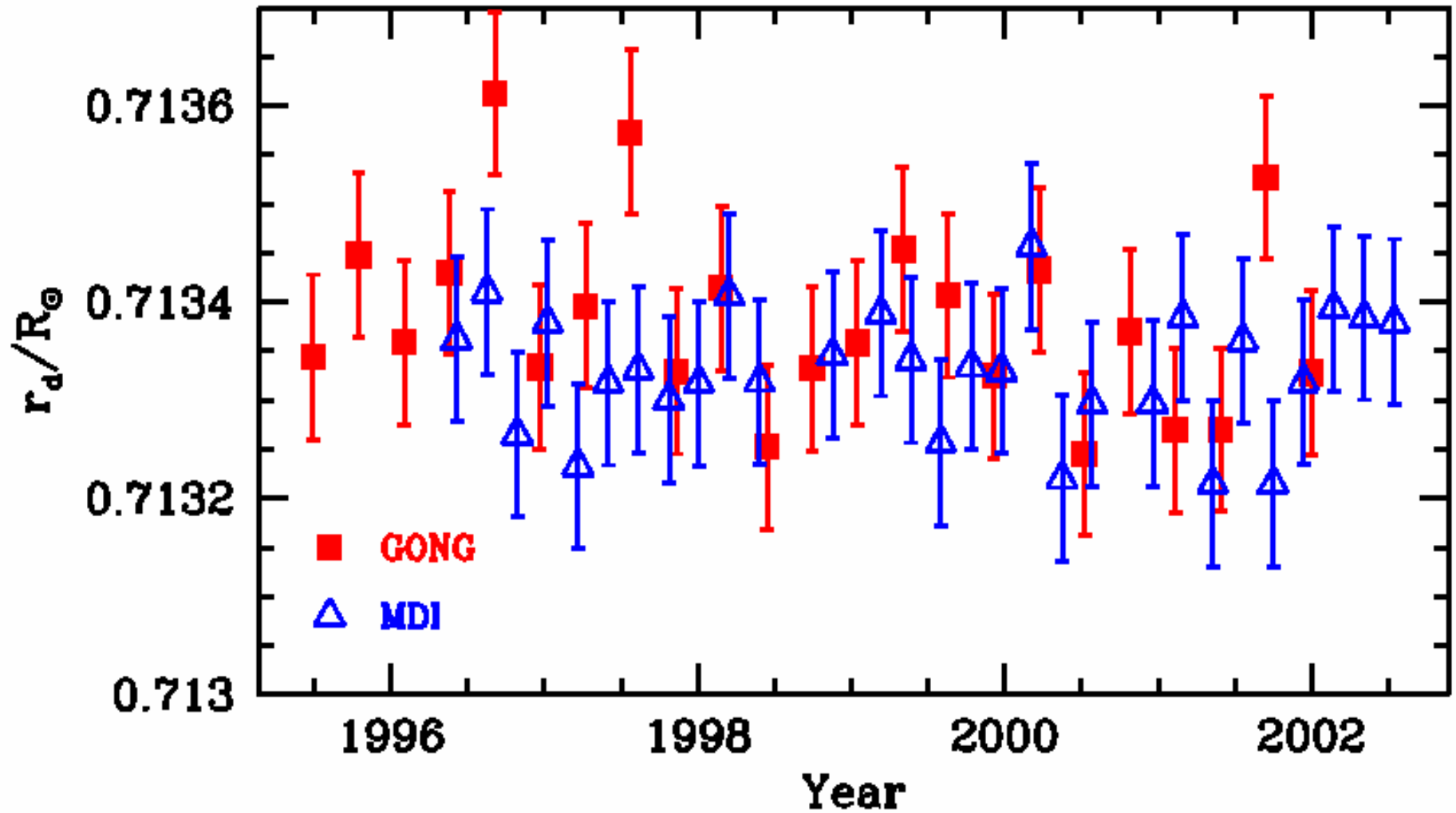
IN THE ABSENCE OF A THEORY ON THE MODULATION OF TURBULENCE BY A MAGNETIC FIELD, WE POSTULATED A SIMPLE ARBITRARY RELATIONSHIP LINKING THEM.

WE NEED TO MODEL THIS INTERACTION.

Observation: P-mode frequency



Observations: CZ base

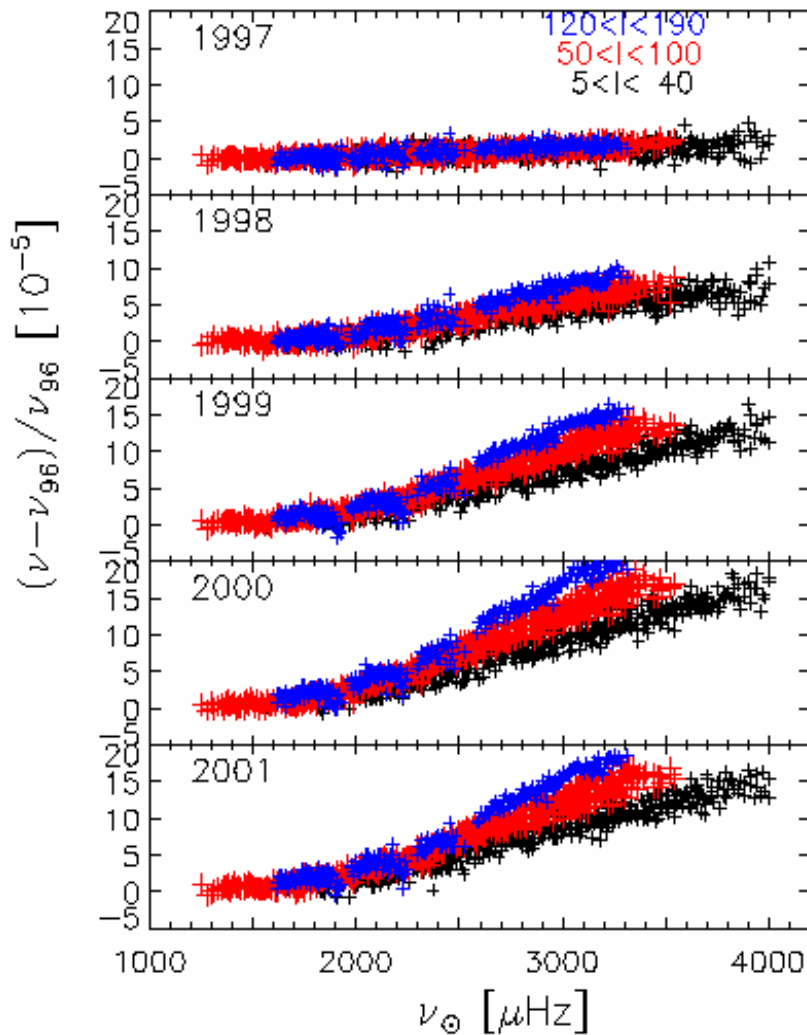


Observational constraints

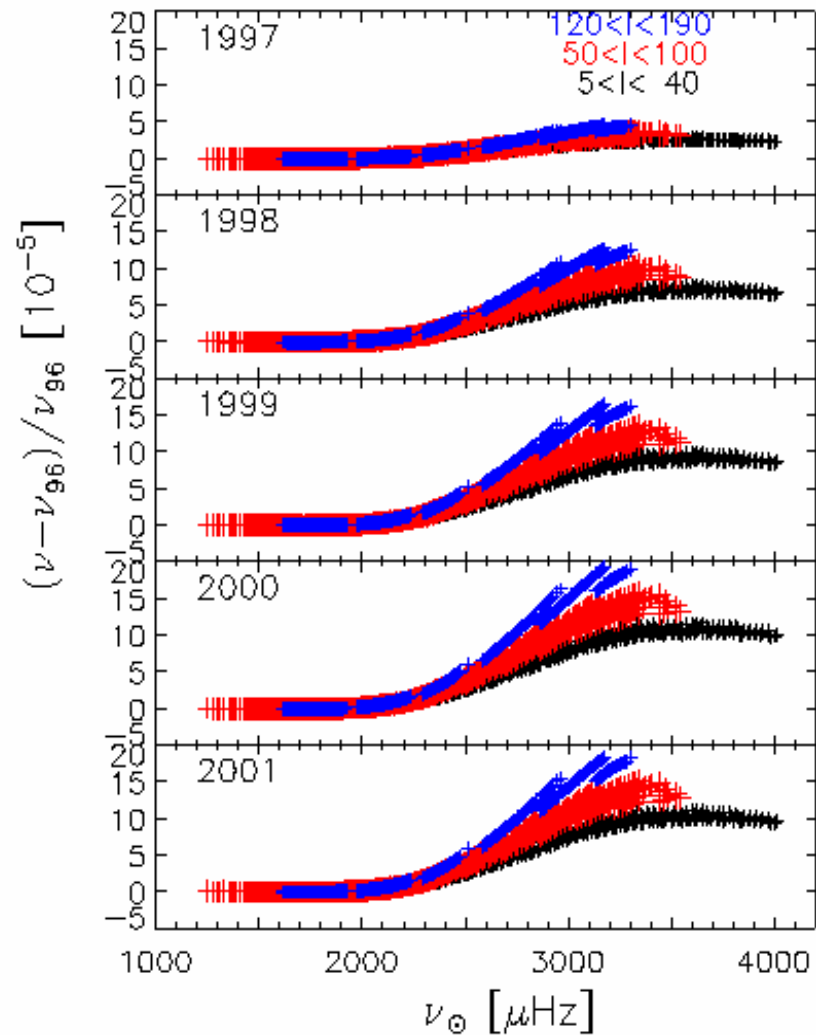
		Observational constraints				
Model	Group	ΔL	$\Delta T_{e\#}$	ΔR	ΔR_{GZ}	Δv
Models with a Gaussian B profile						
A	I	✓	×	×	×	×
B	I	✓	×	×	×	×
C	I	✓	✓	×	✓	×
D	I	✓	✓	×	✓	×
E	I	✓	✓	×	✓	×
F	I	×	×	×	✓	×
G	II	✓	✓	×	✓	×
H	II	✓	✓	×	✓	×
I	II	✓	✓	×	✓	×
J	II	×	×	×	✓	×
K	III	×	×	×	✓	×
L	III	×	×	✓	✓	×
Models with B profile from turbulence						
M	I	×	×	×	✓	×
N	II	×	×	×	✓	×
O	III	×	×	×	✓	×
P	III	×	×	×	✓	×
Q	IV	×	×	✓	✓	✓
R	IV	✓	✓	✓	✓	✓

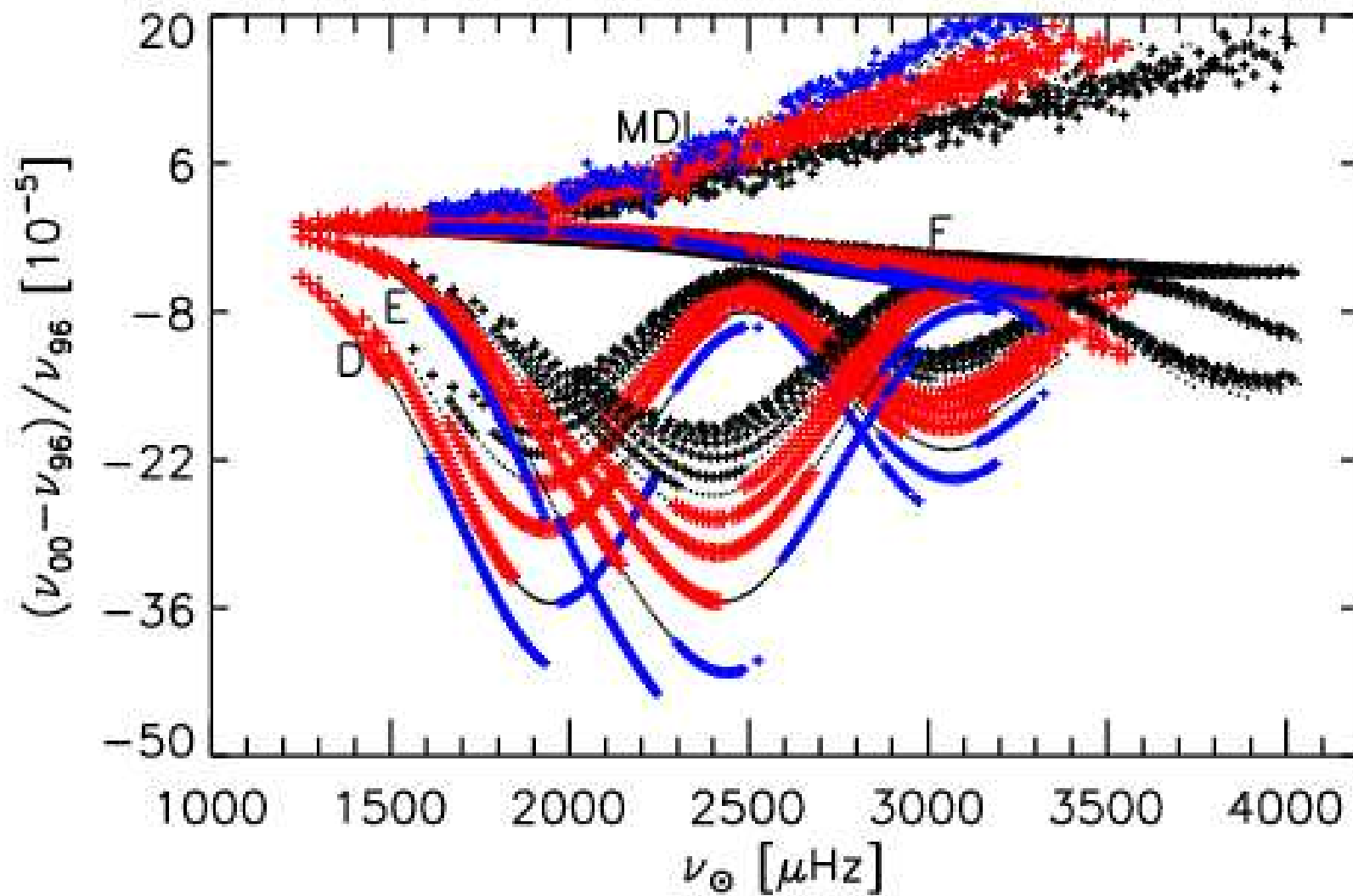
Magnetically –modulated turbulent models

MDI OBSERVATION



FEEDBACK MODEL

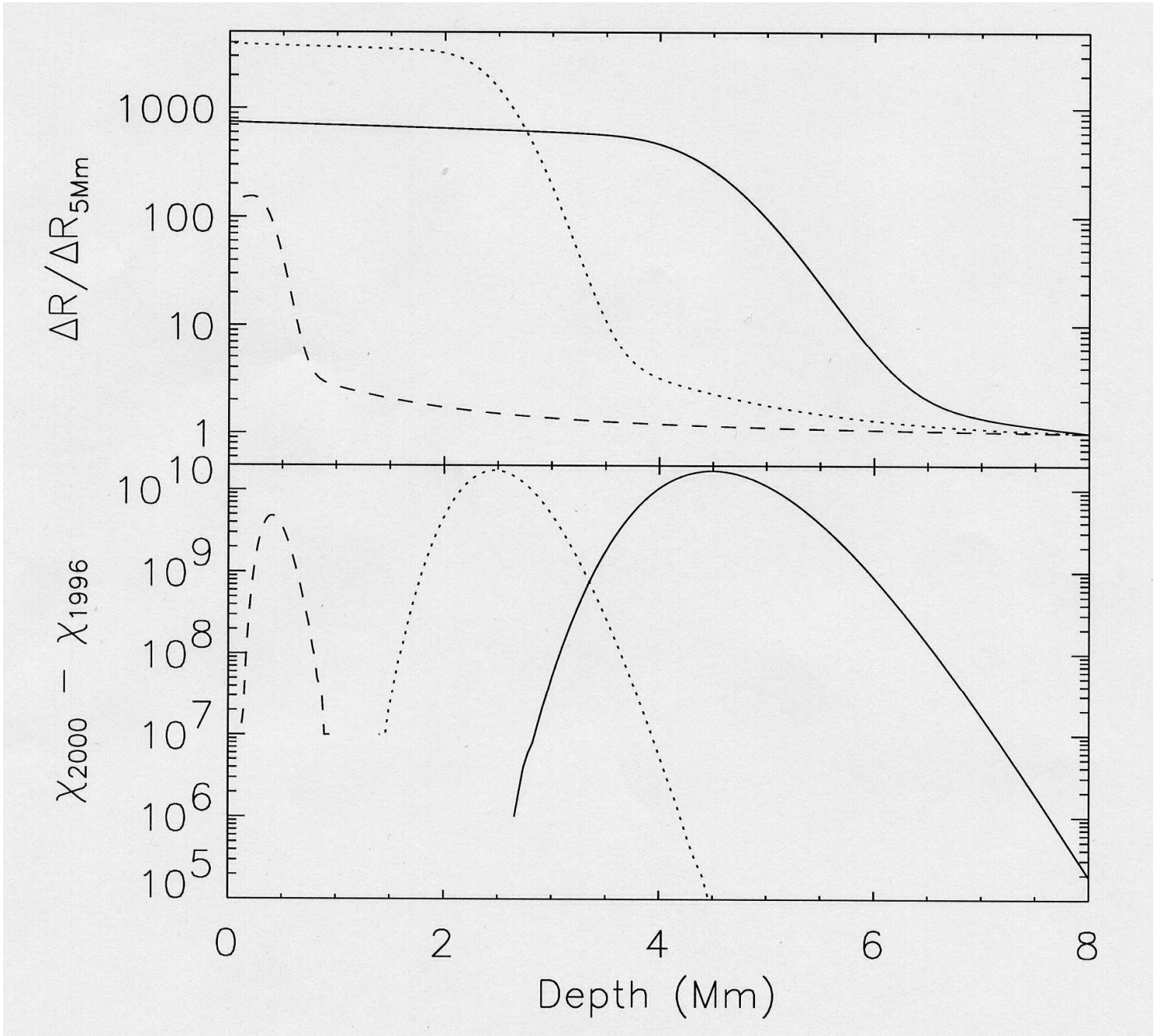


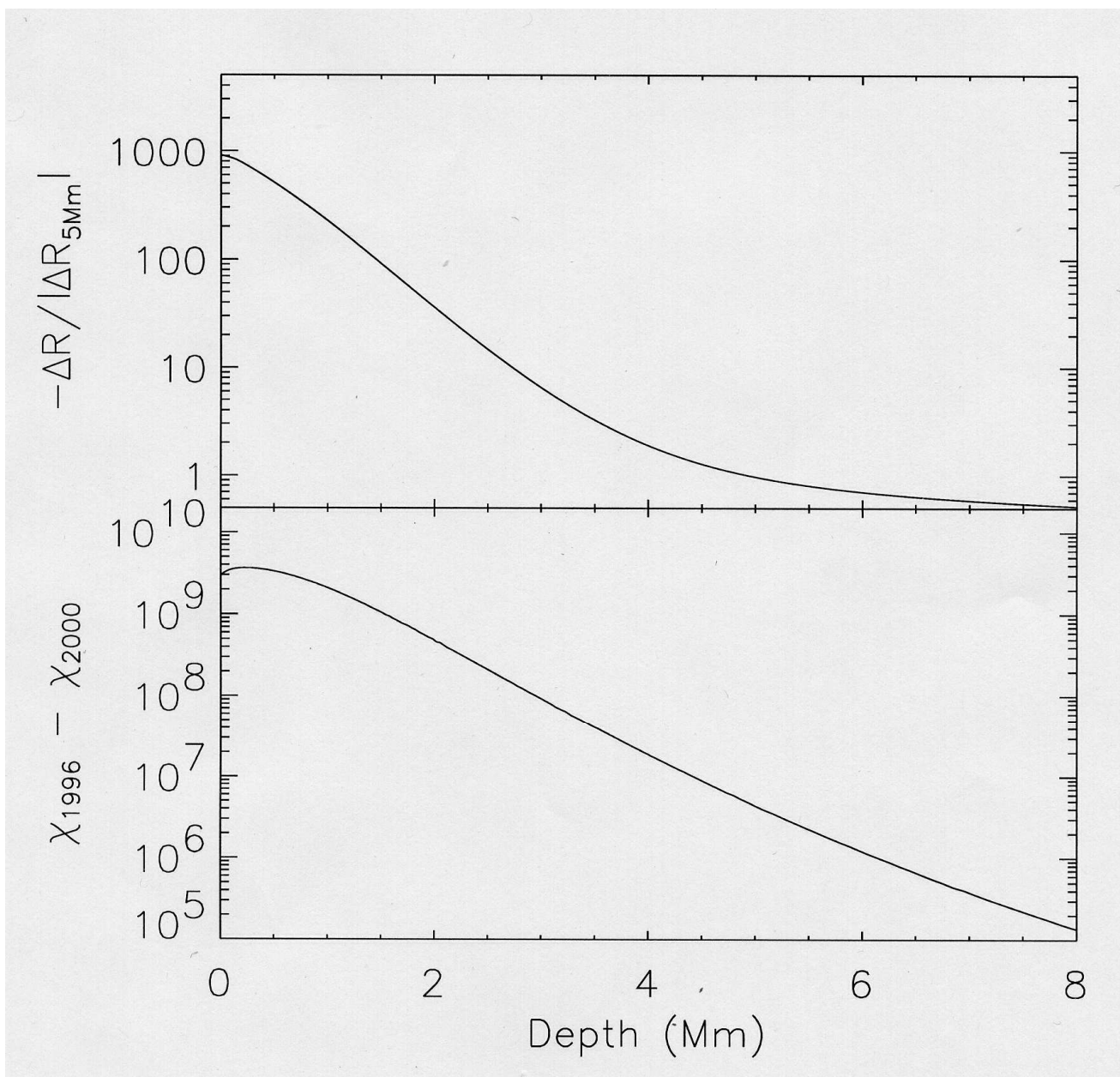


*AN APPARENT PROBLEM IS THAT THE HELIOSEISMIC
RADIUS VARIATIONS ARE SMALL*

ABOUT 1 KM/YEAR OR LESS

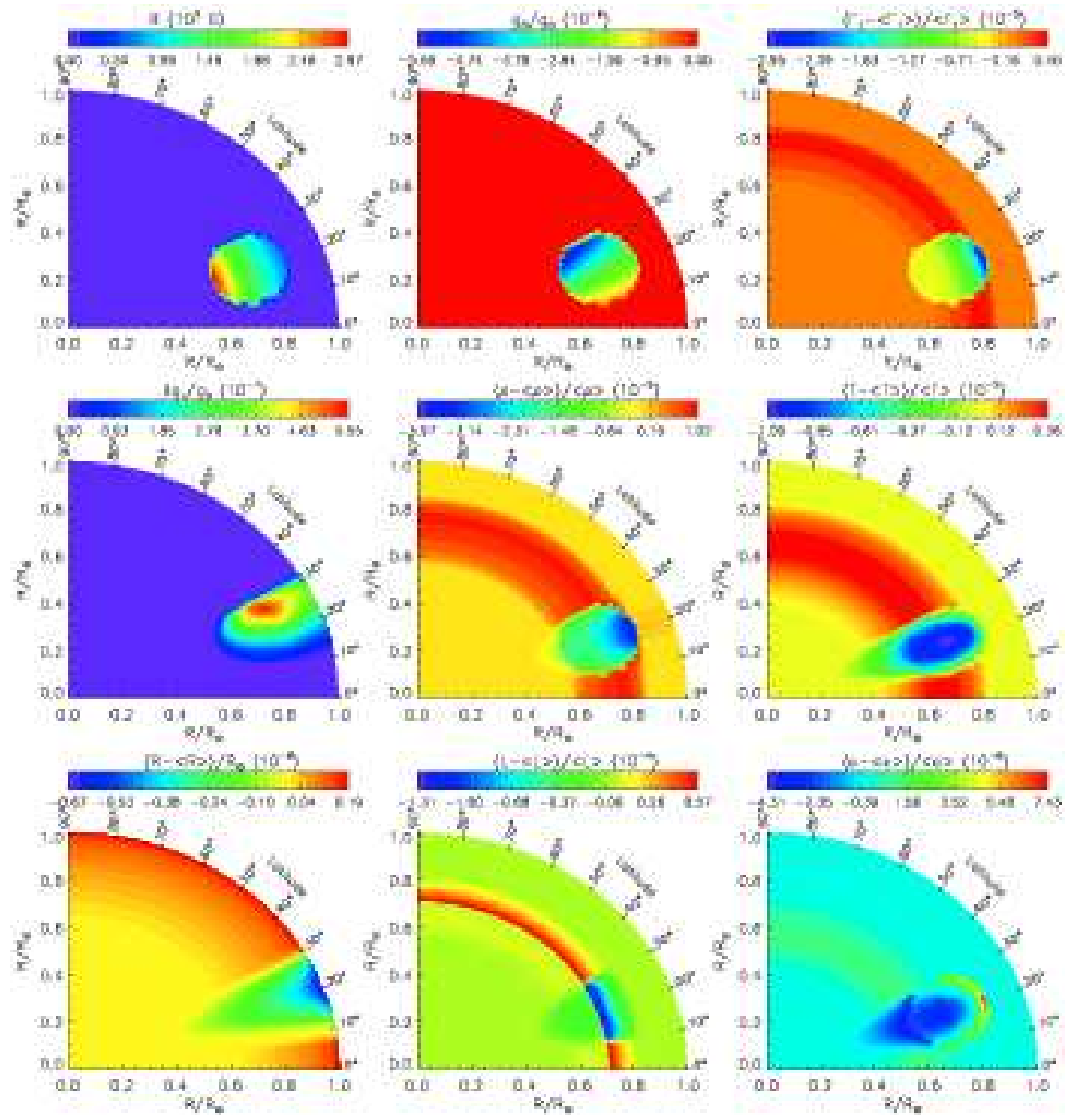
*THIS QUANTITY WOULD BE EVEN BELOW THE
SENSITIVITY OF **PICARD***

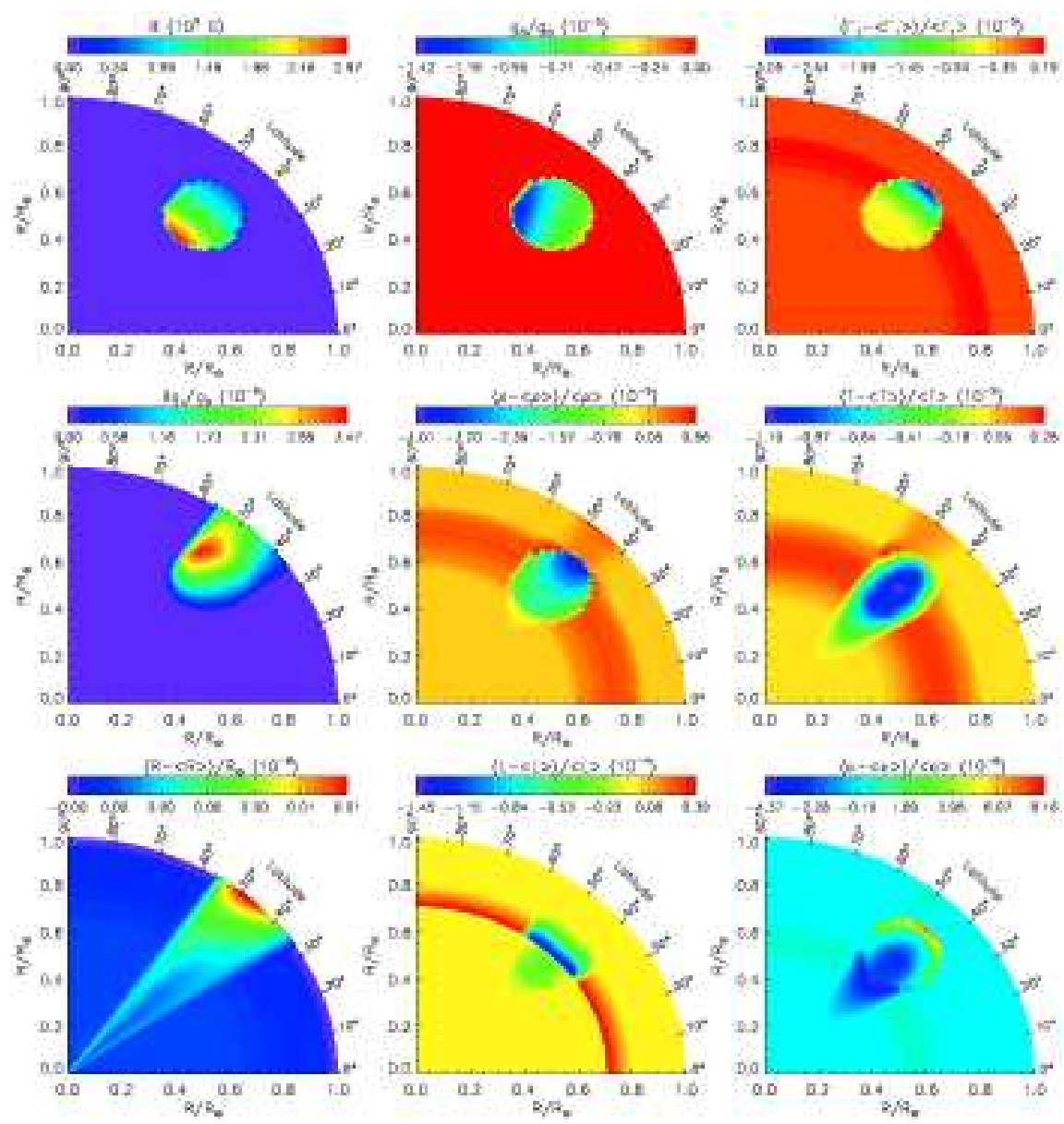


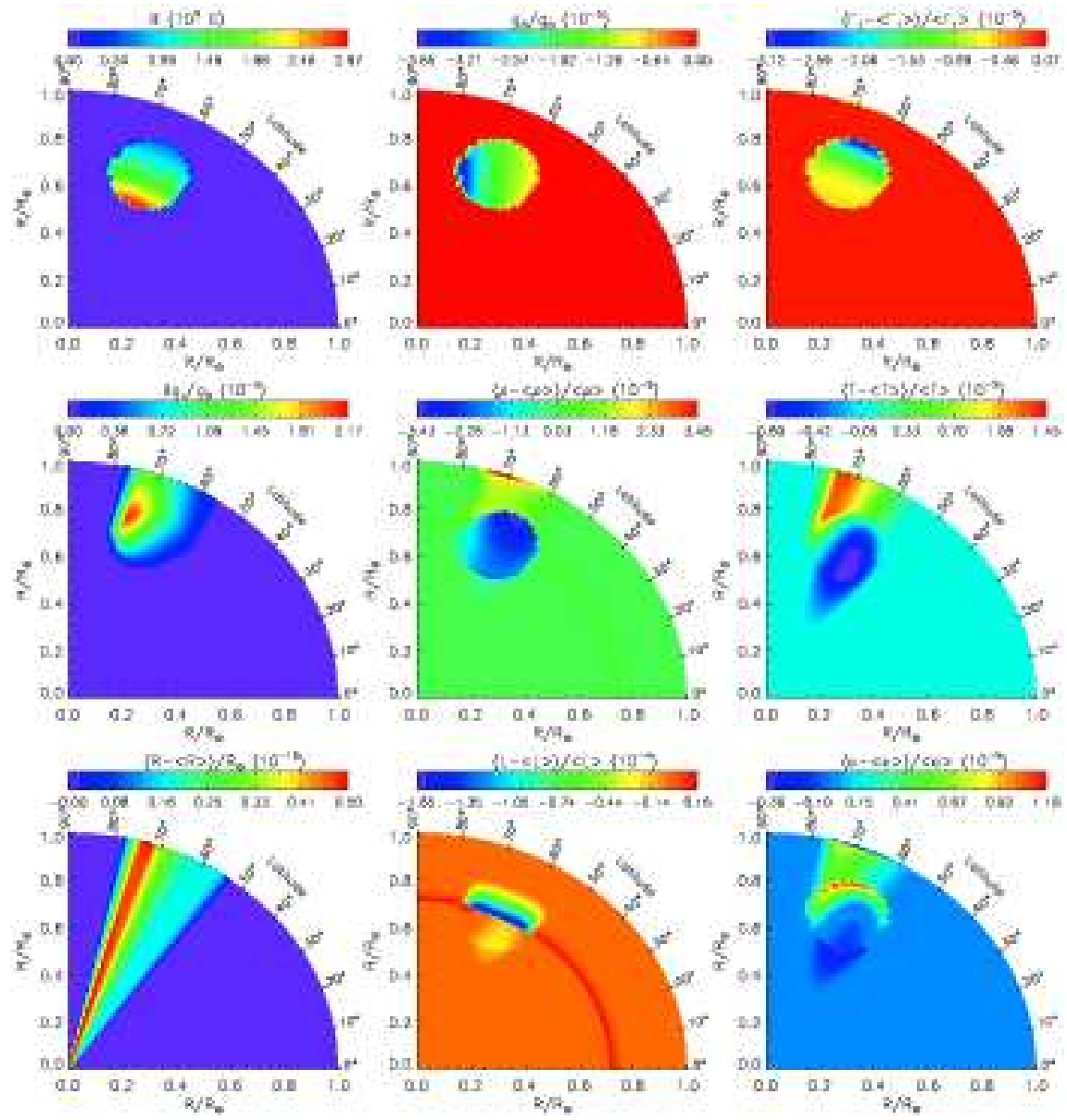


THE 1D TREATMENT IMPOSES UNREALISTIC RESTRICTIONS TO THE CONFIGURATION OF THE DYNAMO FIELD AND TO THE INTERNAL SOLAR DYNAMICS. REALITY IS MULTIDIMENSIONAL. IN ORDER TO PROVIDE A ROBUST INTERPRETATION OF THE DATA, WE NEED AT LEAST A 2D TREATMENT.

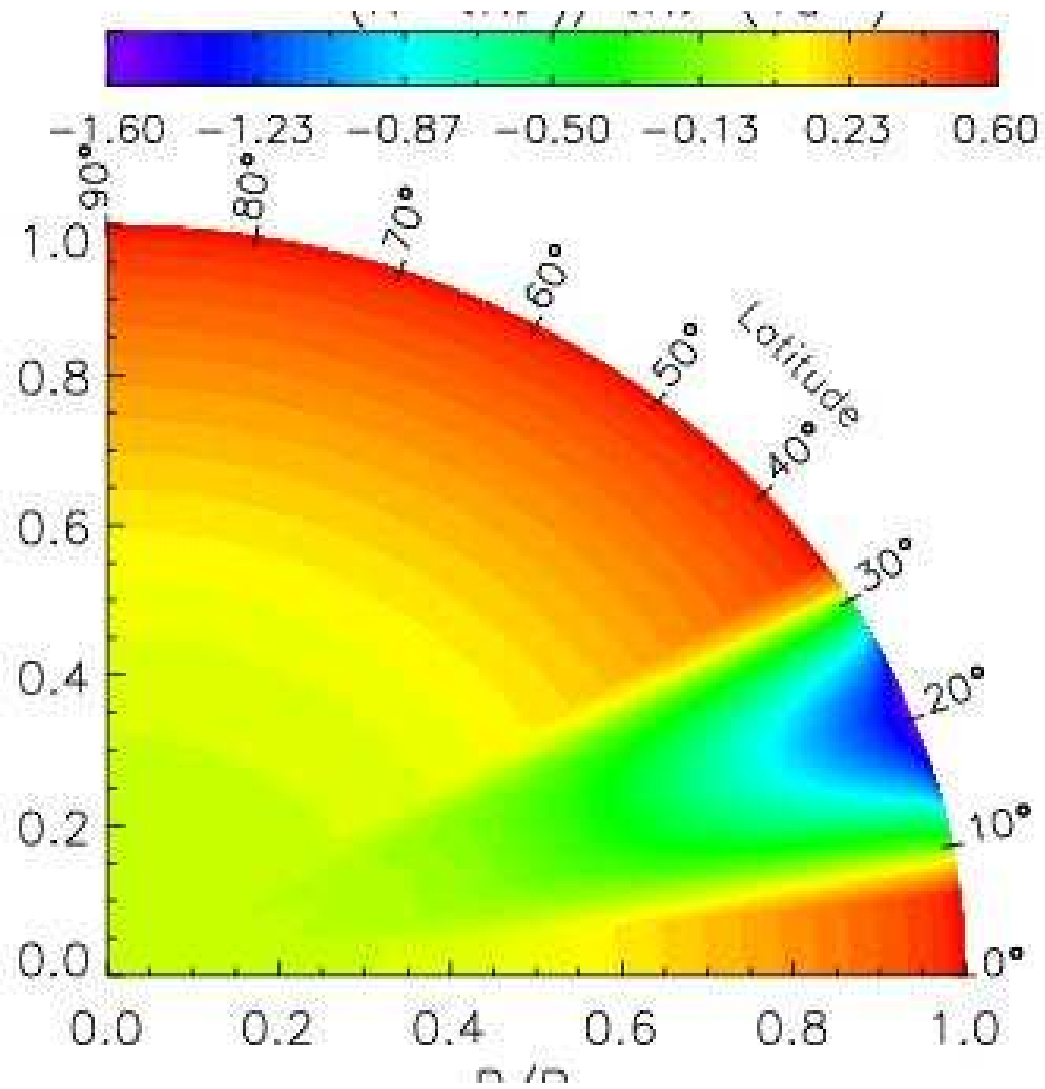
WE HAVE COMPLETED AND FULLY TESTED A 2D MODEL OF THE SOLAR INTERIOR THAT ALLOWS US TO INCLUDE MAGNETIC FIELD AND TURBULENCE. IT *SHOULD* ALSO BE ABLE TO HANDLE ROTATION, ALTHOUGH WE HAVE NOT PROVEN THAT YET.







$$(R - \langle R \rangle) / \langle R \rangle \quad (\text{E-8})$$



***THEORETICALLY, WE NEED TO FINISH THE
FOLLOWING TASKS:***

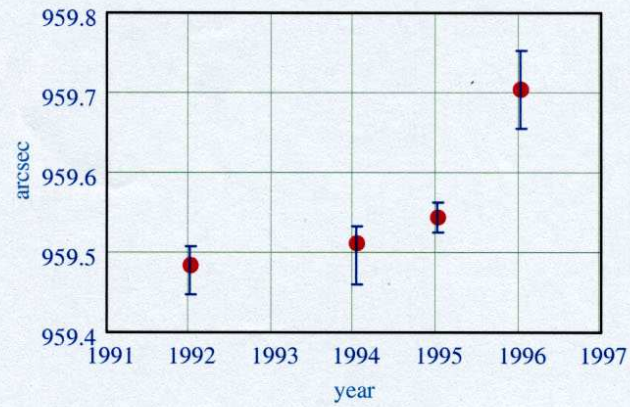
- 1. COMPLETE TEST OF 2D CODE*
- 2. MODEL TURBULENCE-MAGNETIC FIELD
INTERACTION*
- 3. DETERMINE VALUE OF W*

POTENTIAL OF RADIUS MEASUREMENTS

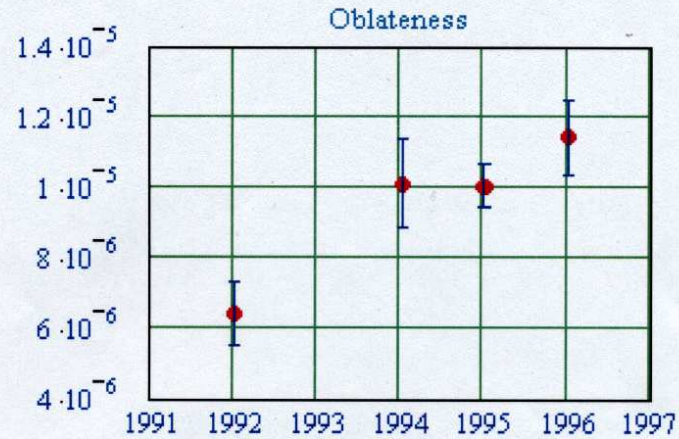
1. *ANGULAR CALIBRATION DOES NOT DEGRADE*
2. *WE CANNOT MEASURE PAST SOLAR IRRADIANCE, BUT WE CAN INFER PAST RADIUS CHANGES*
3. *DETERMINE OBSERVATIONALLY $W = d\ln R / d\ln L$*
4. *COMPARE IT WITH THEORETICAL VALUE OF W*
5. *DETERMINE PAST VALUES FOR L (THUS TSI) TO BE USED IN CLIMATE STUDIES.*



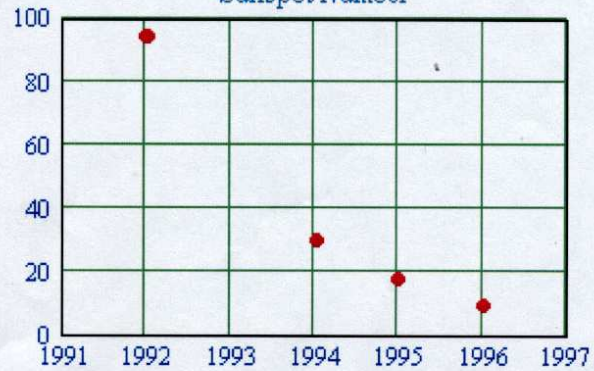


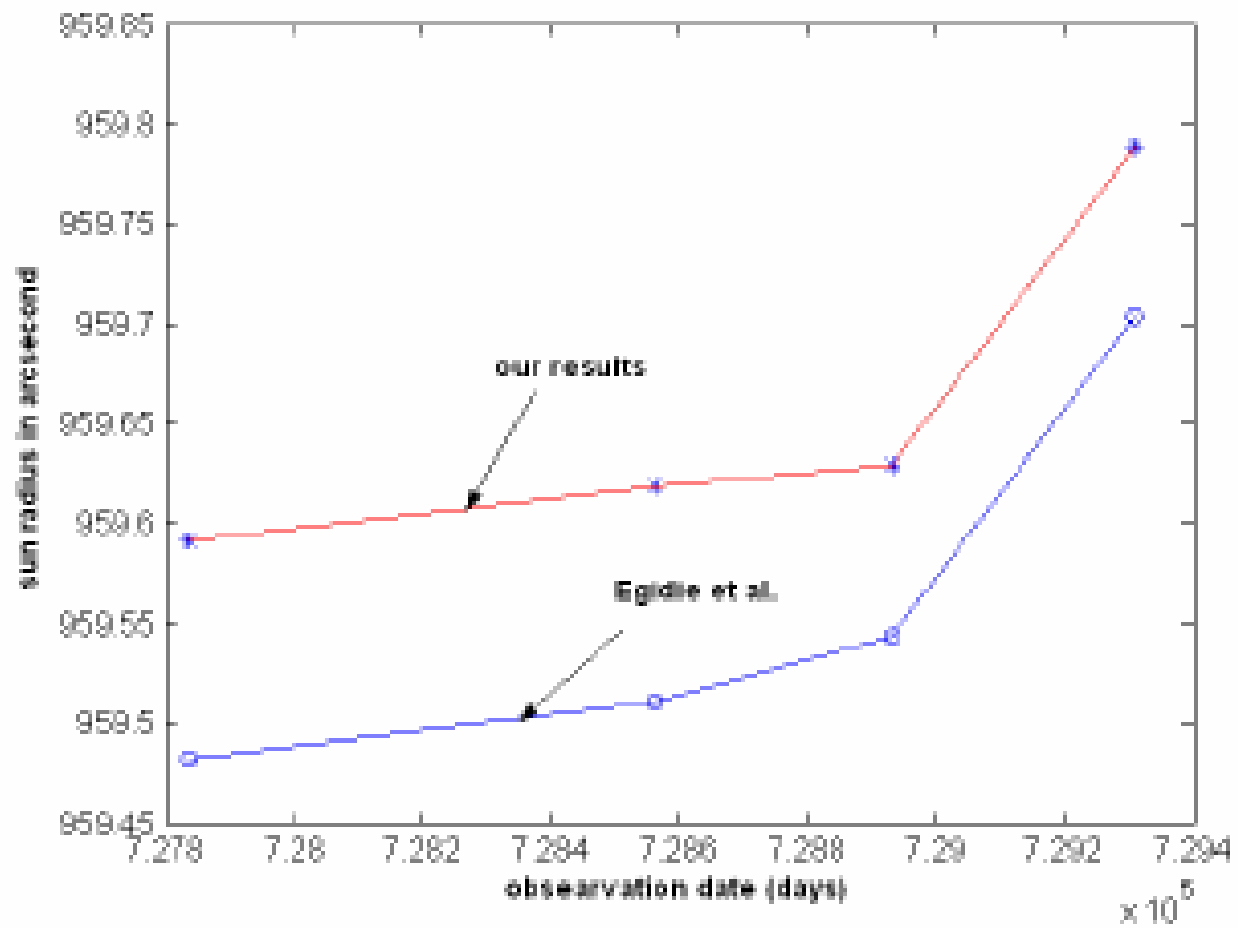


Radius of the Sun

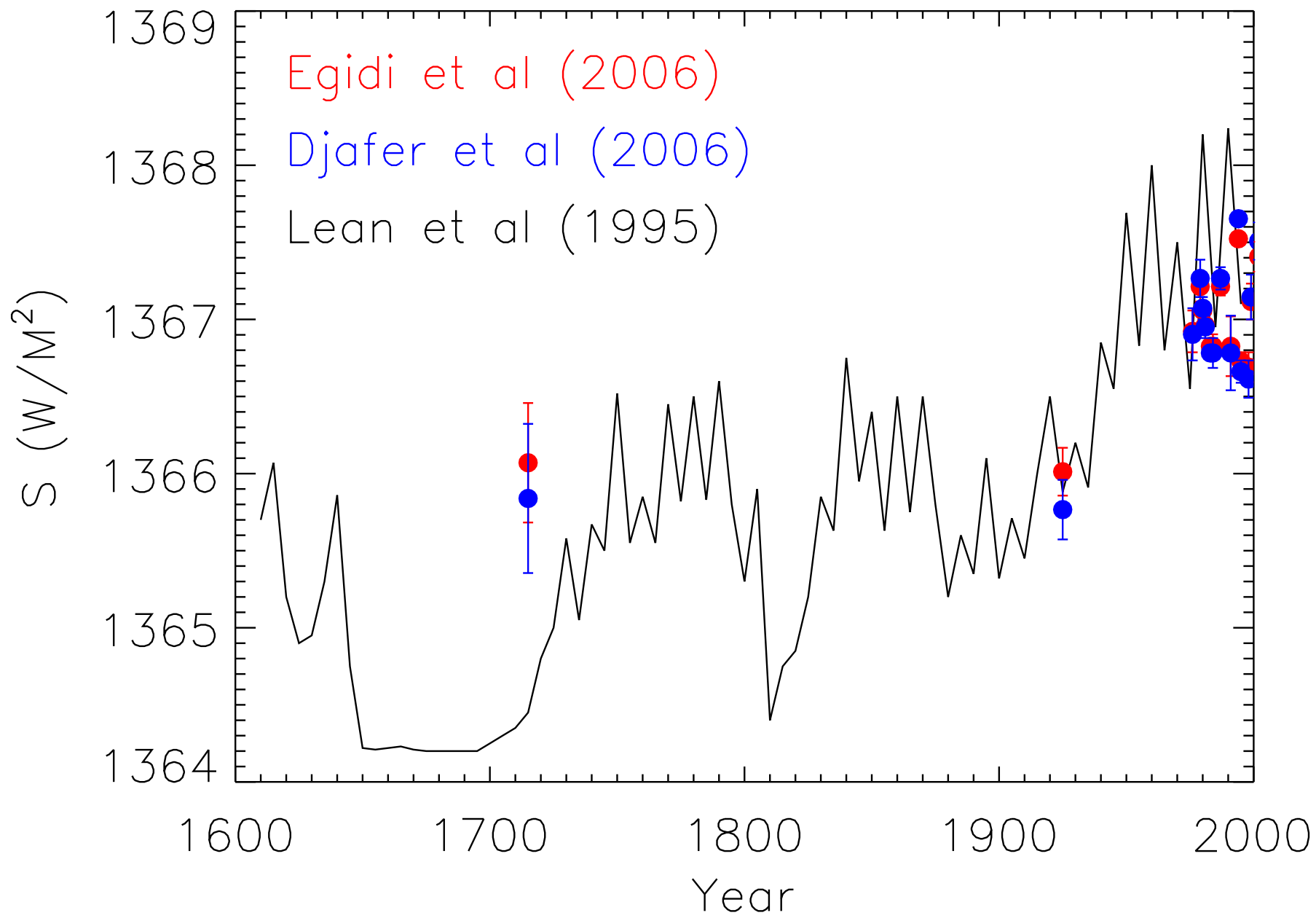


Sunspot Number





Month	Day	Year	Type	Obs.	ΔR	Error	TSI	Error	TSI	Error
					"	\pm "	Egidi et al	\pm	Djafer et al	\pm
Dec.	4	2002	total	58	-0.21	0.05	1367.41	0.10	1367.51	0.12
Aug.	11	1999	total	58	-0.06	0.06	1367.12	0.12	1367.15	0.15
Feb.	26	1998	total	76	0.16	0.05	1366.69	0.10	1366.61	0.12
Otc.	24	1995	total	92	0.14	0.03	1366.73	0.06	1366.66	0.07
May	10	1994	Annular	53	-0.27	0.02	1367.52	0.04	1367.65	0.05
July	11	1991	Total	59	0.09	0.10	1366.83	0.19	1366.78	0.24
Sept.	23	1987	Annular	123	-0.11	0.03	1367.21	0.06	1367.27	0.07
May	30	1984	Hybrid	51	0.09	0.04	1366.83	0.08	1366.78	0.10
June	11	1983	total	201	0.09	0.02	1366.83	0.04	1366.78	0.05
Feb.	4	1981	Annular	153	0.02	0.03	1366.96	0.06	1366.95	0.07
Feb.	16	1980	total	232	-0.03	0.03	1367.06	0.06	1367.07	0.07
Feb.	26	1979	total	47	-0.11	0.05	1367.21	0.10	1367.27	0.12
Otc.	23	1976	total	43	0.04	0.07	1366.92	0.14	1366.90	0.17
Jan.	24	1925	total	8	0.51	0.08	1366.01	0.15	1365.77	0.19
May	3	1715	total	3	0.48	0.20	1366.07	0.39	1365.84	0.48



CURRENT ACTIVITIES

THE 2-D CODE HAS BEEN COMPLETED

IT IS BEING THOROUGHLY TESTED

WE ARE DETERMINING WHICH FEATURES REQUIRE 2D
TREATMENT, AND WHICH DO NOT

***WE ARE ABOUT TO START 3D SIMULATIONS OF THE
INTERACTION BETWEEN MAGNETIC FIELD AND
TURBULENCE***

STRATEGY

COMPLETE DEVELOPMENT OF INTERNAL MODELS

DEVELOP OPTIMAL ANALYSIS TOOLS FOR PICARD DATA, WHICH USED IN CONTEXT OF REFINED INTERNAL MODEL, *UNCOVERS THE PHYSICAL PROPERTIES OF THE ENGINE OF SOLAR VARIABILITY.*

DETERMINE FROM OBSERVATIONS, AND CONFIRM WITH THEORY, *THE VALUE OF $W = d\ln R/d\ln L$ FOR ALL TIMESCALES.*

CARRY OUT EXHAUSTIVE SEARCH FOR OLD ECLIPSE DATA. USING W , *DETERMINE L FOR AS MANY ECLIPSES, AS WELL DISTRIBUTED IN TIME, AS POSSIBLE*

INTERACT WITH CLIMATE SCIENTISTS TO HAVE THEM INCLUDE SOLAR VARIATIONS IN THE MODELS THAT ARE USED TO DETERMINE THE CLIMATE SENSITIVITY TO GLOBAL WARMING, NAMELY:

WHAT IS THE CHANGE IN TEMPERATURE TO BE EXPECTED ONLY FROM A DOUBLING OF THE CONCENTRATION OF CO₂ IN THE ATMOSPHERE OF THE EARTH?

THE END