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THE STARS, THE SUN AND SOLAR NEUTRINOS.

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ABSTRACT

The **Conventional Wisdom** has been that the Standard Solar Model, SSM is very reliable, has justifiably small errors, and gives a neutrino flux significantly higher than the values found by experiment. Thus there is a solar neutrino problem and New Physics is required. But the **pioneering Classical SSM** of Schwarzchild (1957) and Boehm-Vitense (1958), has very little input data (only age, present luminosity, radius and mass and original composition - except helium) which is too little to describe such a complex system as the Sun. But the rotation and magnetic field of the Sun (about a million gauss) are not described and there are discrepancies such as the measured amount of ^{7}Li being only one-hundredth of that predicted. More recently studies of stars have given new information and treating the Sun as a typical star, has allowed new input data to be available. What is needed is a **second generation SSM,** so that **New Standard Stellar Models, NSSM,** are replacing the pioneering Classical SSM. The study of 7Li depletion in stars as a function of effective temperature, age, and evolution, shows unusual features such as the **Boesgaard dip.** A basic explanation of this is that there should exist differential rotation inside the stars which causes turbulent diffusion. This will have the effect of **lowering the flux of neutrinos.**

Experiments to extract a few atoms produced by neutrino interactions from 10^{30} atoms, are very difficult and the **pioneering** experiments are to be respected. The **second generation** experiments, Kamiokande II and III, SAGE II, and GALLEX are now giving reasonable results which are lower that the Classical SSM values but not significantly so depending on which Classical SSM is used and the errors chosen. The inclusion of turbulent diffusion in the NSSM calculations, will lower the theoretical predictions closer to these experimental results.

Thus there is **no compelling evidence for New Physics.** One awaits the further experimental results with smaller errors to compare with the New Stellar Evolutionary Models.

FOR THEORY - EXPERIMENT COMPARISON, USE KAMIOKANDE (1) VERY GOOD EXPERIMENT

2

CONVENTIONAL WISDOM

Kamiokande result is

Data/SSM = 0.46 +/- 0.05 +/- 0.06

or difference (theory) - (expt) = 1.00 - (0.46 +/- 0.08)

= 0.54 +/- 0.08

Clearly there is a <u>SN Problem!</u>

But must add error on Theory also

Bahcall and Ulrich, 7.9 SNU +/- 11%

(Theory) - (expt) = (1.00 +/- 0.11) - (0.46 +/- 0.08)

= 0.54 +/- 0.14

Turck-Chieze et al. 5.8 SNU +/- 22%

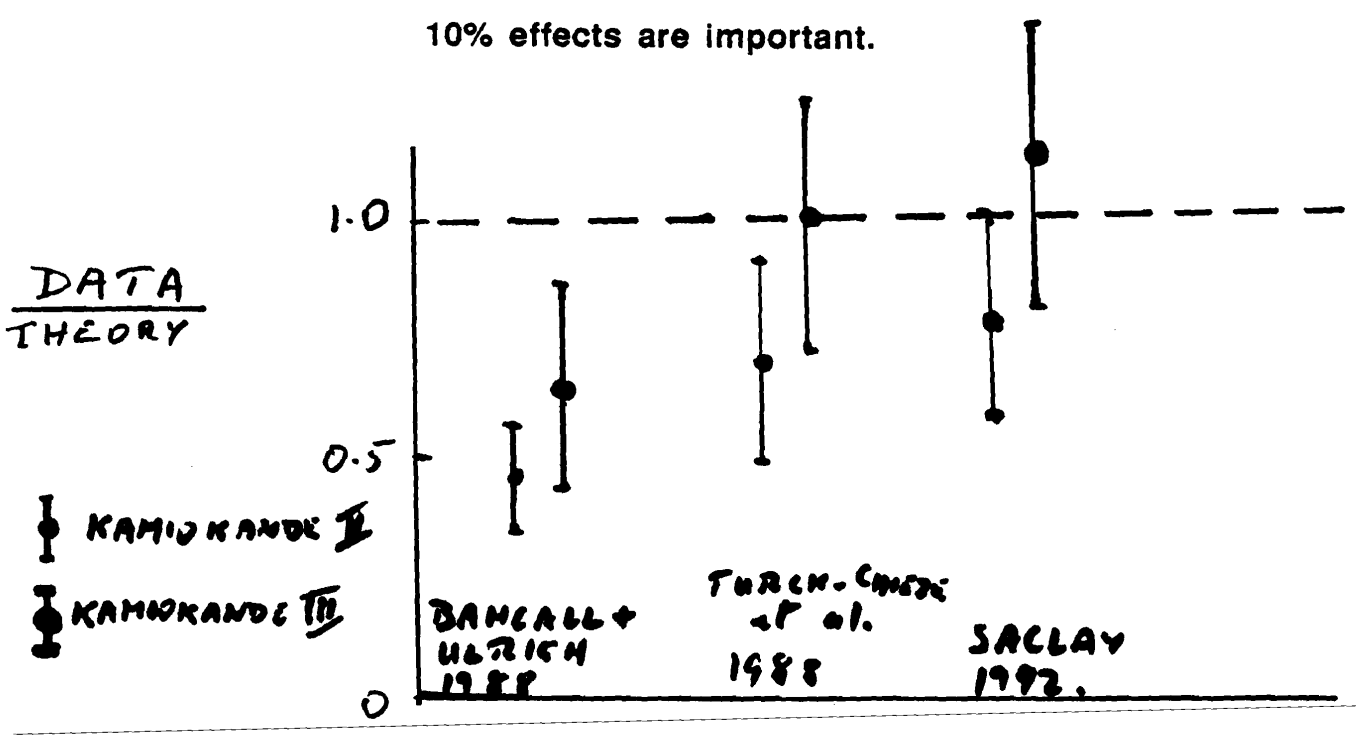
(Theory) - (expt) = (1.00 +/- 0.22) - (0.70 +/- 0.12)

= 0.30 +/- 0.25

Only 1.2 Standard Deviations. <u>NO Problem</u>

<u>CONCLUSION</u> - must check errors on Theory values.

10% effects are important.



PROBLEMS OF SSM

1. RATE $^7Be(p,\gamma)^8B$
   40% VARIATION OVER 10 YEARS. 82–92.
2. RATES (pp), $(^3He\ ^3He)$ REACTIONS
3. ABUNDANCE OF ELEMENTS.
   ESPECIALLY IRON, CARBON, NITROGEN OXYGEN
   1988 → 1992 CHANGE IN IRON ABUNDANCE LOWERS
   ^8B NEUTRINO FLUX 10 TO 20%
4. DIFFUSION
   GRAVITATIONAL SETTLING
   THERMAL DIFFUSION } + 0.3 SNU ^{37}Cl.
   TURBULENT DIFFUSION ? PROB. LOWERS.
5. OPACITY CALCULATIONS
   - VARY WITH TIME
6. CONVECTION ZONE
   - ONLY ONE MIXING PARAMETER
   ALTHOUGH IS VERY COMPLEX
   - TURBULENCE, MAGNETIC FIELD....
7. ^{7}LITHIUM IS $\frac{1}{100}$ OF PREDICTED
   ^9Be IS $\frac{1}{2}$ OF EXPECTED
8. OTHERS. - ROTATION, MAGNETIC FIELD
   - HELIOSEISMOLOGY
9. ERRORS - VARY GREATLY FROM GROUP TO GROUP
   e.g. BAHCALL FOR ^{71}Ga GIVES 132^{+7}_{-6} SNU $^{+5.3\%}_{-4.5\%}$
   BUT TURCK-CHIEZE ESTIMATES SCREENING
   UNCERTAINTIES ALONE TO BE ~ 15%

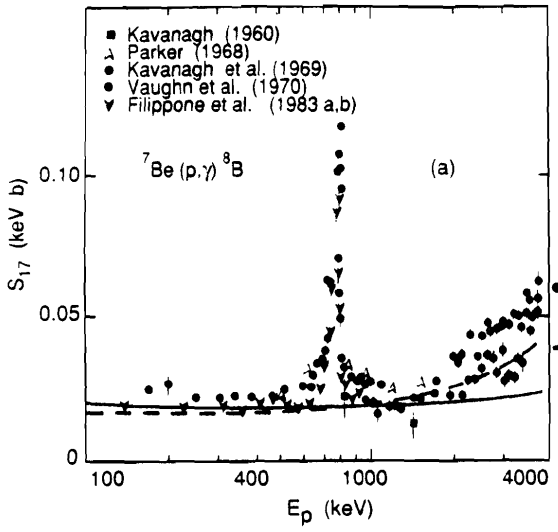
4

$^7Be(p,\gamma)^8B \rightarrow \nu$

HOW TO EXTRAPOLATE FROM EXPTS 117 TO 4000 keV DOWN TO SOLAR CONDITIONS

—— 1988 B+U S-WAVE

--- 1988 T+CH S + d WAVES.



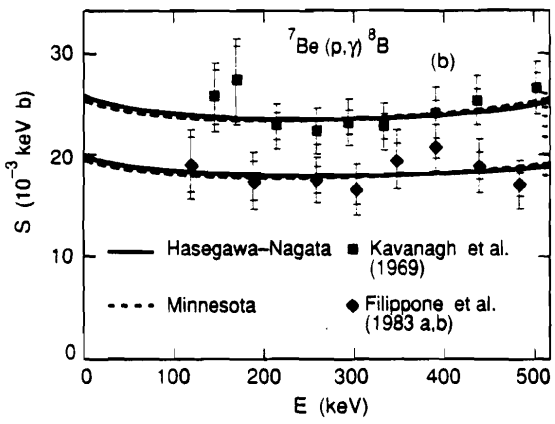


FIGURE 4(a,b)

For the reaction ^7Be (p, γ) ^8B: (a) astrophysical S factor (which is essentially the cross section with the barrier penetration factor removed) S_{17} with experimental points. The solid line is with s wave fit [12] and the dotted line is s and d waves fitted [13]; (b) S_{17} measurement below 450 keV, the Kavanagh et al. [17] and Filippone et al. [16] data are fitted separately by Johnson et al. [19] using s and d waves with two different assumptions.

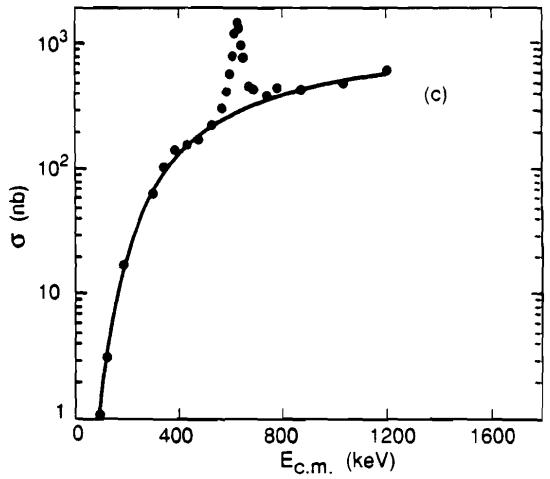


FIGURE 4(c)

Cross section for the reaction ^7Be (p, γ) ^8B.

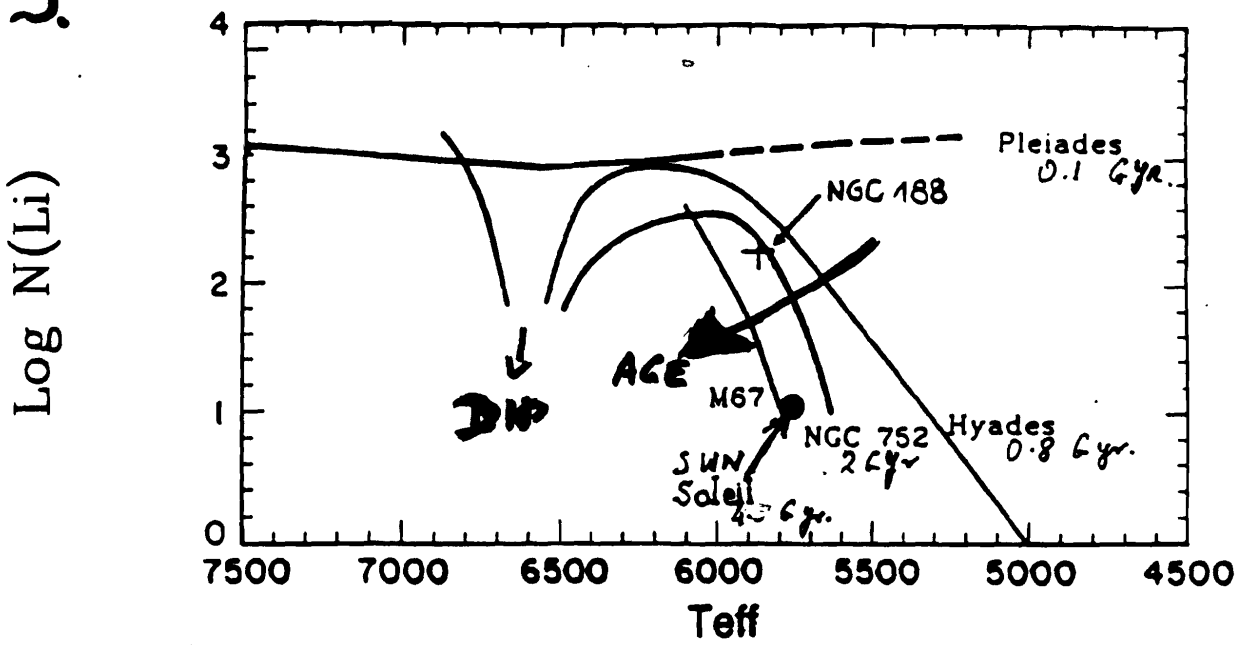
ONLY GOOD LOW-ENERGY EXPT. IS FILIPPONE et al.

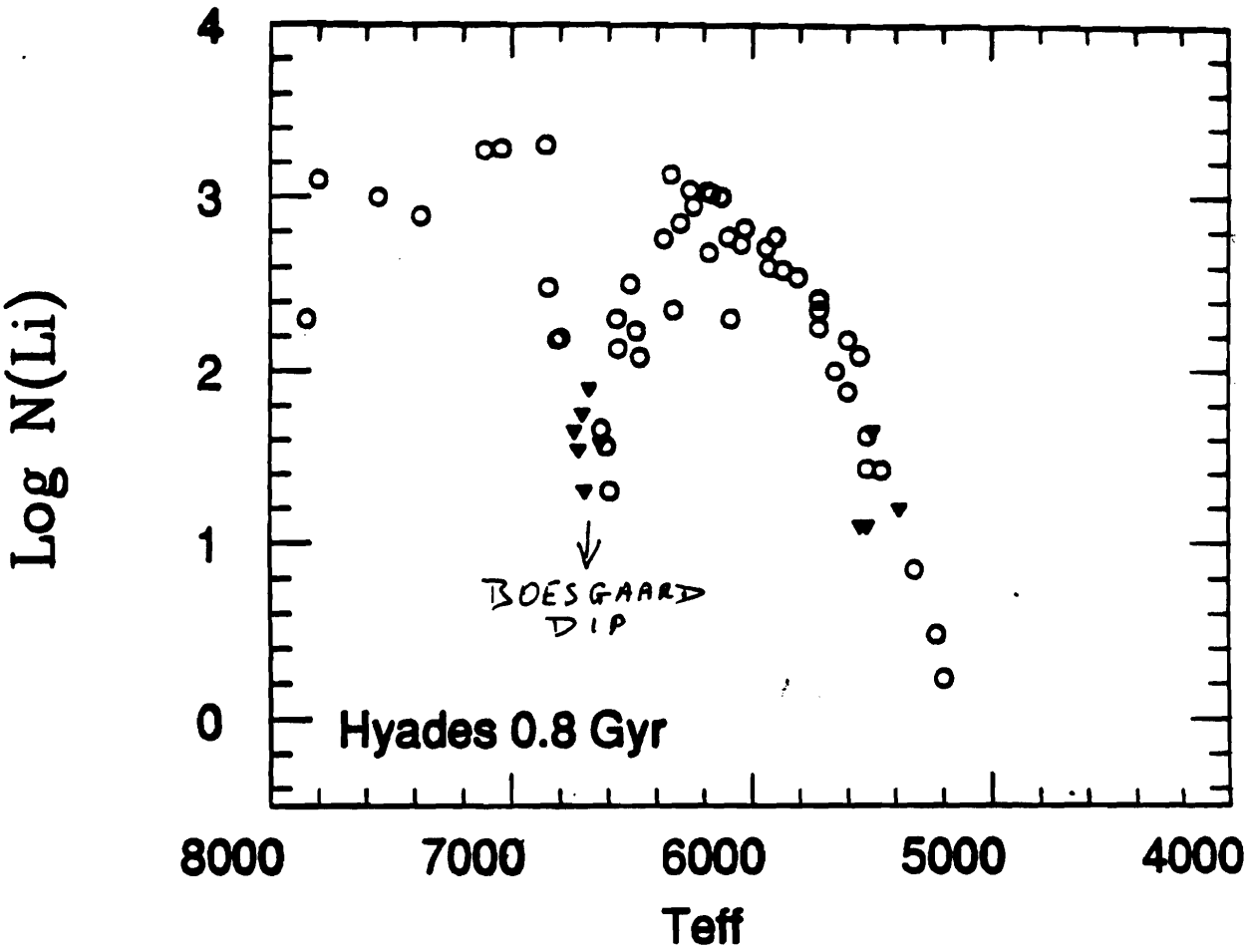
∴ TAKE $S_{17}(0) = 20.2$ keV.b

VARIATION OF $S_{17}(0)$ WITH TIME

1992 STD.	FILIPPONE	$S_{17}(0) = 20.2$	VARIATION 0.0%
1982	BAHCALL et al.	27	+34.0%
1988	BAHCALL & ULRICH	24.3	+20%
1992	BAHCALL + PINSONNAULT	22.6	+11%
1988	TURCK-CHIEZE et al.	21	+4%
1986	BARKER	17	−16%

5.





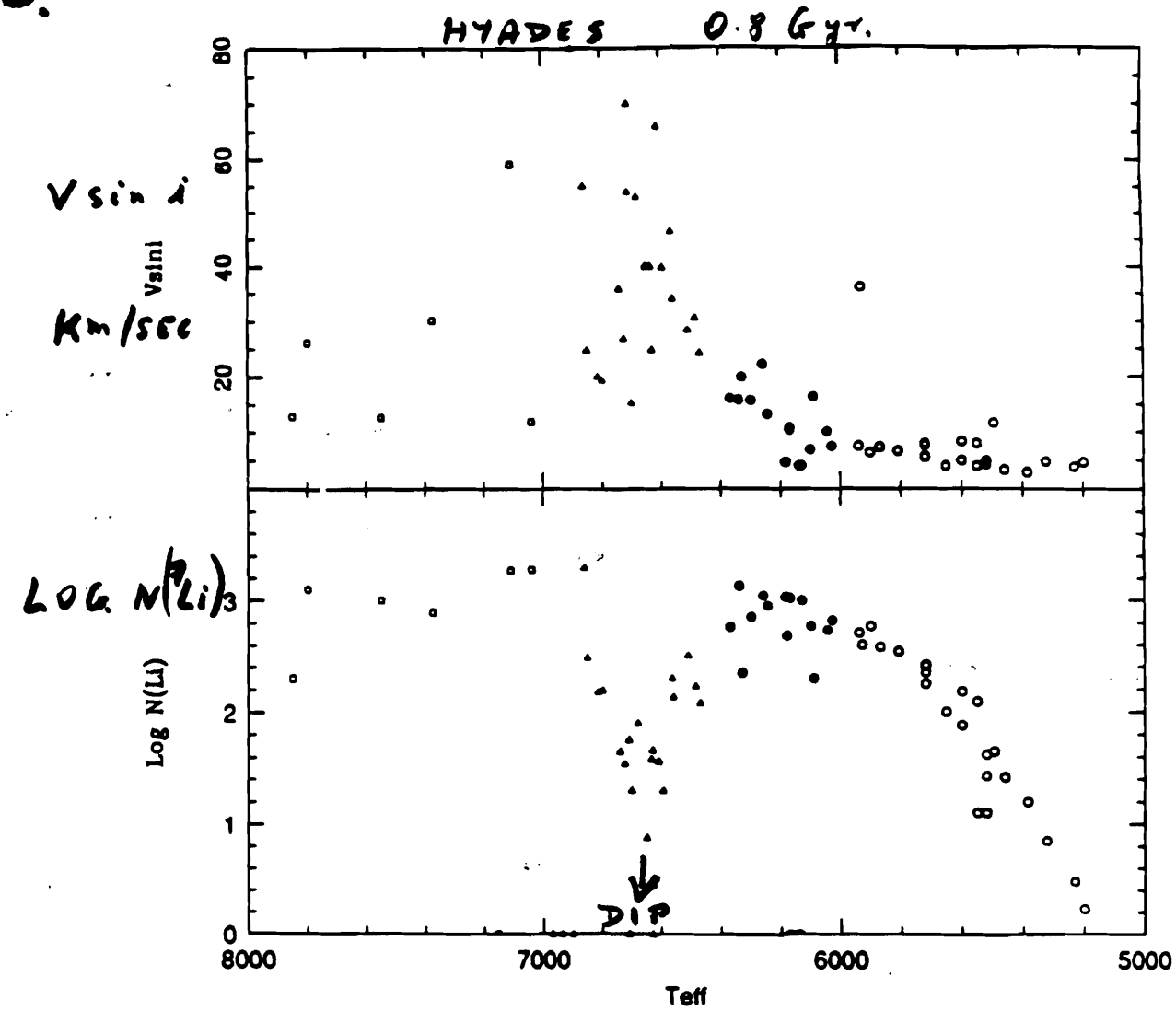
YOUNG STARS, 0.1 Gyr, HAVE NO DIP

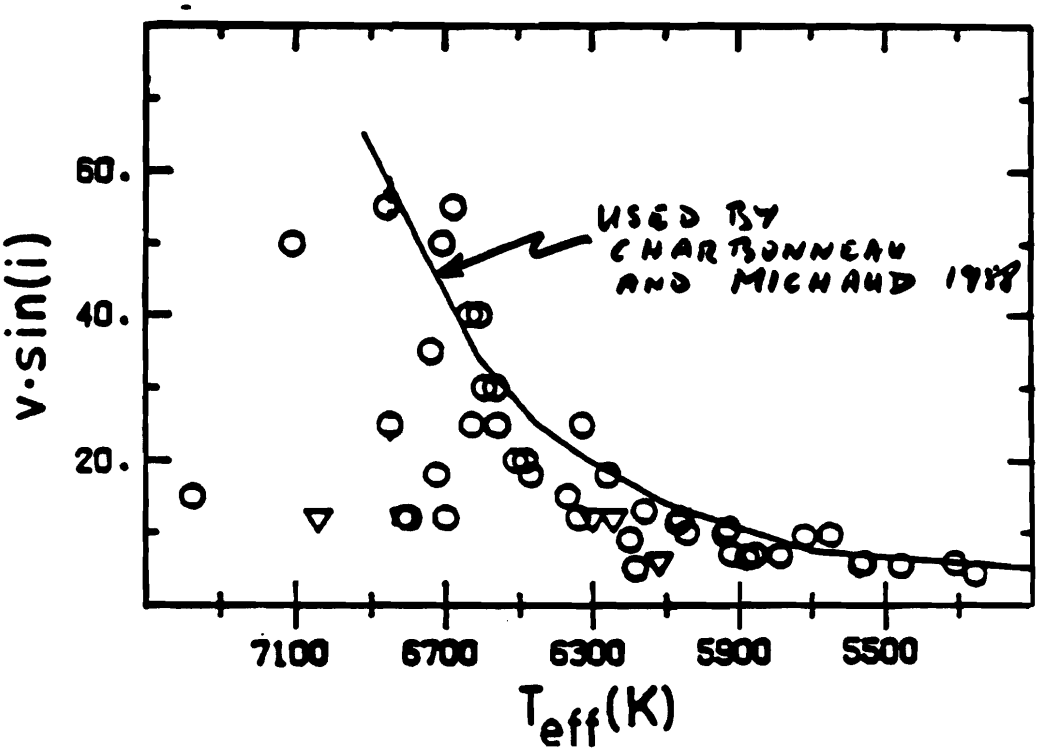
ALL STARS > 0.8 Gyr HAVE BOESGAARD DIP

ON COOL SIDE, LITHIUM DEPLETION INCREASES WITH AGE. OUR SUN FOLLOWS THIS.

LINK OF ^7Li DEPLETION AND SURFACE VELOCITY OF ROTATION V sin i

6.

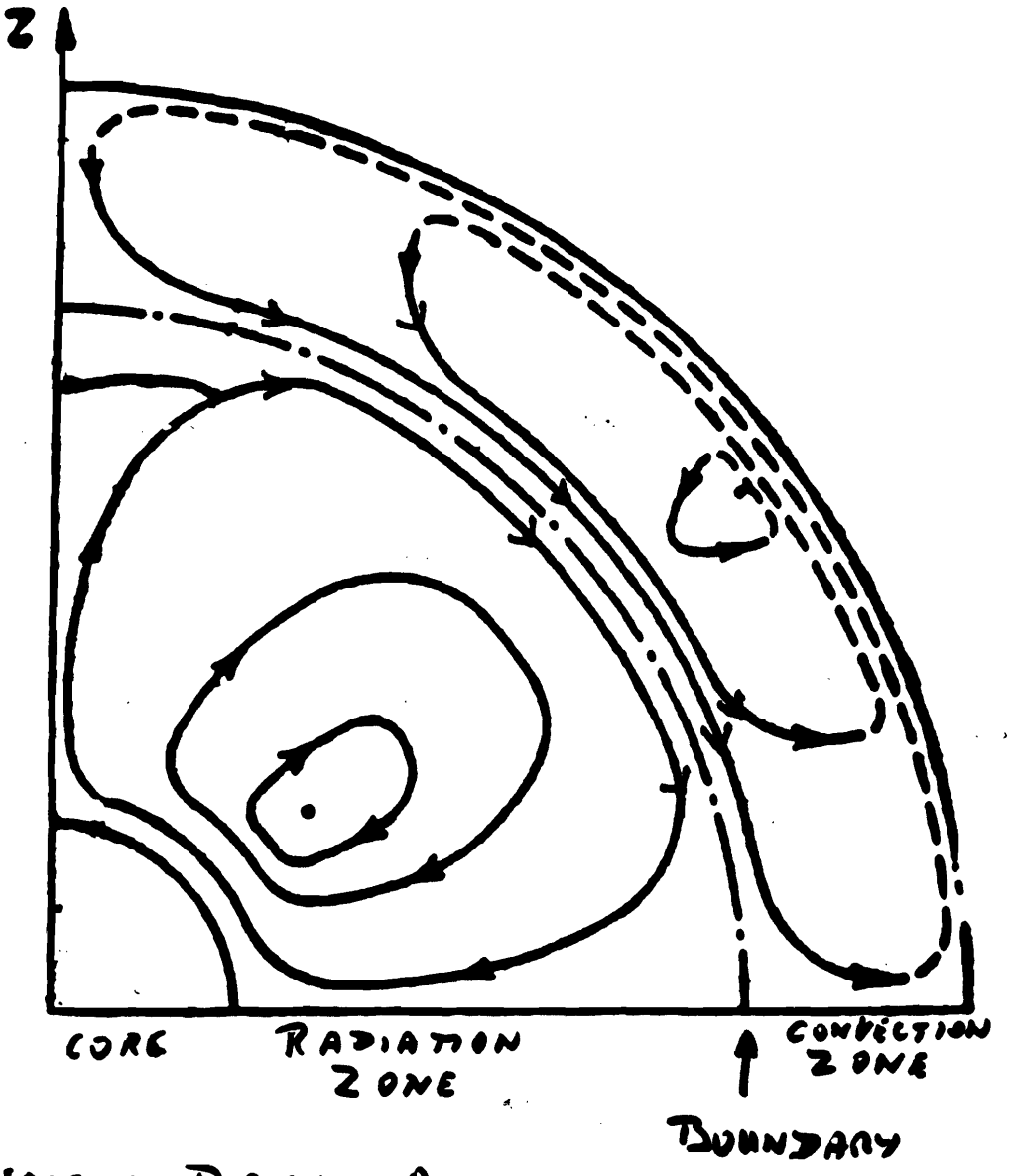




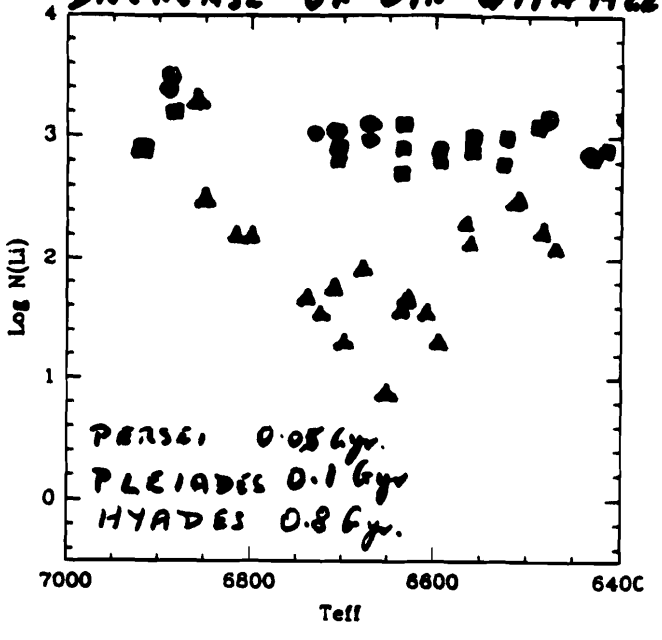
PATTERNS OF MERIDIONAL CIRCULATION

7.

1978 TAYLOR AND YAKOVLEV



INCREASE OF DIP WITH AGE

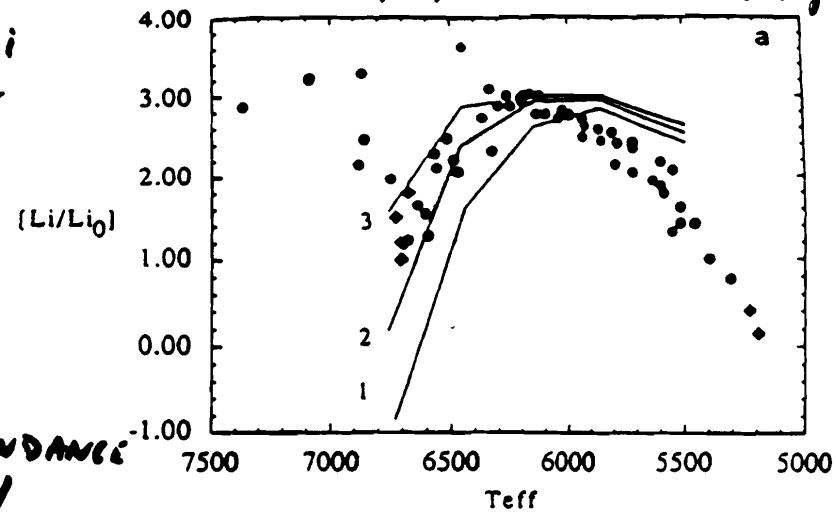


ROTATION INDUCED MIXING FROM LARGE SCALE MERIDIONAL CIRCULATION.

HYADES 0.8 Gyr.

• MEASURED ^7Li

◆ UPPER LIMIT

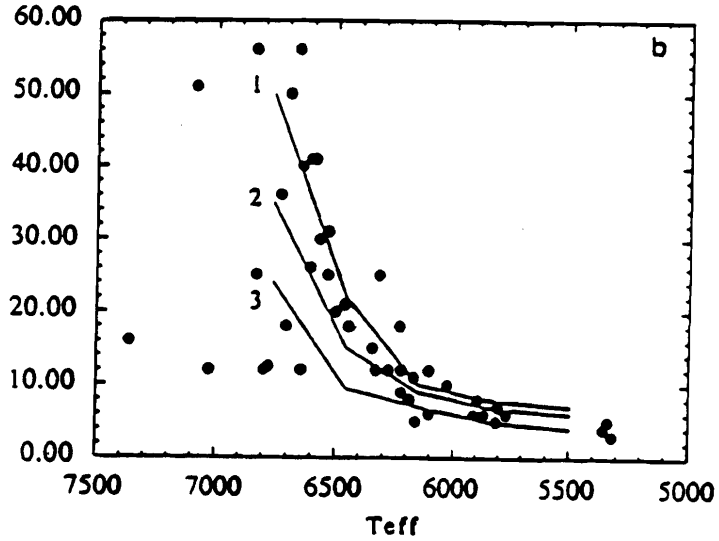


1, 2, 3 CURVES CALCULATED WITH

INITIAL Li ABUNDANCE $Log(Li) = 3.1$

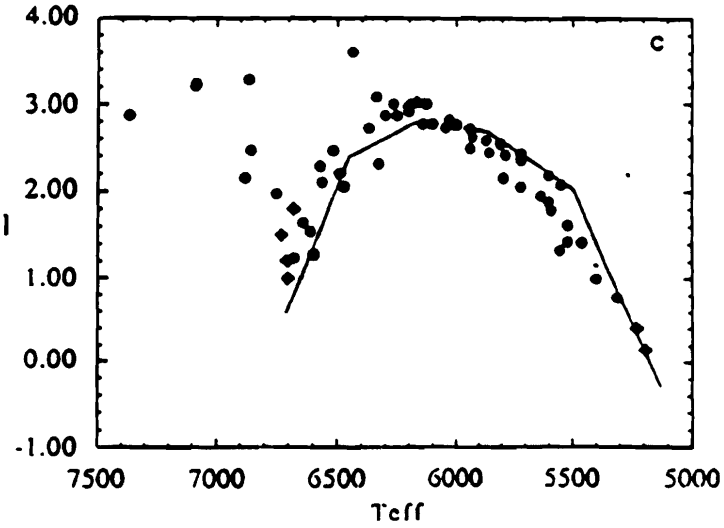
INITIAL VELOCITY $V_i = 100$ km/s

FINAL VELOCITY = Vrot (km.s^{-1})



ADDED FIT WITH PRE-MAIN SEQUENCE Li DEPLETION TAKEN FROM PROFITT & MICHAUD (1989)

⇒ GOOD FIT



FROM C. CHARBONNEL, S. VAUCLAIR, J.-P. ZAHN
ASTRON. ASTROPHYS. 225 (1992) 191

CHLORINE EXPERIMENT

A. RATE

THEORY

4 SSM calculations (1992) from 5.1 to 8.0 SNU

EXPERIMENTAL RESULTS

1970 - 1972 Upper limit < one SNU

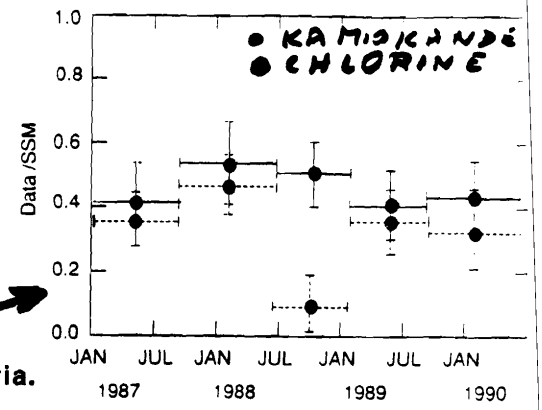
1970 - 1985 2.05 +/- 0.3 SNU

1985 - 1986 Off 18 months - pumps.

1986 - 1988 3.6 +/- 0.7 SNU

1987 - 1990 4 high periods(3.6 SNU) and one low

1970 - 1991 2.25 +/- 0.3 SNU - new selection criteria.



Number of ^{37}Cl Counts/Run;

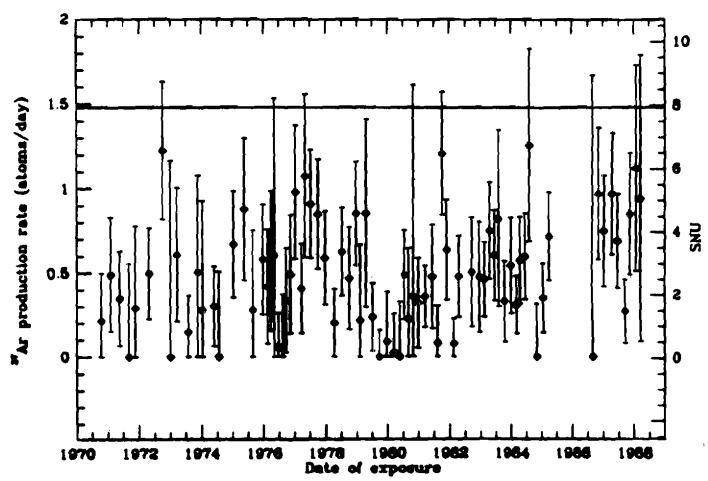
1970-1984 61 Runs 339 counts 4.9 counts/run

1970-1991 93 Runs 750 counts 8.1 counts/run - new calcn.

B. TIME VARIATION

Claimed 5 Std. Dev. variation with Inverse of Sunspot Number.

NOTE - TOO MANY ZERO AND ONE COUNTS FOR AVERAGE OF 5 COUNTS/RUN.



KAMIOKANDE - NO VARIATION

Not with Sunspot number,

Not with Day/Night

Not with Season.

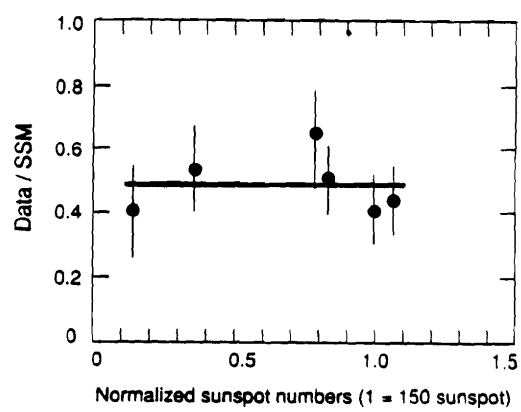


FIGURE 9

Ratio of the Kamiokande data to the SSM calculation of Bahcall and Ulrich [11] plotted against the sunspot number normalized to give 150 sunspots = 1.00.

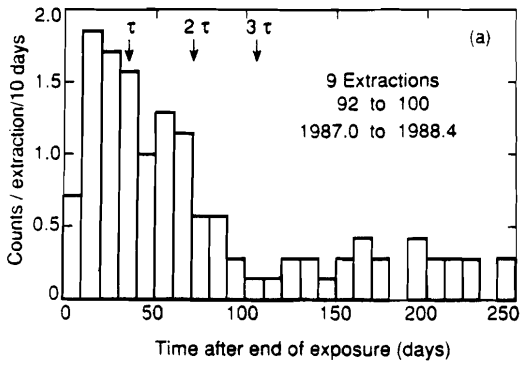
CONCLUSIONS

1. THERE IS NO TIME VARIATION
2. THIS MAY BE THE ACHILLES HEEL OF CHLORIN EXPERIMENT.

$\nu + {}^{37}Cl \rightarrow e^- + {}^{37}A$

$T_{1/2}({}^{37}A) = 35$ DAYS

10



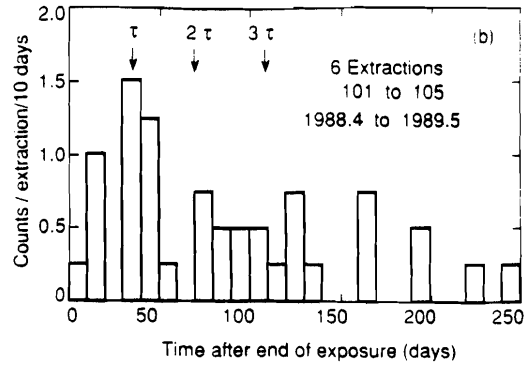
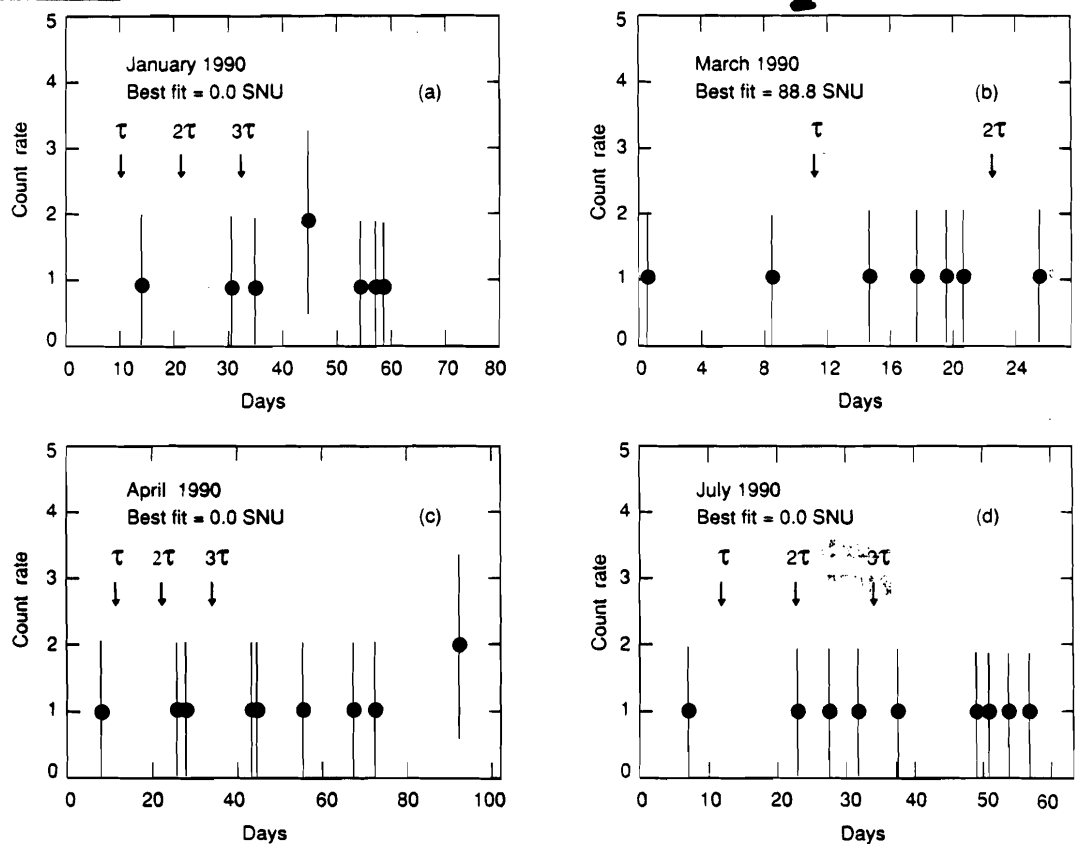


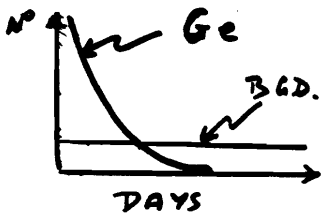
FIGURE 7

Counts in the Chlorine Experiment [27]: (a) for period 1987.0 to 1988.4, (b) for period [illegible] to 1989.5.

SAGE $\nu + {}^{71}Ga \rightarrow e^- + {}^{71}Ge$ $T_{1/2}$ Ge = 11.6 DAYS



EXPECT



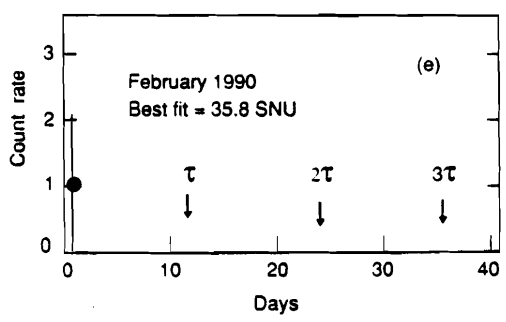


FIGURE 8

Counts recorded by the SAGE collaboration [4] during their five runs in 1990. The arrows correspond to one, two and three half-lifes τ.

SAGE EXPERIMENT

11

SAGE I

2 positive runs - 89 and 36 SNU

3 negative runs - put to 0.0 SNU.

Total - consistent with 0 SNU

SAGE II

5 positive runs - 27, 300, 48, 75 and 93 SNU

Conclusion - not inconsistent with model values of 119 to 132 SNU.

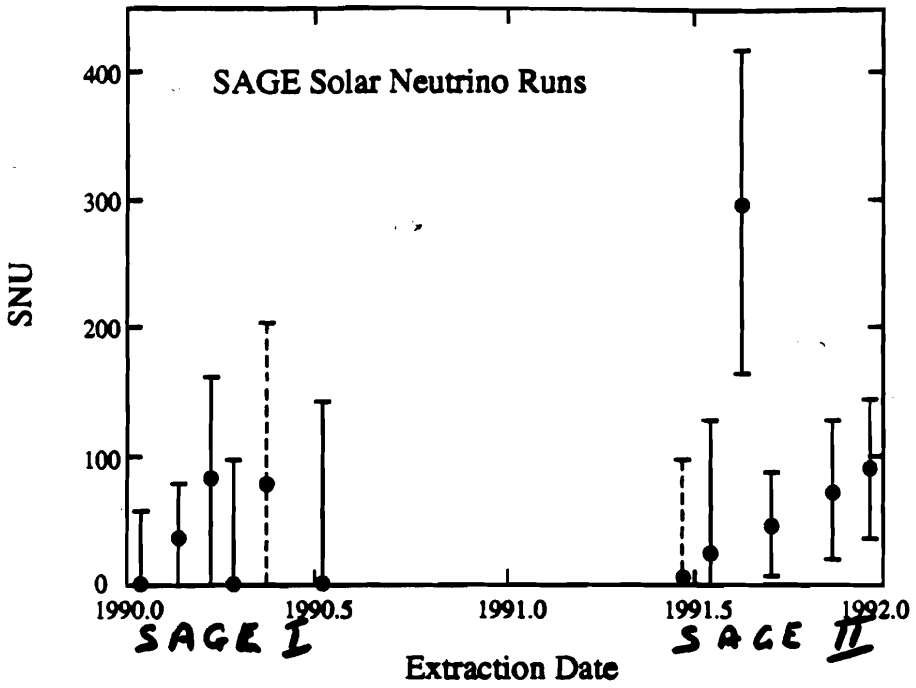


Figure 2: Solar Neutrino rates in SNU for the SAGE I and II experiments as a funtion of time. It should be noted that the runs of 1990.4 and 1991.4 should be treated with circumspection as they did not have a rise-time selection - their exclusion would makes the SAGE I average lower and the SAGE II average higher [51]. After June 1991 the runs used 57 tons of gallium instead of almost 30 tons.

GALLEX EXPERIMENT

The Gallex experiment with 30 tons of ^{71}Ga find after 14 runs, a value of

83 +/- 19 +/- 8 SNU

which is 1.3 to 2 standard deviations from the various SSM estimates.

KAMIOKANDE EXPERIMENT

Kamiokande II with 1040 days running,is consistent with some SSM models but not with Bahcall et al. with very small errors - see panel 2..

Kamiokande III with 220 days running, is 28% higher than the Kamiokande II value but this is not significant for such a short running period.

PIONEERING EXPERIMENTS	SECOND GENERATION
CHLORINE	KAMIOKANDE II and III
SAGE I	SAGE II
	GALLEX

In the HISTORY OF SCIENCE, Pioneering experiments are praised for their initiative, whether or not they agree with theory. Sometimes Second Generation experiments give different results which then agree with theory.

Here the two pioneering experiments are in serious disagreement with Solar Evolutionary Models but the three Second Generation experiments are not inconsistent with models.

More or Third Generation experiments will finally resolve the question.

Similarly in Theoretical models. The pioneering classical SSM has been developed by using information from the Stars, particularly ^{7}Li depletion and rotational velocities, to show that there should be large-scale meridional circulation giving turbulent diffusion and mixing. This should lower the solar neutrino flux. The errors on classical SSM calculations should be greatly increased. One awaits results from the second generation New Standard Stellar Models, NSSM.

CONCLUSION

In the past

there may have been a Solar Neutrino Problem

and in the future

maybe there will be a Solar Neutrino Problem

But today

the evidence is not compelling.