The implications of the deficit of solar neutrinos are discussed. If all of the experiments are taken literally the relative suppressions render an astrophysical explanation unlikely. Allowing MSW conversions, the data simultaneously determine the temperature of the core of the sun to within five percent. The implications of the atmospheric $\nu_\mu/\nu_e$ ratio are briefly discussed.

1. Solar Neutrinos and Cool Sun Models

The predictions of two recent theoretical studies are shown in Table 1. There is reasonable agreement between them, especially for the gallium experiments. However, the Bahcall-Pinsonneault (PB) [1] calculation predicts a somewhat higher $^8B$ flux than that of Turck-Chièze (TC) [2]. These are compared with the experimental results [3]-[6] in Table 2. The standard solar model is not in agreement with the data for any reasonable range of the uncertainties [7], and is therefore excluded.

Still possible is some nonstandard solar model (NSSM), which may differ from the SSM by new physics inputs such as weakly interacting massive particles (WIMPs), a large core magnetic field, core rotation, etc. Most of these models affect the solar neutrinos by leading to a lower core temperature, i.e., $T_c < 1$, where $T_c = 1 \pm 0.006$ corresponds to the SSM. All reasonable models lead to a larger suppression of the Kamiokande rate (which is essentially all $^8B$) than that of Homestake (which has in addition a nontrivial component of $^7Be$ neutrinos), in contrast to the data.

Following Bahcall and Ulrich [8] the temperature dependence is $\varphi(^8B) \sim T_c^{18}$, $\varphi(^7Be) \sim T_c^8$. We assume that the $pp$ flux is reduced by a factor $f(pp)$ chosen so that the total solar luminosity remains constant. The expected counting rates $R$ for each experiment relative to the expectations of the standard solar model are then [9]

$$
R_{cl} = 0.26 \pm 0.04 = (1 \pm 0.033)[0.775(1 \pm 0.10)T_c^{18} + 0.150(1 \pm 0.036)T_c^8 + \text{small}] \\
R_{\text{Kam}} = 0.50 \pm 0.07 = (1 \pm 0.10)T_c^{18} \\
R_{\text{Ga}} = 0.54 \pm 0.11 = (1 \pm 0.04)[0.538(1 \pm 0.0022)f(pp) \\
+ 0.271(1 \pm 0.036)T_c^8 + 0.105(1 \pm 0.10)T_c^{18} + \text{small}] 
$$

The overall uncertainties are from the nuclear detection cross-sections, and those which multiply the individual flux components are from the relevant reactions in the sun, correlated from experiment to experiment.

The best fit is for $T_c = 0.92 \pm 0.01$, an enormous deviation from the SSM. Even worse, it is a terrible fit: $\chi^2 = 20.6$ for 2 d.f., which is statistically excluded at the
99.9% cl. If we accept the experimental values, a cool sun model cannot account for the data [9]. This conclusion is more general than the specific exponents assumed.

2. MSW Conversions

There have been a number of recent studies of the MSW solution [9]-[13]. There are two solutions for oscillations into active neutrinos (ν_µ or ν_τ), the non-adiabatic (small mixing angle) and the large-angle. The non-adiabatic solution gives a much better fit [9]. In this region there is more suppression of the intermediate energy 7Be neutrinos, accounting for the larger suppression seen by Homestake. The large-angle fit is much poorer, corresponding to χ^2 = 3.8 for 1 df, because there the survival probability varies slowly with neutrino energy. One can also consider the possibility that the ν_e is oscillating into a sterile neutrino. There is no large-angle solution at 90% C.L. There is a non-adiabatic solution but even that yields a relatively poor fit χ^2 = 3.6 for 1 df.

It is also interesting to consider MSW oscillations for an arbitrary core temperature T_c, that is for NSSM. One now has three parameters, T_c, sin^2 2θ, and Δm^2. There are sufficient constraints to determine all three [9]. There is an expanded non-adiabatic solution with T_c = 1.02^{+0.03}_{-0.05} at 90% C.L. Similarly, there is a large-angle solution with T_c = 1.04^{+0.03}_{-0.04}. Thus the core temperature is measured by the solar neutrino experiments, even allowing for the complication of MSW oscillations. It

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Table 1: Predictions of Bahcall-Pinsonneault (BP) [1] and Turck-Chièze (TC) [2] for the solar neutrino fluxes. All uncertainties are at one standard deviation.

<table>
<thead>
<tr>
<th>Theory</th>
<th>SSM (BP)</th>
<th>SSM (TC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Homestake (Cl)</td>
<td>8 ± 1 SNU</td>
<td>6.4 ± 1.3 SNU</td>
</tr>
<tr>
<td>Kamiokande</td>
<td>1 ± 0.14 (arb units)</td>
<td>0.77 ± 0.20</td>
</tr>
<tr>
<td>gallium</td>
<td>132 ± 7 SNU</td>
<td>125 ± 5 SNU</td>
</tr>
</tbody>
</table>

Table 2: The observed rates, and the rates relative to the calculations of BP and TC.

<table>
<thead>
<tr>
<th>Rate</th>
<th>Rate/SSM (BP)</th>
<th>Rate/SSM (TC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Homestake</td>
<td>2.1 ± 0.3 SNU</td>
<td>0.26 ± 0.04</td>
</tr>
<tr>
<td>Kam-II (1040 days)</td>
<td>0.47 ± 0.05 ± 0.06</td>
<td>0.56 ± 0.07 ± 0.06</td>
</tr>
<tr>
<td>Kam-III (395 days)</td>
<td>0.50 ± 0.07</td>
<td>0.65 ± 0.09</td>
</tr>
<tr>
<td>Kam-II + III (prelim syst.)</td>
<td>0.63 ± 0.14</td>
<td>0.67 ± 0.15</td>
</tr>
<tr>
<td>GALLEX</td>
<td>83 ± 19 ± 8 SNU</td>
<td>0.44 ± 0.19</td>
</tr>
<tr>
<td>SAGE (90 + 91)</td>
<td>58^{+15}_{−24} ± 14 SNU</td>
<td>0.54 ± 0.11</td>
</tr>
<tr>
<td>GALLEX + SAGE</td>
<td>71 ± 15 SNU</td>
<td>0.54 ± 0.11</td>
</tr>
</tbody>
</table>
Figure 1: Allowed regions for MSW conversions of $\nu_e \rightarrow \nu_\mu$ or $\nu_\tau$, from [9]. The 90% c.l. ($\Delta \chi^2 = 4.6$) regions allowed by the Homestake, Kamiokande, and gallium experiments and by the combined fit are shown. The astrophysical and nuclear uncertainties are included.

is consistent with the standard solar model prediction $T_e = 1 \pm 0.0057$.

3. Atmospheric Neutrinos

The predicted fluxes $\nu_\mu$ and $\nu_e$ produced by the interactions of cosmic rays in the atmosphere are uncertain by around 20%. However, the ratio $\nu_\mu/\nu_e$ is believed to be accurate to $\sim 5\%$ [14]. There are additional uncertainties associated with interaction cross-sections, particle identification, etc. The Kamiokande and IMB groups have observed a deficit in the ratio of contained muon and electron events

$$\frac{(\mu/e)_{\text{data}}}{(\mu/e)_{\text{theory}}} = \begin{cases} 0.65 \pm 0.08 \pm 0.06 , & \text{Kamiokande [15]} \\ 0.54 \pm 0.05 \pm 0.12 , & \text{IMB [16]} \end{cases}$$

This effect, if real, suggests the possibility of $\nu_\mu \rightarrow \nu_\tau$ or possibly $\nu_\mu \rightarrow \nu_e$. It probably is not compatible with sterile neutrino oscillations $\nu_\mu \rightarrow \nu_s$, because for the relevant parameter range the extra sterile neutrino would violate the nucleosynthesis bound. The oscillation hypothesis requires a mass range $\Delta m^2 \sim (10^{-3} - 1)$ eV$^2$, larger than that relevant to the solar neutrinos, and large mixing angles such as $\sin^2 2\theta \sim 0.5$.

4. Implications

The $\Delta m^2$ range suggested by the solar neutrinos is compatible with the gen-
eral range expected in quadratic up-type seesaw models, such as in grand unified theories [9], for which \( m_{\nu_i} \sim m_u^2/M_N \), where \( u = u, c, t \) and \( M_N \) is the heavy neutrino mass. For \( M_N \sim 10^{11} - 10^{16} \) GeV one obtains the appropriate mass range, for oscillations into \( \nu_\tau \) for \( M_N \sim 10^{16} \) GeV, and into \( \nu_\mu \) for \( M_N \sim 10^{11} \) GeV. However, the simplest models predict equal lepton and quark mixing angles, \( V_{\text{lepton}} = V_{\text{CKM}} \), which is not satisfied by the data unless \( T_c \) is far from the SSM [9].

The various hints suggest two general scenarios. One could have \( \nu_e \rightarrow \nu_\mu \) in the sun for \( m_{\nu_e} \ll m_{\nu_\mu} \sim 3 \times 10^{-3} \) eV, with \( \nu_\tau \) a component of the dark matter (\( m_{\nu_\tau} \sim \text{few} \) eV). This pattern is compatible with the mass predictions of GUT-type seesaws. However, in this scenario there is no room for oscillations to account for the atmospheric neutrinos. A separate possibility is that again \( \nu_e \rightarrow \nu_\mu \) in the sun, with \( \nu_\mu \rightarrow \nu_\tau \) oscillations with \( m_{\nu_\tau} \sim (0.1 - 0.6) \) eV for the atmospheric neutrinos. In this case there would be no room for hot dark matter. This second solution requires large leptonic mixings, \( \sin^2 2\theta_{\nu_e\nu_\tau} \sim 0.5 \).

10. X. Shi and D. N. Schramm, FERMILAB-PUB-92-322-A.