A NEW LIMIT ON THE ANTIPROTON LIFETIME

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ABSTRACT

Measurements of the cosmic ray $\bar{p}/p$ ratio are compared to predictions from an inhomogeneous disk-diffusion model of $\bar{p}$ production and propagation within the Galaxy, combined with a calculation of the modulation of the interstellar cosmic ray spectra as the particles propagate through the heliosphere to the Earth. The predictions agree with the observed $\bar{p}/p$ spectrum. Adding a finite $\bar{p}$ lifetime to the model, we obtain the limit $\tau_{\bar{p}} > 0.8$ Myr (90% C.L.).

Subject headings: elementary particles — ISM: cosmic rays

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1. Introduction

In recent years the presence of antiprotons (p's) in the cosmic ray (CR) flux incident upon the Earth has been firmly established by a series of balloon–borne experiments (Golden et al. 1979; Bogomolov et al. 1979; Bogomolov et al. 1987; Bogomolov et al. 1990; Hof et al. 1996; Mitchell et al. 1996; Moiseev et al. 1997; Yoshimura et al. 1995; Boezio et al. 1997; Matsunaga et al. 1998). The measurements are summarized in Table 1. The observed CR $\bar{p}/p$ ratio has been shown to be in approximate agreement with predictions based on the Leaky Box Model (LBM) (Stephens 1981; Stephens & Golden 1987; Webber &
Potgieter 1989; Gaisser & Schaefer 1992), which assumes that the $\bar{p}$'s originate from proton interactions in the interstellar medium (ISM). The $\bar{p}$'s then propagate within the Galaxy until they “leak out” by diffusion and convection with the characteristic CR Galactic escape time $T \sim 10$ million years (Myr) (Webber & Potgieter 1989; Gaisser & Schaefer 1992). If the $\bar{p}$ lifetime $\tau_{\bar{p}}$ is not long compared to $T$ the predicted $\bar{p}/p$ spectrum will be modified. The agreement of the LBM predictions with the observed $\bar{p}/p$ spectrum has therefore been used to argue that $\tau_{\bar{p}} > 10$ Myr (Golden et al. 1979; Bogomolov et al. 1979; Stephens 1981; Stephens & Golden 1987). This estimated limit is based on early CR $\bar{p}$ data and does not take into account the reduction of the $p$ decay rate due to time dilation, the effect of the heliosphere on the observed $\bar{p}/p$ spectrum, or the systematic uncertainties associated with the predictions. In this paper we compare recent CR data with the predictions of an improved LBM extended to permit a finite $\tau_{\bar{p}}$. Heliospheric corrections and systematic uncertainties are taken into account. Assuming a stable $\bar{p}$, we find excellent agreement between our predictions and the CR observations. Allowing the $\bar{p}$ to decay, we obtain a lower limit on $\tau_{\bar{p}}$ which is significantly more stringent than current laboratory bounds obtained from searches for $\bar{p}$ decay in ion traps (Gabrielse et al. 1996) and storage rings (Geer et al. 1994; Hu et al. 1998). The analysis presented in this paper improves on our earlier analysis (Geer & Kennedy 1998) by including new data from Matsunaga et al. (1998).

CPT invariance requires $\tau_{\bar{p}} = \tau_p$, where the proton lifetime $\tau_p$ is known to exceed $\mathcal{O}(10^{32})$ yr (Caso et al. 1998). Although there is no compelling theoretical motivation to suspect a violation of CPT invariance, and hence a short $p$ lifetime, it should be noted that string theories can accommodate CPT violation. Consider a mass–dimension–$n$ CPT–violating quantum field operator suppressed by the characteristic scale $m_X$, with $n > 4$. Dimensional analysis provides the estimate $m_p \tau_{\bar{p}} \sim [m_p/m_X]^{2n-8}$, yielding $m_X/m_p \sim [4.5 \times 10^{38} \cdot \tau_{\bar{p}}/10$ Myr]${1/(2n-8)} (Kennedy 1999). For a given lower limit on $\tau_{\bar{p}}$, the implied lower limit on $m_X$ is most stringent for $n = 5$. Note that if $m_X$ is at the Planck scale ($1.2 \times 10^{19}$ GeV/$c^2$) and $n = 5$, the expected $\tau_{\bar{p}}$ would be $\sim 10$ Myr. Hence, a search for $\bar{p}$ decay with a lifetime approaching 10 Myr provides a test for CPT violation well beyond the scale accessible at high energy colliders. Finally, since the antiproton is the only long lived antiparticle that could decay into other known particles without violating charge conservation, a search for a modification of the CR $\bar{p}$ spectrum by $\bar{p}$ decay provides a unique test of the stability of antimatter.
2. Galactic Production and Propagation

In the LBM the ISM $p$'s are produced by the interactions of CR $p$'s (Stephens 1981; Stephens & Golden 1987; Webber & Potgieter 1989; Gaisser & Schaefer 1992): $pN_Z \rightarrow \bar{p}X$, where $N_Z$ is a nucleus of charge $Z$, and $X$ is anything. Our calculations use the elemental ISM abundances given in Webber & Potgieter (1989) and Gaisser & Schaefer (1992), and the measured cross sections for $Z = 1$ (the dominant contribution) given in Stephens (1981). For $Z > 1$, we have used the “wounded nucleon” results also used by Gaisser & Schaefer (1992).

The $\bar{p}$'s are assumed to propagate within the Galaxy until they are lost either by leakage into intergalactic space or by $p\bar{p}$ annihilation. The dominant loss process is leakage. Energy loss is included in the model. Comparisons between predicted and observed CR isotopic abundances imply that reacceleration can be neglected (Webber et al. 1992). Reacceleration is not included in our calculation. The LBM incorporates space-dependent diffusive and convective CR leakage into a single escape term with a single characteristic escape time. This picture is known to be too simple. A more accurate picture of Galactic CRs (Webber et al. 1992) is provided by a two-zone diffusion-convection model which we refer to as the inhomogeneous leaky disk model (ILDM). The model is based on a $h \simeq 100$ pc-thick matter disk (radius $R \simeq 20$ kpc), with a halo extending above and below the disk by $L \simeq \pm 3$ kpc. The CRs diffuse off the disk into the halo by magnetic turbulence. It has been shown that convection driven by the Galactic wind can be neglected (Bloemen 1993). The ILDM disk storage time $\sim L^2/4K$, where the diffusion transverse to the Galactic disk $K \simeq (6 \pm 4) \times 10^{23}$ m$^2$ sec$^{-1}$ (Bloemen 1989; Webber et al. 1992). The ILDM with these parameters ($h, R, L, K$) has been numerically solved by Chardonnet et al. (1996) for the secondary CR $\bar{p}$ spectrum. Although the ILDM provides a more realistic physical description of CR propagation than the LBM, Chardonnet et al. found that the fluxes in the Galactic disk predicted by the ILDM are reproduced within uncertainties by a modified LBM (MLBM) in which the momentum-dependent escape time $T(P)$ is given by: $T(P) = (13$ Myr $)[1 + cP/(3\text{ GeV})]^{-0.6}$. This escape time is longer than that used by Webber & Potgieter (1989) and Gaisser & Schaefer (1992) and, since the $\bar{p}$ flux is proportional to $T(P)$, raises the predicted $\bar{p}$ flux and continues the trend of the last two decades toward longer CR escape times/lengths, as discussed by these authors.

The uncertainties on the parameters of the MLBM result in uncertainties on the normalization of the predicted $\bar{p}/p$ ratio but, to a good approximation, do not introduce significant uncertainties in the shape of the predicted spectrum. Uncertainties on four parameters must be considered: (i) the storage time $(\pm 67\%)$ (Webber et al. 1992), (ii) the ISM primary $p$ flux $(\pm 35\%)$ (Gaisser & Schaefer 1992), (iii) the $\bar{p}$ production cross section...
and the composition of the ISM, which introduces an uncertainty of $< 6\%$ on the predicted $\overline{p}/p$ flux (Gaisser & Schaefer 1992). We neglect the last of these uncertainties since it is relatively small. Within the quoted fractional uncertainties on the other three parameters we treat all values as being a priori equally likely. Note that the predicted $\overline{p}/p$ ratio is approximately proportional to each of the parameters under consideration.

3. Heliospheric Modulation

The solid curves in Figure 1 show the MLBM $\overline{p}/p$ spectra for the parameter choices that result in the largest and smallest $\overline{p}/p$ predictions. The predicted ISM spectrum does not give a good description of the observed distribution at the top of the atmosphere. Good agreement is not expected because the CR spectra observed at the Earth are modulated as the particles propagate through the heliosphere, which consists of the solar magnetic field $B$ and solar wind (Stix 1989; Encrenaz et al. 1990; Longair 1992). The wind, assumed to blow radially outwards, has equatorial speed $V_W \simeq 400$ km sec$^{-1}$. *Ulysses* has found a latitude-dependent $V_W(\theta)$. At high latitudes ($|\theta - 90^\circ| \gtrsim 20^\circ$), $V_W \simeq 750$ km sec$^{-1}$ (Smith et al. 1995; Marsden et al. 1996; *Ulysses* 1999). The latitude-dependent solar rotation $\Omega_\odot(\theta)$ (Howard 1984) twists the field lines into a Parker spiral. The smoothed heliomagnetic field ($B_\odot \sim 5$ nT at the Earth’s orbit) declines as it changes from radial at the Sun to azimuthal in the outer solar system. The heliomagnetic polarity $\text{sgn}(A)$ is opposite in northern and southern solar hemispheres and switches sign somewhat after sunspot maximum. Note that $A > 0$ in the 1990-99 epoch. The regions of opposite magnetic polarity are separated by an approximately equatorial, unstable neutral current sheet. The sheet is spiraled and wavy; its waviness is measured by the tilt angle $\alpha$, which relaxes from $\simeq 50^\circ$ at polarity reversal to $\simeq 10^\circ$ just before reversal. The wavy sheet locus in heliographic co-ordinates is

$$\cos \theta + \sin \alpha \cdot \sin[\varphi + \Omega_\odot r/V_W] = 0$$

(Jokipii & Kopriva 1979; Encrenaz et al. 1990; NSO 1999).

Cosmic rays enter the heliosphere on ballistic trajectories and are then transported by drift and diffusion (Jokipii & Kopriva 1979; Risken 1984). The transport model includes energy loss as CRs perform work against the wind, CR solar wind convection, drift of CRs across inhomogeneous field lines, and diffusive scattering by field turbulence. Particles with $qA > 0$ ($qA < 0$) drift in along a polar (sheet) route. Since the polar $V_W$ is approximately twice the equatorial $V_W$, particles with $qA > 0$ find it more difficult to drift in along a polar route than do $qA < 0$ particles along a sheet route. In the following, we restrict our analysis to CR $p$’s and $\overline{p}$’s with kinetic energies $> 500$ MeV. At these energies, (a) the
wind and magnetic drift (Isenberg & Jokipii 1979, 1981) dominate the transport; and (b) the diffusion is charge–symmetric and, for a given rigidity, modulates the $p$'s and $\bar{p}$'s by the same factor, and hence cancels in the ratio of fluxes (see Ulysses $e$ and $p$ scans: Smith et al. 1995; Marsden et al. 1996; Fisk et al. 1998).

We compute the modulation of the CR fluxes by the method of characteristics, numerically implemented in three dimensions by a combination of Runge–Kutta and Richardson–Burlich–Stoer techniques (Press et al. 1992). The calculation is based on the heliospheric transport model of Jokipii & Kopriva (1979), Jokipii & Thomas (1981), and Jokipii & Davila (1981), but that model has been updated with Pioneer, Voyager, Helios, IMP and Ulysses heliospheric measurements (Smith et al. 1995; Marsden et al. 1996; NSSDC 1999; SEC 1999). The improvements include the latitude-dependent $V_W(\theta)$ and $\Omega_\odot(\theta)$. The calculation is simplified by ignoring diffusion where its effects on the $p/p$ ratio are small, which for our energy range means everywhere except across the sheet (Jokipii & Thomas 1981). The effects of diffusion away from the sheet are essential for particles with energies below the range we are considering. For particles with speed $v$ the across-sheet diffusion coefficient $\kappa_\perp = [(2 - 3) \times 10^{17} \text{ m}^2/\text{sec}] [B_\odot/B(r)](P/\text{GeV})^{1/3}(v/c)$ is used (Smith et al. 1995; Marsden et al. 1996). The implied field fluctuation spectral index is the Kolmogorov value of 5/3. The modulated fluxes at Earth depend only weakly on $\kappa_\perp$ in our energy range, for this and larger values of $\kappa_\perp$.

4. Results

We use the data sets recorded by the MASS91, IMAX, BESS, and CAPRICE experiments (Table 1). These data were recorded in the period 1991–1995, corresponding to a well–behaved part of the solar cycle for which the heliospheric modulation corrections can be confidently calculated. To explore the dependence of the predicted spectrum on the heliospheric parameters (equatorial $V_W$, polar $V_W$, and $B_\odot$) we have computed the modulated spectra for 11 parameter sets (F1 – F11) that span the range of acceptable parameter values (Table 2). Using the central parameter values for our MLBM, and assuming a stable antiproton, the predicted modulated $p/p$ spectra for a fixed time in the solar cycle (July 1995) are shown in Figure 2 for each of the 11 heliospheric parameter sets. Figure 2 also shows the epoch–corrected measured CR spectra, obtained by multiplying each measurement by the factor $f \equiv R(\text{July 1995})/R(t)$, where $R(t)$ is the predicted $p/p$ ratio at time $t$. The factors $f$, which are shown in Table 1 and have been computed using the F6 parameters, vary by up to $\pm 0.06$ with the parameter set choice. The MLBM predicted $p/p$ spectra give an excellent description of the measurements. There is no evidence for an
unstable \( \bar{p} \).

To obtain a limit on \( \tau_{\bar{p}} \) we add to the MLBM one additional loss mechanism, \( \bar{p} \) decay. The results from maximum likelihood fits to the measurements are shown in Figure 3 as a function of the assumed \( \tau_{\bar{p}} \) for the 11 heliospheric parameter sets. The fits, which take account of the Poisson statistical fluctuations on the number of observed events and the background subtraction for each data set (Table 1), also allow the normalization of the MLBM predictions to vary within the acceptable range (Figure 1). For a stable \( \bar{p} \), at the 95% C.L. all of the heliospheric parameter sets yield predictions that give reasonable descriptions of the observed \( p/p \) spectrum. Allowing for a finite \( \tau_{\bar{p}} \), the heliospheric parameter sets with larger wind speeds permit lower \( \bar{p} \) lifetimes. This can be understood by noting that, as the wind speed increases, the predicted flux of polar–routed particles (protons in the present solar cycle) is depleted at kinetic energies \( \lesssim 10 \) GeV, which increases the predicted \( \bar{p}/p \) ratio in this energy range. Antiproton decay would compensate for this distortion in the predicted spectrum. Hence our fits using the extreme parameter set F11 determine the limits on \( \tau_{\bar{p}} \). Under the assumption that there are no significant non–standard sources of cosmic ray antiprotons, we obtain the bounds:

\[
\tau_{\bar{p}} > 0.8 \text{ Myr (90\% C.L.)}, \quad 0.7 \text{ Myr (95\% C.L.)}, \quad 0.5 \text{ Myr (99\% C.L.)}. \quad (1)
\]

Our simple dimensional analysis suggests that if a dimension–\( n \) CPT–violating coupling results in antiproton decay, the mass scale \( m_X \) at which this new physics takes place exceeds \( \mathcal{O}(10^{19}) \) GeV/\( c^2 \) \( \mathcal{O}(10^9) \) GeV/\( c^2 \), for \( n = 5 (6) \).

The limits (1) are significantly more stringent than those obtained from the most sensitive laboratory search for inclusive \( \bar{p} \) decay (\( \tau_{\bar{p}} > 3.4 \) months) (Gabrielse et al. 1996) or the most sensitive search for an exclusive \( \bar{p} \) decay mode (\( \tau_{\bar{p}}/B(\bar{p} \to \mu^-\gamma) > 0.05 \) Myr) (Hu et al. 1998). Note however that these limits are less restrictive than the estimate \( \tau_{\bar{p}} \gtrsim 10 \) Myr given in Caso et al. (1998), which takes no account of time dilation, systematic uncertainties, or propagation effects and which is therefore overconstraining.

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REFERENCES

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Table 1: Summary of Cosmic Ray Antiproton Results

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Field Pol.</th>
<th>Flight Date</th>
<th>$\bar{f}$</th>
<th>KE Range (GeV)</th>
<th>Candidates</th>
<th>Background</th>
<th>Observed $\bar{p}/p$ Ratio</th>
<th>Prediction $\bar{p}/p$ Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Golden et al. 1979†</td>
<td>+</td>
<td>June 1979</td>
<td>–</td>
<td>5.6 – 12.5</td>
<td>46</td>
<td>18.3</td>
<td>(5.2 ± 1.5) × 10^{-4}</td>
<td>–</td>
</tr>
<tr>
<td>Bogomolov et al. 1979†</td>
<td>+</td>
<td>1972-1977</td>
<td>–</td>
<td>2.0 – 5.0</td>
<td>2</td>
<td>–</td>
<td>(6 ± 4) × 10^{-4}</td>
<td>–</td>
</tr>
<tr>
<td>Bogomolov et al. 1987‡</td>
<td>–</td>
<td>1984-1985</td>
<td>–</td>
<td>0.2 – 2.0</td>
<td>1</td>
<td>–</td>
<td>(6^{+14}_{-5}) × 10^{-5}</td>
<td>–</td>
</tr>
<tr>
<td>Bogomolov et al. 1990‡</td>
<td>–</td>
<td>1986-1988</td>
<td>–</td>
<td>2.0 – 5.0</td>
<td>3</td>
<td>–</td>
<td>(2.4^{+2.4}_{-1.3}) × 10^{-4}</td>
<td>–</td>
</tr>
<tr>
<td>MASS91 d</td>
<td>+</td>
<td>Sep. 1991</td>
<td>1.1</td>
<td>3.70–19.08</td>
<td>11</td>
<td>3.3</td>
<td>(1.24^{+0.88}_{-0.51}) × 10^{-4}</td>
<td>1.3 × 10^{-4}</td>
</tr>
<tr>
<td>IMAX e</td>
<td>+</td>
<td>July 1992</td>
<td>–</td>
<td>0.25 – 1.0</td>
<td>3</td>
<td>0.3</td>
<td>(3.14^{+3.4}_{-1.9}) × 10^{-5}</td>
<td>1.5 × 10^{-5}</td>
</tr>
<tr>
<td>IMAX e</td>
<td>+</td>
<td>July 1992</td>
<td>0.96</td>
<td>1.0 – 2.6</td>
<td>8</td>
<td>1.9</td>
<td>(5.36^{+3.5}_{-2.4}) × 10^{-5}</td>
<td>6.5 × 10^{-5}</td>
</tr>
<tr>
<td>IMAX e</td>
<td>+</td>
<td>July 1992</td>
<td>1.1</td>
<td>2.6 – 3.2</td>
<td>5</td>
<td>1.2</td>
<td>(1.94^{+1.8}_{-1.1}) × 10^{-4}</td>
<td>1.1 × 10^{-4}</td>
</tr>
<tr>
<td>BESS93 f</td>
<td>+</td>
<td>July 1993</td>
<td>–</td>
<td>0.20 – 0.60</td>
<td>7</td>
<td>~ 1.4</td>
<td>(5.2^{+4.4}_{-2.8}) × 10^{-6}</td>
<td>8.9 × 10^{-6}</td>
</tr>
<tr>
<td>CAPRICE g</td>
<td>+</td>
<td>Aug. 1994</td>
<td>0.94</td>
<td>0.6 – 2.0</td>
<td>4</td>
<td>1.5</td>
<td>(2.5^{+3.2}_{-1.9}) × 10^{-5}</td>
<td>3.5 × 10^{-5}</td>
</tr>
<tr>
<td>CAPRICE g</td>
<td>+</td>
<td>Aug. 1994</td>
<td>1.0</td>
<td>2.0 – 3.2</td>
<td>5</td>
<td>1.3</td>
<td>(1.9^{+1.6}_{-1.0}) × 10^{-4}</td>
<td>1.1 × 10^{-4}</td>
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<tr>
<td>BESS95 h</td>
<td>+</td>
<td>July 1995</td>
<td>1.0</td>
<td>0.175 – 0.3</td>
<td>3</td>
<td>0.17</td>
<td>(7.8^{+8.3}_{-4.8}) × 10^{-6}</td>
<td>–</td>
</tr>
<tr>
<td>BESS95 h</td>
<td>+</td>
<td>July 1995</td>
<td>1.0</td>
<td>0.3 – 0.5</td>
<td>7</td>
<td>0.78</td>
<td>(7.4^{+4.7}_{-3.3}) × 10^{-6}</td>
<td>1.1 × 10^{-5}</td>
</tr>
<tr>
<td>BESS95 h</td>
<td>+</td>
<td>July 1995</td>
<td>1.0</td>
<td>0.5 – 0.7</td>
<td>7</td>
<td>1.4</td>
<td>(7.7^{+5.3}_{-3.7}) × 10^{-6}</td>
<td>5.5 × 10^{-6}</td>
</tr>
<tr>
<td>BESS95 h</td>
<td>+</td>
<td>July 1995</td>
<td>1.0</td>
<td>0.7 – 1.0</td>
<td>11</td>
<td>2.8</td>
<td>(1.01^{+5.7}_{-3.3}) × 10^{-5}</td>
<td>1.3 × 10^{-5}</td>
</tr>
<tr>
<td>BESS95 h</td>
<td>+</td>
<td>July 1995</td>
<td>1.0</td>
<td>1.0 – 1.4</td>
<td>15</td>
<td>3.5</td>
<td>(1.99^{+0.91}_{-0.73}) × 10^{-5}</td>
<td>3.1 × 10^{-5}</td>
</tr>
</tbody>
</table>

a Heliomagnetic field polarity $\text{sgn}(A)$.  
b Epoch correction factor; see text.  
c MLBM prediction using F6 heliospheric parameters; see text.  
d Hof et al. 1996.  
e Mitchell et al. 1996.  
g Boezio et al. 1997.  
h Matsunaga et al. 1998.  
† Not shown in Fig. 1 or used in analysis.  
‡ Not used in analysis.  
* Statistical and systematic uncertainties on ratio added in quadrature.
Table 2: Heliospheric Parameter Sets

<table>
<thead>
<tr>
<th>Set</th>
<th>Equatorial $V_W$ (km sec$^{-1}$)</th>
<th>Polar $V_W$ (km sec$^{-1}$)</th>
<th>$B_{\oplus}$ (nT)</th>
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<tbody>
<tr>
<td>F1</td>
<td>375</td>
<td>700</td>
<td>4.0</td>
</tr>
<tr>
<td>F2</td>
<td>380</td>
<td>710</td>
<td>4.1</td>
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<tr>
<td>F3</td>
<td>385</td>
<td>720</td>
<td>4.2</td>
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<td>F4</td>
<td>390</td>
<td>730</td>
<td>4.3</td>
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<td>F5</td>
<td>395</td>
<td>740</td>
<td>4.4</td>
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</tr>
<tr>
<td>F9</td>
<td>415</td>
<td>780</td>
<td>4.8</td>
</tr>
<tr>
<td>F10</td>
<td>420</td>
<td>790</td>
<td>4.9</td>
</tr>
<tr>
<td>F11</td>
<td>425</td>
<td>800</td>
<td>5.0</td>
</tr>
</tbody>
</table>
Fig. 1.— Observed $p/p$ ratio at the top of Earth atmosphere (see Table 1). The solid curves show the upper and lower interstellar ratios predicted by the MLBM described in the text, without solar modulation. The broken curve shows the MLBM prediction with the same parameters used for the modulated predictions of Fig. 2.
Fig. 2.— Observed $\bar{p}/p$ spectrum (kinetic energy > 500 MeV) at the top of the atmosphere compared with the MLBM predictions (see broken curve on Fig. 1) after modulation using the heliospheric parameter sets indicated (see Table 2). The curves are predictions for the spectrum observed in July 1995. The data have been corrected to correspond to this epoch (see text).
Fig. 3.— Fit results as a function of the assumed $\tau_p$ for the eleven heliospheric parameter sets (F1 – F11) shown in Table 2.