Evaluation of Galactic Cosmic Ray Models

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Abstract

Models of the galactic cosmic ray spectra have been tested by comparing their predictions to an evaluated database containing more than 380 measured cosmic ray spectra extending from 1960 to the present.

1.0 Introduction

For most of the mission time (i.e. during solar quiet periods) the dominant component of the ionizing radiation environment in interplanetary space that affects the electronic components in space is galactic cosmic rays (GCRs). All computational tools used to estimate radiation effects on spacecraft contain a model to predict the GCR elemental spectra, but these models have not been updated for over a decade. In the last 10 years much more accurate measurements of GCRs have been made on balloons and satellites. Two of the GCR models have been revised in light of these data. The CREME96 model is currently being revised. The purpose of this paper is to test these GCR models against measurements of the GCR elemental spectra and select one for use in the revised CRÈME model. The GCR intensity varies with energy and time in 11- and 22-year cycles. The pattern of intensities does not repeat exactly with each cycle. For example, GCR intensities during the current minimum of the 11-year solar cycle are the highest in more than 50 years. Because of the long-term variability in GCR fluxes, we are assembling an extensive evaluated database containing GCR measurements made over the past 48 years that will be used to select the GCR model for the CRÈME revision. This is done with the expectation that the model which best reproduces the data in the past will provide the most accurate representation of GCR elemental spectra for future missions. The results of these tests will be reported at the conference.

The important radiation effect from GCRs is single event effects (SEEs). The electronic components susceptible to SEEs are typically protected by at least 100 mils (0.7 g/cm^2) of aluminum. The minimum particle energy required to penetrate to the electronic components sets a lower limit for the energy spectrum of interest for each particle species. Protons and heavy ions at the same energy per nucleon have ranges that depend on atomic number as A/Z^2, where A is the atomic mass and Z is the atomic number. To penetrate 100 mils of aluminum, the lower limits of the elemental energy spectra are 23 MeV/nuc for protons and helium, 42 MeV/nuc for carbon, 50 MeV/nuc for oxygen and 90 MeV/nuc for iron. Because of these lower energy limits, particles accelerated in co-rotating interaction regions are not important and among the anomalous cosmic rays, only helium ions can contribute.

2.0 Models of Galactic Cosmic Ray Elemental Spectra:

These models must describe the GCR elemental spectra of protons and heavy ions with energies that will penetrate ~100 mils of aluminum (and it is better to extend this down to 25 mils to be sure all cases are covered). That corresponds to 10.4 MeV for protons and higher energies for heavier ions as shown above. The energy range of the models must extend up to at least 10^5 MeV/nuc and include the elemental spectra from hydrogen up to U for complete coverage. There are several existing models that can be used individually or in combination to meet these requirements.

2.1 The Nymmik Model: This model was originally developed by Riho Nymmik back in the early1990s and has been adopted as the ISO standard model for the GCR environment. It is the model used in CREME96. The latest update of this model is INTERNATIONAL STANDARD ISO/DIS 15390 (see Nymmik, 2003) that was proposed to the ISO in 2002 and adopted in 2003. It provides the spectra of electrons and all ions from protons to uranium for energies >10 MeV/nuc. It models the GCR fluxes assuming that they are time invariant beyond the heliosphere. The temporal variation in the fluxes is attributed to large scale variations in the heliospheric magnetic field. This results in roughly cyclic variations in the GCR spectra with periods of ~11 and ~22 years. The actual modulation of the interstellar GCR spectra is indexed using the Wolf number (this is a count of the number of spots on the sun following an internationally-agreed procedure). The Wolf number serves as a measure of solar activity and is known to be anti-correlated with the GCR flux (see Cliver and Ling, 2001). Cosmic ray modulation can be thought of as a consequence of the pileup of interplanetary shocks at the heliospheric boundary. The frequency with which the Sun launches these shocks is correlated with solar activity and hence with the Wolf number. Because of the propagation time of these shocks to the boundary, the Wolf number is a leading indicator providing a predictive power for solar modulation levels extending several months into the future.

2.2 The CHIME Model: This model was developed in the early 90's by Chenette et al. (1994). It provides the spectra of all ions from protons to uranium for all energies >10 MeV/nuc. Like the Nymmik model, CHIME assumes time-invariant interstellar spectra that are modulated by large scale variations in the heliosphere. It uses the theoretical model of Gleeson and Axford (1968) for solar modulation which describes the level of modulation by a single parameter, Φ. CHIME chooses the value for Φ using the 70-95 MeV/nuc helium ion flux as measured on the IMP-8 satellite. The measurements of this flux from IMP-8 are no longer widely available since NASA ended mission operations support in 2001. As Chenette et al. point out in their paper, there are many proxies for the solar activity level, the solar neutron monitors have been found to correlate best with the GCR fluxes that are relevant to radiation effects. While NSF has recently discontinued support for 13 monitors operated by the University of Delaware and the University of New Hampshire, 38 remain in operation, worldwide and the data from many of these is available online in real-time.

2.3 The Badhwar-O'Neill Model: This model was developed first in the 1990s. The most recent revision is O'Neill (2006). It provides the spectra of all ions from protons to nickel for all energies >10 MeV/nuc. Using the published data on elemental composition beyond iron, it will be straight-forward to scale the iron spectrum to predict the spectra of all the heavier elements up to uranium. Modulation is treated in a way similar to CHIME, but the spherically symmetric Fokker-Planck equation is solved using the methods of Fisk (1971) to obtain the modulated spectra. The solar modulation parameter, Φ, can be determined using measurements of the GCR oxygen spectrum between ~70 and ~200 MeV averaged over 10-40 days as measured by the CRIS instrument on the ACE spacecraft. ACE is expected to remain operational until 2014. Alternately, this model determines Φ from the count rate of the neutron monitor in Climax, Colorado, but this monitor is no longer supported. Φ values based on ACE and Climax data are available from derived from http://www.srl.caltech.edu/personnel/ad/GCRspectra/index.cgi.

2.4 Other models: We examined two additional models. The Castagnoli-Lal Model (Castagnoli and Lal, 1980, corrected by Masarik and Reedy, 1996) provides reliable estimates of the GCR proton spectra, but not the heavier elements needed here. The Caltech model (Davis et al., 2000, 2001a and 2001b is available at http://www.srl.caltech.edu/personnel/ad/GCRspectra/index.cgi. This model does not provide proton spectra and it does not propagate Li and Be correctly, so it is not suitable for the CRÈME revision.

3.0 Testing the models: We are evaluating the Badhwar-O'Neill, CHIME and Nymmik models by comparing them to measured elemental spectra from an evaluated database we are developing. This database will contain more than 380 measurements of the elemental spectra of GCRs ranging from hydrogen to iron and from 10 MeV/nuc to 1 TeV/nuc. These measurements cover the time period from 1960 to the present. We compare these individual evaluated spectra with each model by calculating the reduced chi-square between each model and each spectrum, were reduced chi-square is defined as

$$\frac{\chi^2}{\nu} = \frac{1}{\nu}\sum_{i=1}^{N}\frac{1}{\sigma_i^2}\left[\phi_i - f(E_i)\right]^2\Big]$$

Where ϕ_i is the measured flux at E_i, σ_i is the error in this measurement and $f(E_i)$ is the flux calculated at E_i from the model under test. ν is $N - p - 1$ where N is the number of data points in the spectrum and p is the number of free parameters in the model under test and χ^2/ν is reduced chi-square. σ_i is proportional to $\sqrt{n_i}$ where n_i is the number of detected cosmic rays used to construct ϕ_i. Here we have bounded σ_i to be $\geq 0.1\phi_i$ to account for systematic errors, especially in the determination of the geometrical factor of the instrument.

Evaluation of the data base for testing the models is underway as of this writing. Figure 1 shows an example in which the three models are being compared to a measurement of the GCR helium spectrum in July of 1992 (Menn et al., 2000).

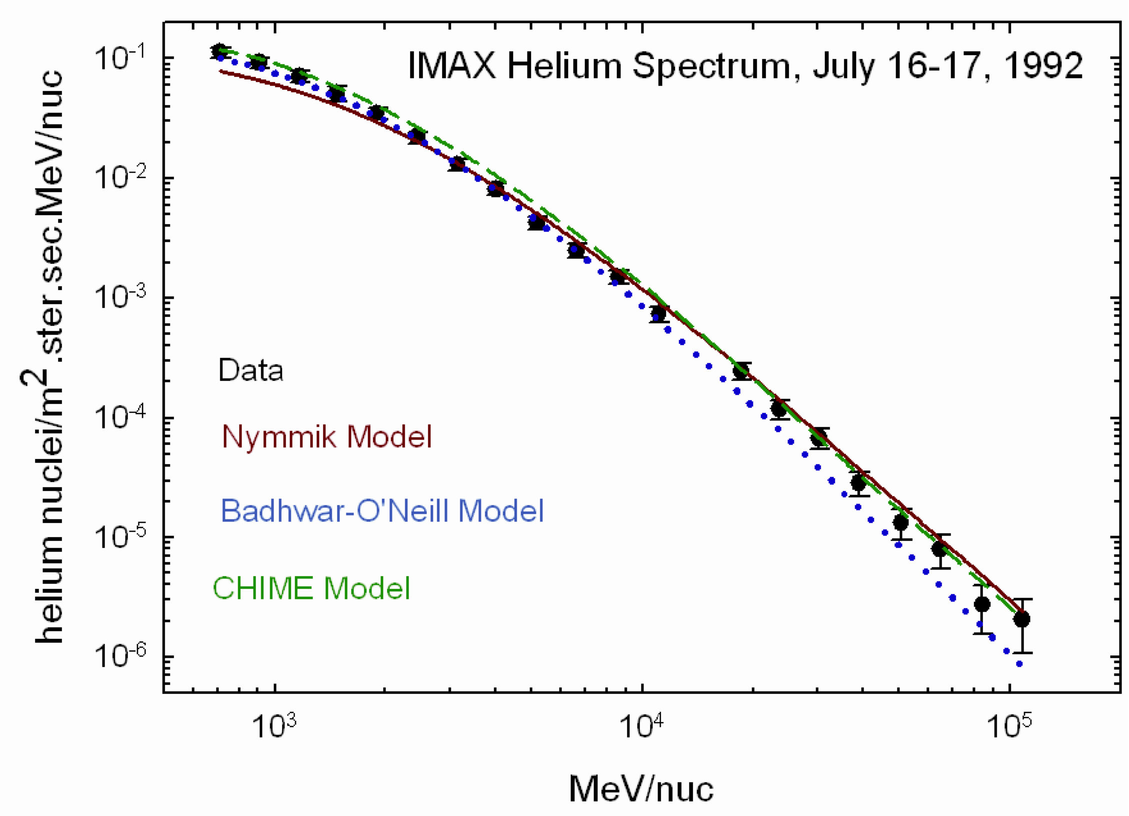

Figure 1: This figure is an example of comparing the three models with a spectral measurement. Here the models are compared to a measurement of part of the helium spectrum. This measurement was made with the balloon-borne experiment Isotope Matter-Antimatter Experiment (IMAX) launched from Lynn Lake, Manitoba, Canada, in 1992.

Figures 2 shows the reduced chi-squares resulting from the comparisons of the three models with individual iron spectrum measurements from a sample of 36 in our data base. Our data base currently contains 44 iron spectra. It also contains 131 proton spectra, 108 helium spectra as well as many spectra of Li, Be, B, C, N, O, F, Ne, Mg, Si, P, S, Ar and Ca. All these will be compared with the models.

4.0 Summary

This paper provides a brief introduction to radiation environment models that may be used to predict radiation effects on spacecraft electronic systems during solar quiet periods. In the talk we will compare these models with and extensive data set, determine the overall accuracy of the models and recommend one model for use in the new CRÈME-MC model currently under development.

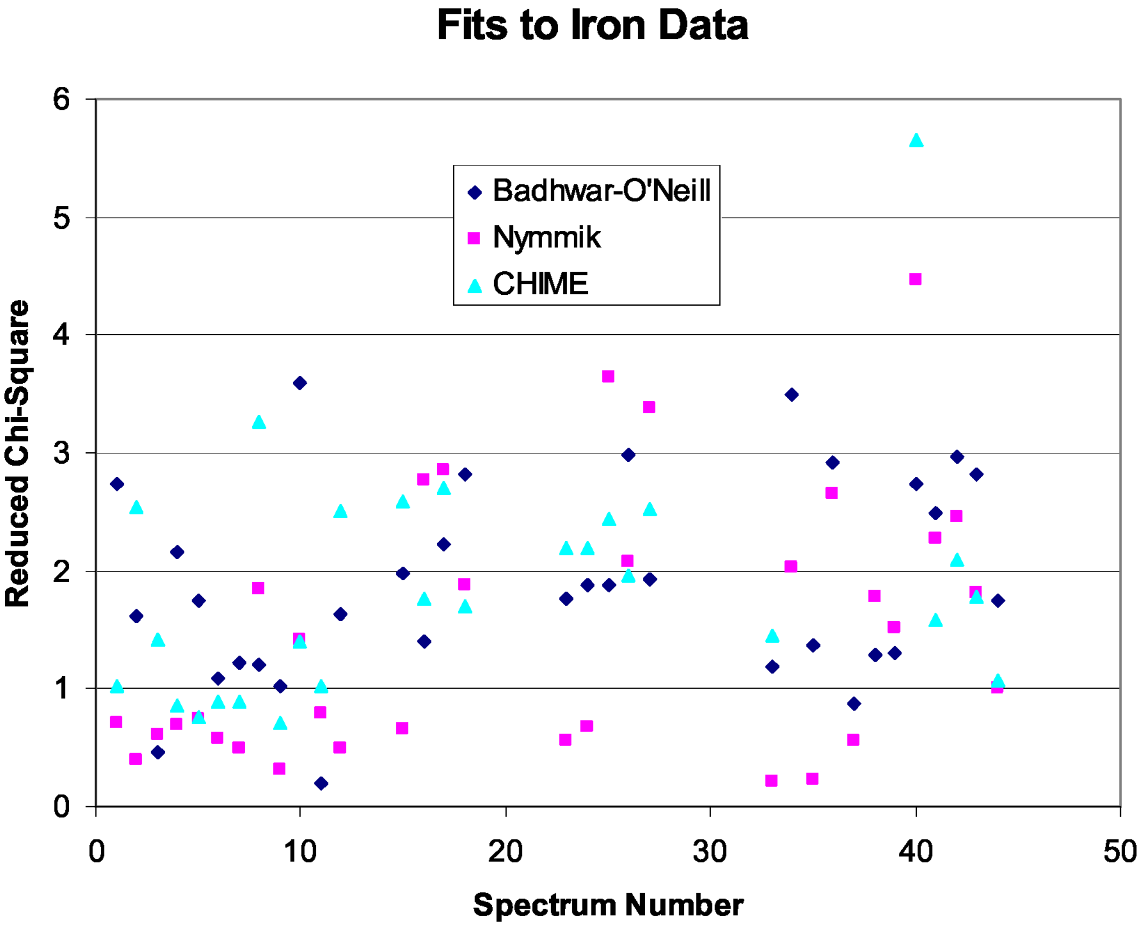

Figure 2: This figure shows reduced chi-square from comparing the three models to 36 measurements of the GCR iron spectrum made between 1965 and 2003. The horizontal axis is a serial number that has been assigned to each measurement.

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Abstract: The published galactic cosmic ray models have been examined been compared with published measurements to select the models best suited for estimating radiation effects in electronics. The models chosen for evaluation were ones that provided representations of the differential energy spectra of the elements from hydrogen to uranium (or could be extended to do so in a straight-forward way). The models also had to provide spectra for the years since 1950 (or could be extended straight-forwardly to do so). We found three models that met these criteria. These models were evaluated against and extensive data base of published measurements of elemental differential energy spectra spanning the time period from 1954 to the present. The most recent version of Nymmik Model (ISO 15390:2004) was selected. It will be used in the new CRÈME-MC model.

Introduction: For most of the on-orbit time, the dominant component of the ionizing radiation environment in interplanetary space that affects the electronic components is galactic cosmic rays (GCRs). All tools used to estimate radiation effects on spacecraft contain a model to predict the GCR elemental spectra, but these tools have not been updated for over a decade. In the last 10 years much more accurate measurements of GCRs have been made and two of the GCR models have been revised in light of these data. The purpose of this paper is to test these GCR models against measurements of the GCR elemental spectra and select the one best suited for estimating radiation effects.

The GCR intensity varies with energy and time in 11- and 22-year cycles. The pattern of intensities does not repeat exactly with each cycle. Because of this long-term variability in GCR fluxes, we assembled an extensive evaluated database containing published GCR measurements made over the past 55 years. This database was used to select the GCR model which most closely reproduces the data. This is done with the expectation that the model which best reproduces the data in the past will provide the most accurate representation of GCR elemental spectra for future missions.

The important radiation effect from GCRs is single event effects (SEEs). The electronic components susceptible to SEEs are typically protected by at least 25 mils (0.171 g/cm^2) of aluminum. The minimum particle energy required to penetrate to these electronic components is given in Table 1.

Table 1: Minimum Energy Needed to Penetrate 100 mils of Aluminum

Element	Energy in MeV/nuc
H	9.86
He	9.91
C	18.0
O	21.1
Fe	36.0

Models of Galactic Cosmic Ray Spectra: We examined five GCR models: the Badhwar-O'Neill Model [1], the Buchvarova-Velinov Model [2], Castignoli-Lal Model [3], the CHIME Model [4] and the Nymmik Model [5]. The parameters of the Buchvarova-Velinov Model could not be derived for a given date in any straight-forward way. Also it did not extend far enough in energy or atomic number to be useful for estimating radiation effects on electronics. The Castignoli-Lal Model [5] is simple and straight forward to use. Unfortunately it only provides representations of proton spectra. The remaining three models met the basic requirements.

The original Nymmik Model was used in CREME96. The latest update was adopted by the ISO in 2004. It provides the spectra of electrons and all ions from protons to uranium for energies >10 MeV/nuc. It models the GCR fluxes assuming that they are time invariant beyond the heliosphere. The temporal variation in the fluxes is attributed to large scale variations in the heliospheric magnetic field. This results in roughly cyclic variations in the GCR spectra with periods of ~11 and ~22 years. The actual modulation of the interstellar GCR spectra is indexed using the Wolf number which serves as a measure of the modulation level.

The CHIME Model provides the spectra of all ions from protons to uranium for all energies >10 MeV/nuc. Like the Nymmik model, CHIME assumes time-invariant interstellar spectra that are modulated by large scale variations in the heliosphere. It uses the theoretical model of Gleeson and Axford [6] for solar modulation which describes the level of modulation by a single parameter, Φ.

The Badhwar-O'Neill Model provides the spectra of all ions from protons to nickel for all energies >10 MeV/nuc. Using the relative elemental composition beyond iron, it will be straight-forward to extend the spectrum to uranium. Modulation is treated in a way similar to CHIME, but the spherically symmetric Fokker-Planck equation is solved using the methods of Fisk [7] to obtain the modulated spectra. The solar modulation parameter, Φ, can be determined from data collected by instruments on the ACE spacecraft, or from solar neutron monitor data.

Testing the Models: The models were tested against published measurements of the GCR elemental spectra using reduced Chi-Square, defined as,

$$\frac{\chi^2}{\nu} = \frac{1}{\nu}\sum_{i=1}^{N}\frac{1}{\sigma_i^2}\left[\phi_i - f(E_i)\right]^2$$

where ϕ_i is the measured flux at E_i, σ_i is the error in this measurement and $f(E_i)$ is the flux calculated at E_i from the model under test. ν is $N-p-1$, where N is the number of data points in the spectrum and p is the number of free parameters in the model under test. χ^2/ν is reduced Chi-Square.

Example of Spectral Fits: Figure 2 shows how the three models represent the helium spectrum measured during the Isotope Matter-Antimatter Experiment (IMAX) balloon flight in 1992 across northern Canada.

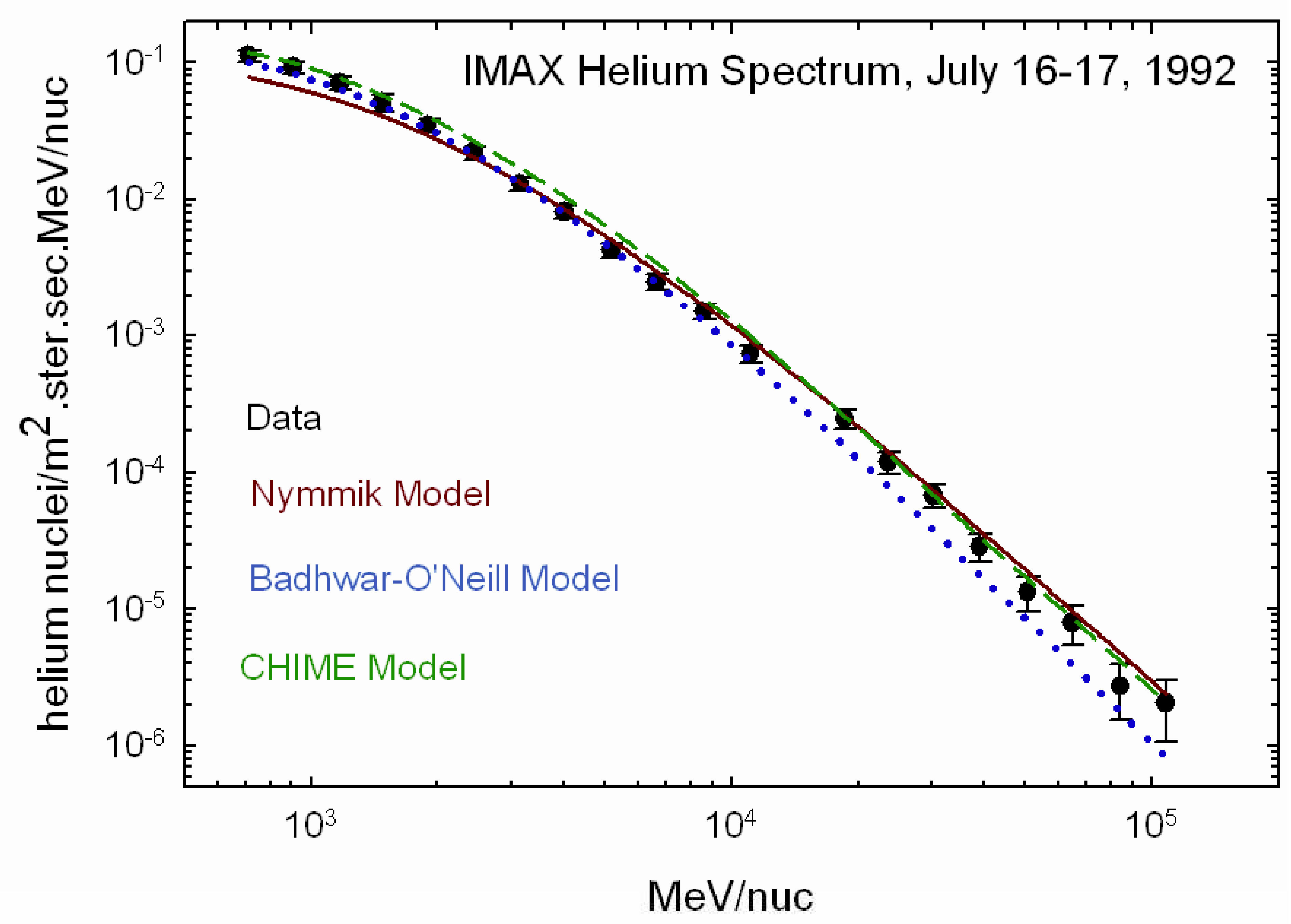

Figure 2: The measurements of helium [8] are compared to the three models.

Results: Reduced Chi-Square was computed between each of the models and each of the 311 measured spectra. Figure 3 shows, for example, the results for the hydrogen spectra. The final results are given in Table 2

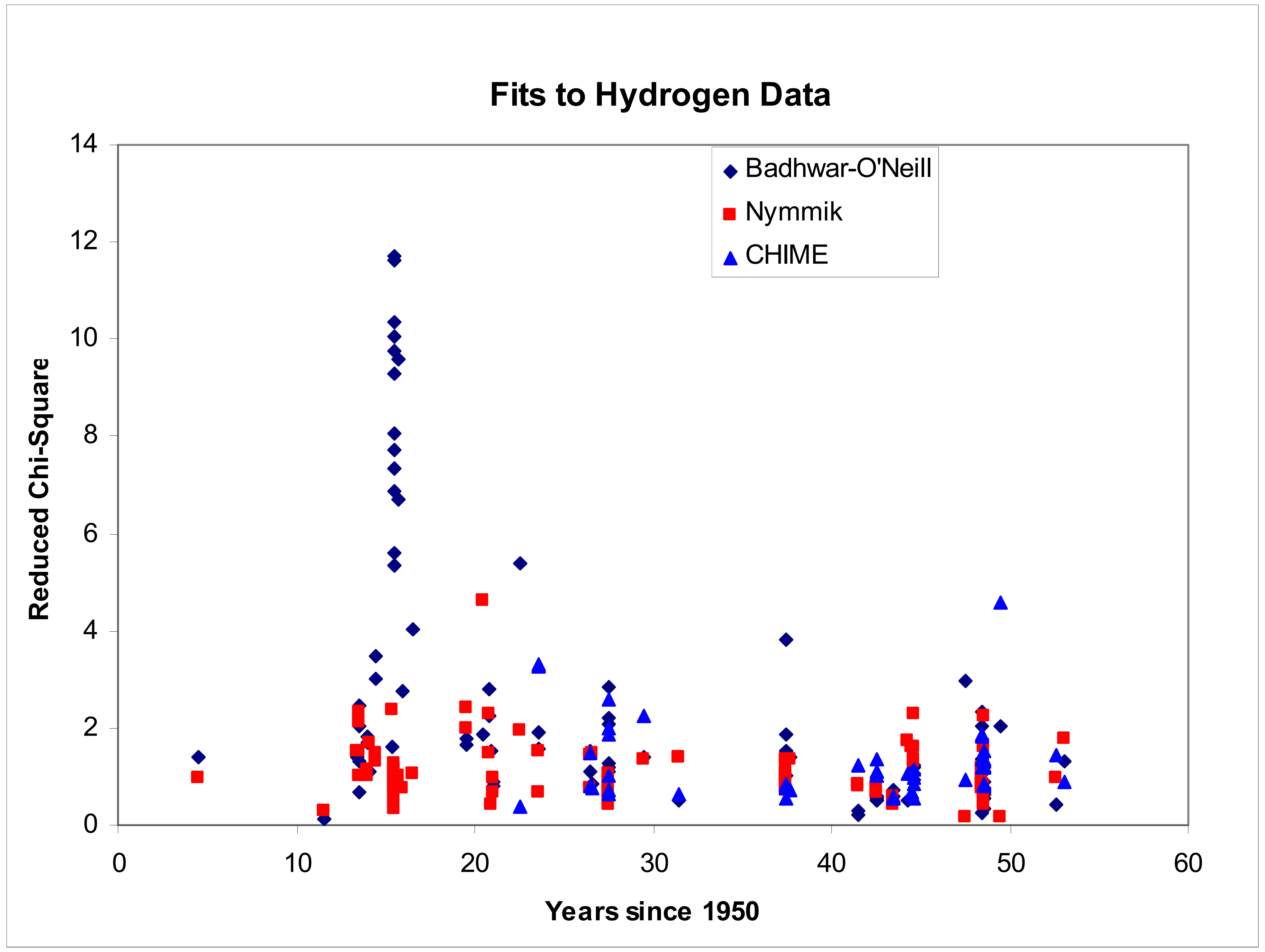

Figure 3: Reduced χ^2 versus the year when the spectra were measured.

Table 2: The weighted mean results on the reduced Chi-Squares for all the spectral fits. The Nymmik Model gives the best fits overall.

	Badhwar-O'Neill	Nymmik	CHIME
Reduced Chi Square	2.46	1.31	1.46

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