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**20-125 MeV/nuc COSMIC RAY CARBON NUCLEI INTENSITIES
BETWEEN 2004-2010 IN SOLAR CYCLE #23 AS MEASURED NEAR THE EARTH,
AT VOYAGER 2 AND ALSO IN THE HELIOSHEATH AT VOYAGER 1 -
MODULATION IN A TWO ZONE HELIOSPEHRE**

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Abstract

20
21 The recovery of cosmic ray Carbon nuclei of energy ~20-125 MeV/nuc in solar cycle #23
22 from 2004 to 2010 has been followed at three locations, near the Earth using ACE data and at V2
23 between 74-92 AU and also at V1 beyond the heliospheric termination shock at between 91-113
24 AU. To describe the observed intensity changes and to predict the absolute intensities measured
25 at all three locations we have used a simple spherically symmetric (no drift) two-zone
26 heliospheric transport model with specific values for the diffusion coefficient in both the inner
27 and outer zones. The diffusion coefficient in the outer zone is determined to be ~5-10 times
28 smaller than that in the inner zone out to 90 AU. For both V1 and V2 the calculated C nuclei
29 intensities agree within an average of $\pm 10\%$ with the observed intensities. Because of this
30 agreement between V1 and V2 observations and predictions there is no need to invoke an
31 asymmetrical squashed heliosphere or other effects to explain the V2 intensities relative to V1 as
32 is the case for He nuclei. The combination of the diffusion parameters used in this model and the
33 interstellar spectrum give an unusually low overall solar modulation parameter $\phi = 250$ MV to
34 describe the Carbon intensities observed at the Earth in 2009. At all times both the observed and
35 calculated spectra are very closely $\sim E^{1.0}$ as would be expected in the adiabatic energy loss
36 regime of solar modulation.
37

38 **Introduction**

39 The intensity recovery of lower energy galactic cosmic rays at the Earth in the solar 11-year
40 cycle #23 between 2004-2010 and the unusually high intensities observed in 2009 is well
41 documented using spacecraft data (e.g., McDonald, Webber and Reames, 2010; Mewaldt, et al.,
42 2010). The cosmic ray recovery in this cycle started in early 2004 at the Earth after the large
43 “Halloween” events in October-November, 2003, and has been observed by neutron monitors
44 and various spacecraft near the Earth including ACE, IMP and others. This recovery was
45 observed by V2 and V1 to begin in the outer heliosphere in late 2004 after the Halloween event
46 had propagated out to their respective locations at 76 and 93 AU (McDonald, et al., 2006). At
47 the end of 2004 V1 crossed the HTS at 94 AU and has continued to move outward so that by
48 2010.5 it was at ~114 AU, perhaps ~30 AU or more beyond the current HTS location, estimated
49 to be between 80-85 AU (Webber and Intriligator, 2011). Thus V1 has spent essentially the
50 entire recovery cycle beyond the HTS in the heliosheath region where the solar wind parameters
51 are measurably different from those in the inner heliosphere. V2 remained in the “inner” part of
52 the heliosphere until 2007.66 when at ~84 AU it also crossed the HTS.

53 At about 2010.0 the cosmic ray Carbon nuclei intensity at the Earth reached its maximum
54 (Mewaldt, et al., 2010). At V1 the intensity of Carbon nuclei continues to increase as of 2010.5
55 whereas at V2 it reached a maximum in early 2009, then decreased, but after 2010.5 began a
56 rapid increase. At the Earth the Carbon intensities reached levels ~25% higher than those
57 observed during the previous 11-year intensity maximum in 1997-98 (McDonald, Webber and
58 Reames, 2010; Mewaldt, et al., 2010). At V1 the cosmic ray Carbon intensities are at the highest
59 levels yet observed and at energies ~100 MeV/nuc at 2010.5 are within ~20% of the estimated
60 LIS intensities for Carbon nuclei (see Webber and Higbie, 2009; George, et al., 2009).

61 It is the purpose of this paper to compare the Carbon nuclei intensities between 20-125
62 MeV/nuc observed at the Earth and those observed at V1 and V2 during this time period, within
63 the framework of simple modulation models, with the objective of understanding better the
64 global characteristics of the solar 11-year modulation cycle, including, particularly, the
65 modulation effects beyond the HTS in the heliosheath.

66 This is the third of several articles dealing with the recovery of cosmic ray intensities at
67 V1, V2 and the Earth during this extended time period. The initial article considered He nuclei
68 between 150-250 MeV/nuc (Webber, et al., 2011a). The second article studies the H nuclei from

69 150-250 MeV (Webber, et al., 2011b). Each of these individual nuclei gives its own specific
70 information on the overall radial extent of the heliosphere modulation process and the required
71 interstellar spectrum of the galactic particles involved. These studies of Carbon nuclei, which
72 simultaneously involve the inner and outer heliosphere, are now possible because of ACE
73 measurements at the Earth covering an entire solar 11 year cycle from 1997 to 2010, and the V1
74 (V2) measurements from the outer heliosphere including the heliosheath from 2005 to 2010.

75 The energies involved in the Carbon nuclei study are in the low energy part of the
76 spectrum below ~ 125 MeV/nuc where the energy spectrum, dj/dE , has an $E^{1.0}$ dependence, the so
77 called adiabatic regime in which adiabatically cooled higher energy particles populate the
78 spectrum. This is in contrast to the He nuclei and H nuclei studies at ~ 200 MeV/nuc noted
79 above, which are above the peak in the differential energy spectrum and in an energy region
80 where “diffusive” modulation effects are important.

81 **Observations at the Earth and at V1 and V2**

82 In Figures 1A and 1B we show the time history of ~ 56 -125 and 20-56 MeV/nuc Carbon
83 nuclei from 2004 to 2010.5. The Voyager data is smoothed by taking 5 interval 26 day moving
84 averages. The data at the Earth is from the ACE/CRIS experiment from Mewaldt, et al., 2010
85 (also <http://www.srl.caltech.edu/ACE>). For the energy interval 94-125 MeV/nuc we use the O
86 nuclei intensities at V1 and V2 as a proxy for the C nuclei since this energy interval is beyond
87 the range for C. At this energy it has been shown (e.g., the ACE web-site) that the C/O ratio is =
88 1.05 ± 0.05 for a wide range of modulation levels, therefore this is a strong proxy. As a result we
89 can use energy intervals for C nuclei on V1 and V2 that almost exactly match those available
90 from ACE from 20 to 125 MeV/nuc.

91 At the beginning of the recovery time period the intensity of 56-125 MeV/nuc Carbon at
92 V1 was ~ 3 -4 times that at the Earth. This is a measure of the overall interplanetary gradient at
93 this energy between 1 and ~ 94 AU, the location of V1 at that time. By 2010.5 this intensity ratio
94 is reduced to ~ 2 implying that the intensity changes between 2004 and 2010.5 at the Earth are
95 greater than those at V1. For 20-56 MeV/nuc particles these ratios at 2004 and 2010.5 are ~ 3
96 and 2 respectively. These changing intensity ratios at both energies are shown in Figure 2.

97 In Figure 3 we show the 56-125 MeV/nuc data at the Earth superimposed on the data at
98 V1 (with different intensity scales), with the data at Earth delayed to account for the solar wind
99 propagation time from the Earth to V1. This delay time is varied from 0.5 to 1.5 years in 26 day

100 increments and the correlation coefficient rapidly improves, reaching a maximum value 0.923 for
 101 time delays between 0.86 and 0.93 years. This correspondence of time histories is remarkable
 102 considering the 100 AU difference in the radial location of the spacecraft.

103 This correlation throughout the heliosphere is also evident in Figures 4A and 4B which
 104 shows the intensities at each energy at V1 and V2 vs. those at the Earth, with a delay ~ 0.89 yrs.

105 We seek to fit the data in Figures 4A and 4B and to interpret it using a simple global
 106 modulation model in conjunction with a realistic interstellar (IS) C spectrum. The goal of this
 107 calculation is to predict the absolute intensities at all three locations and also the changing ratios
 108 of intensities at V1 beyond the HTS, at V2 mainly just inside the HTS, and the intensities at the
 109 Earth vs. time as given by Figures 1A and 1B and also Figures 4A and 4B. In addition the
 110 calculation should predict the average slopes of the regression lines between V1 and V2 and the
 111 Earth data at each location and at each energy as plotted in Figures 4A and 4B.

112 **The Cosmic Ray Transport Equation in the Heliosphere**

113 Here we use a simple spherically symmetric quasisteady state no-drift transport model for
 114 cosmic rays in the heliosphere. While this simplified model obviously cannot fit all types of
 115 observations it does provide a useful insight into the inner heliospheric/outer heliospheric
 116 modulation and helps to determine which aspects of this modulation need more sophisticated
 117 models for their explanation. The numerical model was originally provided to us by Moraal
 118 (2003, private communications) and is similar to the model described originally in Reinecke,
 119 Moraal and McDonald, 1993, and in Caballero-Lopez and Moraal, 2004, and also to the
 120 spherically symmetric transport model described by Jokipii, Kota and Merenyi, 1993 (Figure 3
 121 of that paper). The basic transport equation is (Gleeson and Urch, 1971);

$$122 \quad \frac{\partial f}{\partial t} + \nabla \cdot (C \nabla f - K \cdot \nabla f) + \frac{1}{3p^2} \frac{\partial}{\partial p} (p^2 \mathbf{V} \cdot \nabla f) = Q$$

123 Here f is the cosmic ray distribution function, p is momentum, \mathbf{V} is the solar wind velocity,
 124 $K(r,p,t)$ is the diffusion tensor, Q is a source term and C is the so called Compton-Getting
 125 coefficient.

126 For spherical symmetry (and considering latitude effects to be unimportant for this
 127 calculation) the diffusion tensor becomes a single radial coefficient K_{rr} . We assume that this
 128 coefficient is separable in the form $K_r(r,P) = \beta K_1(P) K_2(r)$, where the rigidity part, $K_1(P) \equiv K1$
 129 and radial part, $K_2(r) \equiv K2$. The rigidity dependence of $K_1(P)$ is assumed to be $\sim P$ above a low

130 rigidity limit P_B . The units of the coefficient K_{tr} are in terms of the solar wind speed $V =$
 131 $4 \cdot 10^2 \text{ km s}^{-1}$, the distance $1 \text{ AU} = 1.5 \times 10^8 \text{ Km}$, so $K_{tr} = 6 \cdot 10^{20} \text{ cm}^2 \cdot \text{s}^{-1}$ when $K1 = 1.0$.

132 Based on our earlier studies using He and H nuclei (Webber, et al., 2011a, b) we consider
 133 a two zone heliosphere (e.g., Jokipii, Kota and Merenyi, 1993). In this case the inner zone
 134 extends out to 90 AU, the average distance to the HTS. In this inner region $V=400 \text{ km s}^{-1}$ and
 135 the diffusion parameters $K1$ and $K2$ are determined in our approach by a fit to the cosmic ray
 136 data being compared (the Earth and V2).

137 The outer zone extends from 90 AU to ~ 120 AU, the approximate distance to the
 138 heliopause (HP) or an equivalent “outer boundary” and essentially encompasses the heliosheath.
 139 In this region V is taken to be 130 km s^{-1} (from V2 measurements, Richardson, et al., 2008) and
 140 the diffusion parameters are $K1H$ and $K2H$, which are different from those in the inner
 141 heliosphere, and again determined by the cosmic ray intensity changes at V1. The distance to the
 142 HP and the source spectrum are important in this calculation.

143 For the LIS Carbon spectrum we use the recent spectrum of Webber and Higbie, 2009.
 144 This spectrum can be approximated to an accuracy \sim few % above $\sim 100 \text{ MeV/nuc}$ by

$$145 \quad \text{Carbon FLIS} = (0.0456/T^{2.76}) / (1.63/T^{0.12} + 6.10/T^{1.19} + 1.07/T^{2.85} + 0.12/T^{4.40})$$

146 where T is in GeV/nuc . At the average energies of 92 and 38 MeV/nuc for the energy intervals
 147 used for the Carbon data, this equation gives input intensities of 2.05×10^{-2} and 1.15×10^{-2}
 148 $\text{p/m}^2 \cdot \text{sr} \cdot \text{s} \cdot \text{MeV/nuc}$ at the boundary of 120 AU. The measured intensities at V1 at 2010.5 are 1.73
 149 and 0.75 at these energies (see Figures 1A and 1B).

150 For a simple one zone heliosphere with a boundary at 120 AU, a 1st step is to fit the
 151 measured intensities at the Earth to determine the overall modulation. The measured intensities
 152 at the Earth are 0.075 and 0.039 in the above units at the two average energies of 92 and 38
 153 MeV/nuc in late 2009 (see ACE web site). For $K2=0$ these intensities at the Earth can be fit with
 154 a value of $K1 = 160$. This value for $K1$ corresponds to a modulation potential = 248 MV in the
 155 equivalent force field approximation where the modulation potential is defined as

$$156 \quad \phi = \int_1^{R_B} \frac{V dr}{3K1}$$

157 (see Caballero-Lopez and Moraal, 2004).

158 We note that this modulation potential is much lower than the average value of ~ 400 -500
 159 MV observed at previous sunspot minima in the modern era from 1950 (see e.g., Webber and

160 Higbie 2010), in keeping with the unusually high intensities observed at this time (McDonald,
161 Webber and Reames, 2010; Mewaldt, et al., 2010). In fact the low modulation potential that we
162 now find using Carbon nuclei is very similar to the modulation potential of 235 MV obtained by
163 Mewaldt, et al, 2010, using ACE measurements of C and Fe nuclei at the Earth also in late 2009.
164 In their calculations, Mewaldt, et al., 2009, used the George, et al., 2009, LIS Carbon spectrum
165 which differs only slightly from the Webber and Higbie, 2009, LIS spectrum above ~ 100
166 MeV/nuc.

167 In Figure 6 we show the observed spectrum of C nuclei at V1, V2 and the Earth at two
168 times. One is at the beginning of the time interval of interest, at 2005.0. The second is at the end
169 of the time interval at 2010.5. All of these spectra are consistent with spectral slopes = 1.0 for
170 energies below ~ 100 MeV/nuc. This Figure also illustrates the reasons why the apparent
171 modulation potential at the Earth is so low in 2010. It is because the IS spectra themselves for C
172 are also much lower than many of the earlier IS spectra that have been used (e.g., see Ngobeni
173 and Potgieter, 2011).

174 For a two zone model with the inner heliosphere boundary at the HTS (taken here to be at
175 90 AU) and the HP at 120 AU, we find that values of $K1=175$ (max) and 42 (min) and $K2 = 0$ in
176 the inner heliosphere and values of $K1H$ between 18 (max) and 10 (min), and $K2H=0$ with
177 $V=0.33$ in the outer heliosphere along with the IS spectrum given by the equation CARBON-
178 FLIS, we are able to fit the average Carbon data in both energy ranges at the Earth and at V1 and
179 V2 as shown in Figures 4A and 4B and Figures 5A and 5B. A graph of this diffusion coefficient
180 vs. time and rigidity is shown in Figure 5 of Webber, et al., 2011a, b.

181 The predicted V1 “fit lines” in Figures 4A and 4B lie an average of 5% above the data at
182 56-125 MeV/nuc and the fit is equally good for 20-56 MeV/nuc. None of the smoothed data
183 points in Figures 4A and 4B or the spectra in Figure 6 lie more than $\pm 15\%$ from the predicted
184 lines.

185 Note that the fits to the Carbon data is the generally good for V2 in contrast to the
186 calculations for He and H nuclei which require some form of an asymmetrical heliosphere along
187 with other effects to explain the V2 intensities which are at times equal to those at V1 (Webber,
188 et al., 2001a, b). The calculation for Carbon is for a spherical heliosphere with no N-S
189 asymmetry included. The Carbon data reflect the spectrum in the “adiabatic” energy range
190 where the spectra are expected to be $\sim E^{1.0}$. Indeed the ratio of the intensities in the 56-125 to 20-

191 56 MeV/nuc intervals remains essentially constant throughout the entire recovery time period
 192 from 2005 to 2010 at all three locations, V1, V2 and the Earth. This behavior is shown in Figure
 193 7 for the 20-56 to 56-125 MeV/nuc ratio at V1. The average value for this ratio between 2004
 194 and 2010 is 0.42 ± 0.02 and is the same for all three locations V1, V2 and the Earth. The ratio of
 195 the average energies of the two intervals is 0.41. This intensity ratio remains nearly constant
 196 with time although the intensities increase by a factor of ~ 3 at V1 (and V2) between 2004 and
 197 2010. This ratio also is nearly the same at the Earth and at V1 and V2 even though, as we have
 198 shown in Figure 2, the intensities at these locations differ by a factor of 2-4. This constancy
 199 implies that over this entire time interval and the large range of “effective” modulation levels and
 200 radial distances from the Earth to V1 and V2, the modulation “acts” to first order like an
 201 adiabatic modulation process similar to that resulting from a simple “force field” modulation of
 202 the type first described by Gleason and Axford, 1968.

203 Thus, in summary, we have the situation where (1): The magnitude of the diffusion
 204 coefficient in the outer zone (heliosheath) is ~ 5 -10 times smaller than that in the inner zone. (2):
 205 During the intensity recovery from 2004-2010 the diffusion coefficient in the inner zone
 206 increases by a factor ~ 4 whereas in the outer zone this increase is only a factor ~ 1.80 . (3): The
 207 modulation in this lower energy region below ~ 100 MeV/nuc acts like a simple “force field”
 208 modulation where the energy spectra of Carbon nuclei, dj/dE , are $\sim E$ throughout the radial range
 209 from ~ 1 -110 AU and for all modulation levels.

210 **Summary and Conclusions**

211 The recovery of the intensity of ~ 20 -125 MeV/nuc cosmic ray Carbon nuclei has been
 212 followed between 2004-2010 at the Earth using the ACE spacecraft and also at V1 and V2 in the
 213 outer heliosphere and in the case of V1, beyond the HTS. The correlation of the intensity
 214 changes at the Earth and V1 in the outer heliosphere (correlation coefficient =0.921), ~ 100 AU
 215 apart in radial distance, is remarkable after accounting for a time delay ~ 0.9 year due to the solar
 216 wind propagation. The relative intensities measured at V1, V2 and at the Earth as well as the
 217 slope of the regression lines between the measurements at the Earth and at V1 and V2 place
 218 limits on the amount of solar modulation in the inner and outer heliosphere and also on the local
 219 IS Carbon spectrum. It is found that the data for Carbon nuclei can be reproduced by a simple
 220 two zone heliosphere where the intensity changes are due to changes in the cosmic ray diffusion
 221 coefficient K in each zone. In the inner zone, out to the HTS assumed to be at 90 AU, the value

222 of K is quite large but varies by a factor ~ 4 from the minimum to maximum modulation in this
223 part of the solar 11-year cycle. In the outer zone from ~ 90 -120 AU, essentially in the
224 heliosheath, the value of the diffusion coefficient is much smaller, by a factor ~ 5 -10 and varies
225 by a factor ~ 1.80 from minimum to maximum modulation. The same set of diffusion
226 coefficients and their variations with rigidity and time that have been used to explain the 150-250
227 MeV He and H nuclei intensity changes measured at V1, V2 and the Earth during the same time
228 interval (Webber, et al., 2011a, b) have been used in the Carbon analysis.

229 For V2 these same diffusion coefficients can also explain the intensity variations of
230 Carbon during the recovery between 2004 and 2010. This is in contrast to both the V2 Helium
231 and H nuclei intensity variations during this time period which require an asymmetric squashed
232 heliosphere to explain the H nuclei data plus additional time dependent asymmetric effects to
233 describe the fact that the He nuclei intensities at V2, are at times, equal to those at V1 much
234 further out in the heliosphere.

235 The Carbon spectrum that is observed throughout this time period as well as the relative
236 modulation at the Earth, V1 and V2 can be described by a simple force field type of modulation,
237 with the spectra at energies from ~ 20 -100 MeV/nuc being described as $dj/dE \sim E$ spectra over the
238 entire radial distance range and at all modulation levels (see Figure 6).

239 The details of the fit to the data beyond the HTS depend on the values of the local
240 interstellar spectrum (LIS) used as an input to the modulation calculation and also the location of
241 the HP or boundary of the modulation region. For the LIS intensities of C nuclei used in this
242 paper, which are lower than many earlier estimates, the data can be well fit for HP distances in
243 the range of 120-130 AU with a simple two zone symmetric heliosphere. The heliosheath region
244 and the lower energy interstellar Carbon spectrum itself below ~ 125 MeV/nuc will be mapped in
245 more detail as V1 continues to move outward in the heliosphere and the intensities continue to
246 increase towards the LIS value.

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249 <http://voyager.gsfc.nasa.gov> and <http://www.srl.caltech.edu/ACE/>.

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288 two zone heliosphere,
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Figure Captions

290
291 **Figure 1A:** 5 x 26-day running average of V1 and V2 and the 27 day average of ACE 56-125
292 MeV/nuc Carbon nuclei intensities near the Earth from 2004 to 2010.5. ACE data is
293 delayed by 0.89 year to account for inner-outer heliosphere delay in modulation due to solar
294 wind propagation time.

295 **Figure 1B:** 5 x 26-day running average of V1 and V2 and the 27 day average of ACE 20-56
296 MeV/nuc Carbon nuclei intensities near the Earth from 2004 to 2010.5. ACE data is
297 delayed by 0.89 year to account for inner-outer heliosphere delay in modulation due to solar
298 wind propagation time.

299 **Figure 2:** Ratio of V1 to ACE intensities for 56-125 and 20-56 MeV/nuc (in red) Carbon nuclei
300 from 2004 to 2010.5 (Earth data delayed by 0.89 year).

301 **Figure 3:** The V1 data in Figure 1 superimposed on the ACE data at the Earth for 56-125
302 MeV/nuc Carbon delayed by 0.89 year (with different intensity scales on the left and right
303 axis). This figure shows the high level of correlation between intensity changes at the Earth
304 and in the outer heliosphere during this time period.

305 **Figure 4A:** Regression plot of the intensities of 56-125 MeV/nuc Carbon nuclei at V1 and V2
306 vs. the intensities at the Earth delayed by 0.89 year.

307 **Figure 4B:** The same as Figure 4A except for 20-56 MeV/nuc Carbon nuclei.

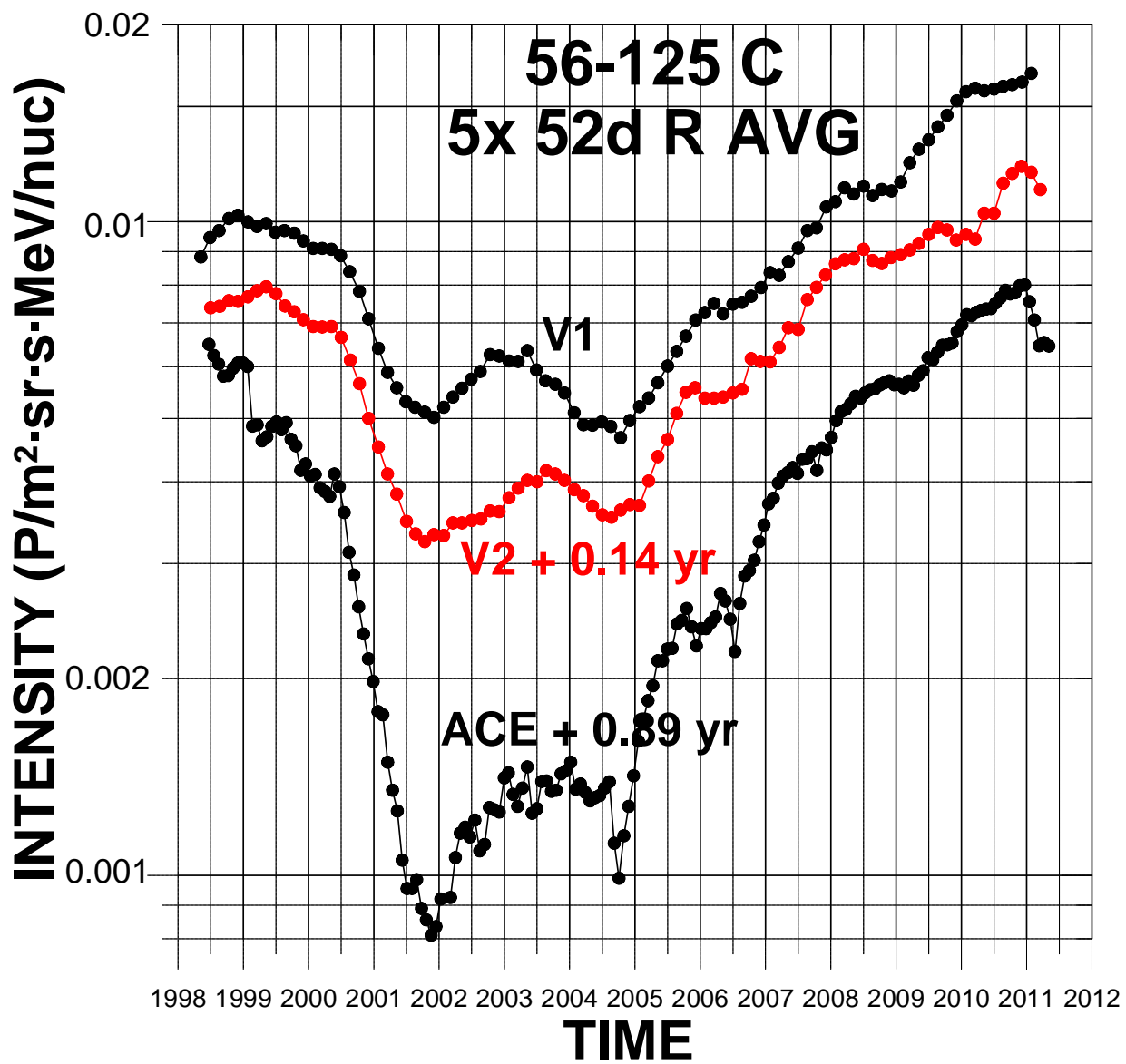
308 **Figure 5A:** Data in Figure 4A superimposed on predictions of a two zone spherically symmetric
309 heliospheric model, $R_B = 120$ AU.

310 **Figure 5B:** Data in Figure 4B superimposed on predictions of a two zone spherically symmetric
311 heliospheric model, $R_B = 120$ AU.

312 **Figure 6:** The spectra of Carbon nuclei at V1, V2 and the Earth, at 2005.0 and 2010.5. Note the
313 similarity of all spectra to a $dj/dE \sim E$ spectrum at energies less than 100 MeV/nuc. The
314 estimated IS Carbon spectra from Webber and Higbie, 2009, and George, et al., 2009 are
315 also shown.

316 **Figure 7:** Ratios of Carbon intensities in the 20-56 and 56-125 MeV/nuc energy intervals
317 between 1998 and 2010, observed at V1. The expected value of 0.41 for a $dj/dE \sim E$
318 spectrum is shown as a horizontal solid line. The values of the ratios at V2 and also at the
319 Earth (ACE) are very similar and are not plotted.

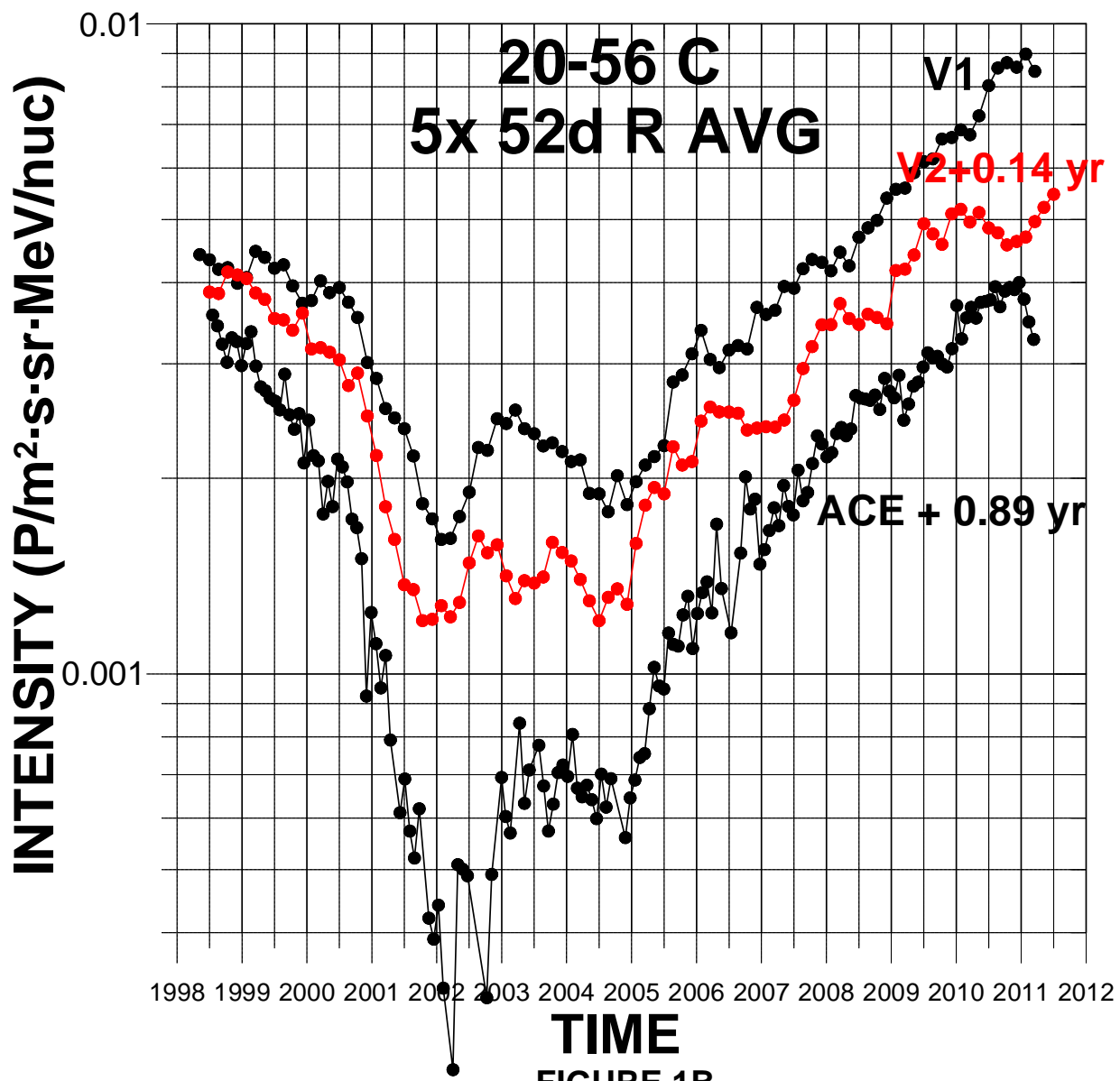
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FIGURE 1A



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FIGURE 1B

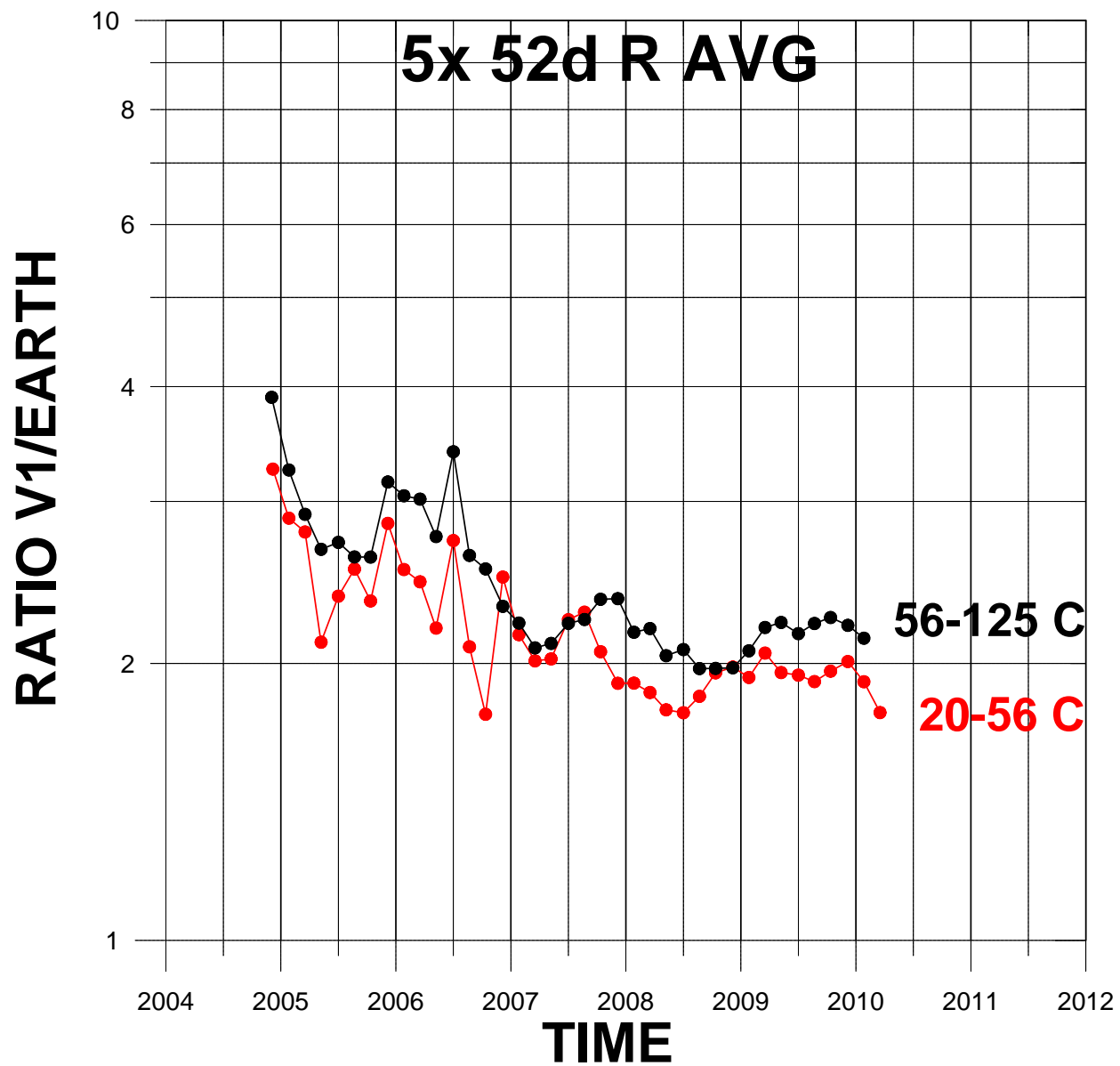


FIGURE 2

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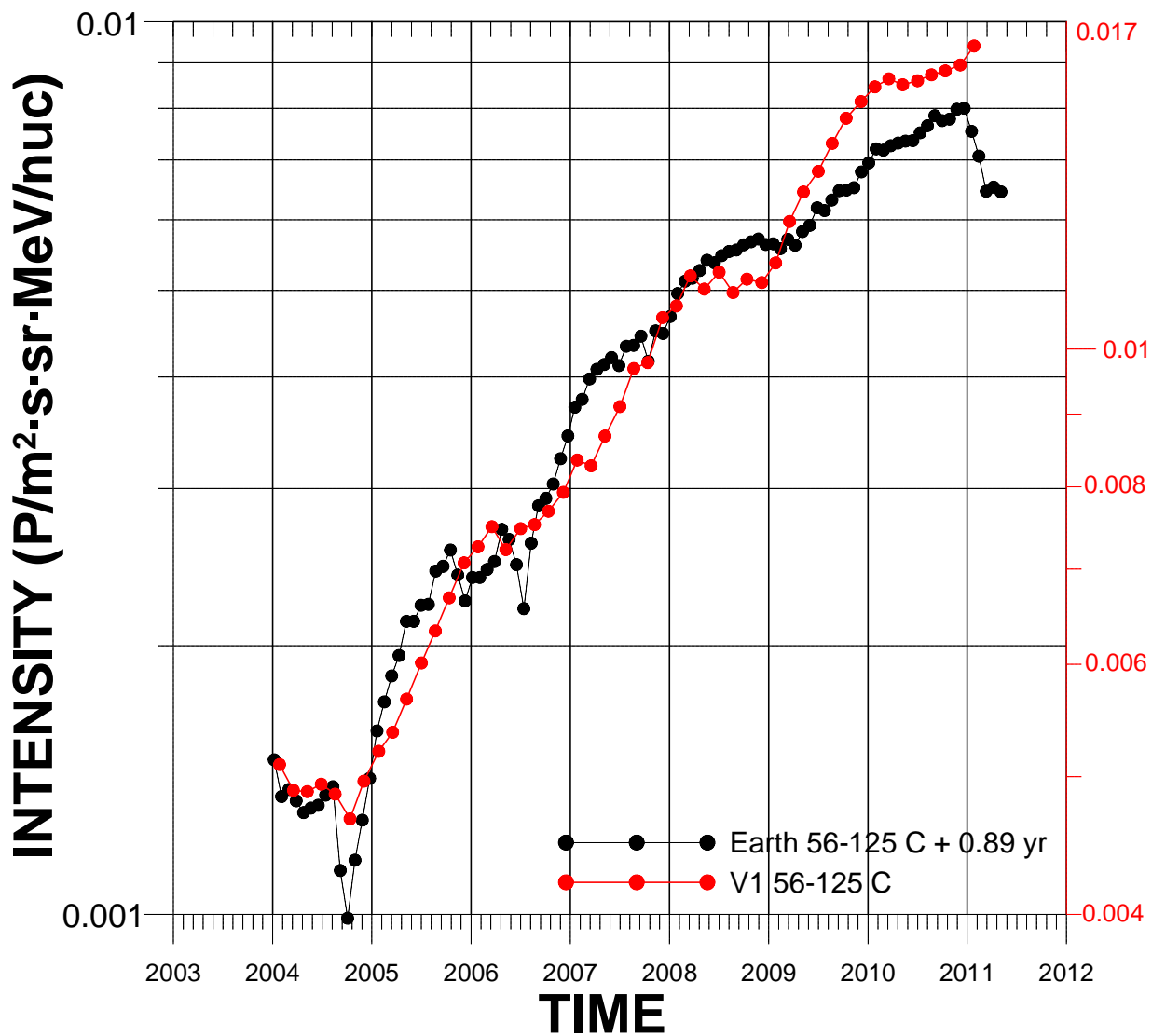


FIGURE 3

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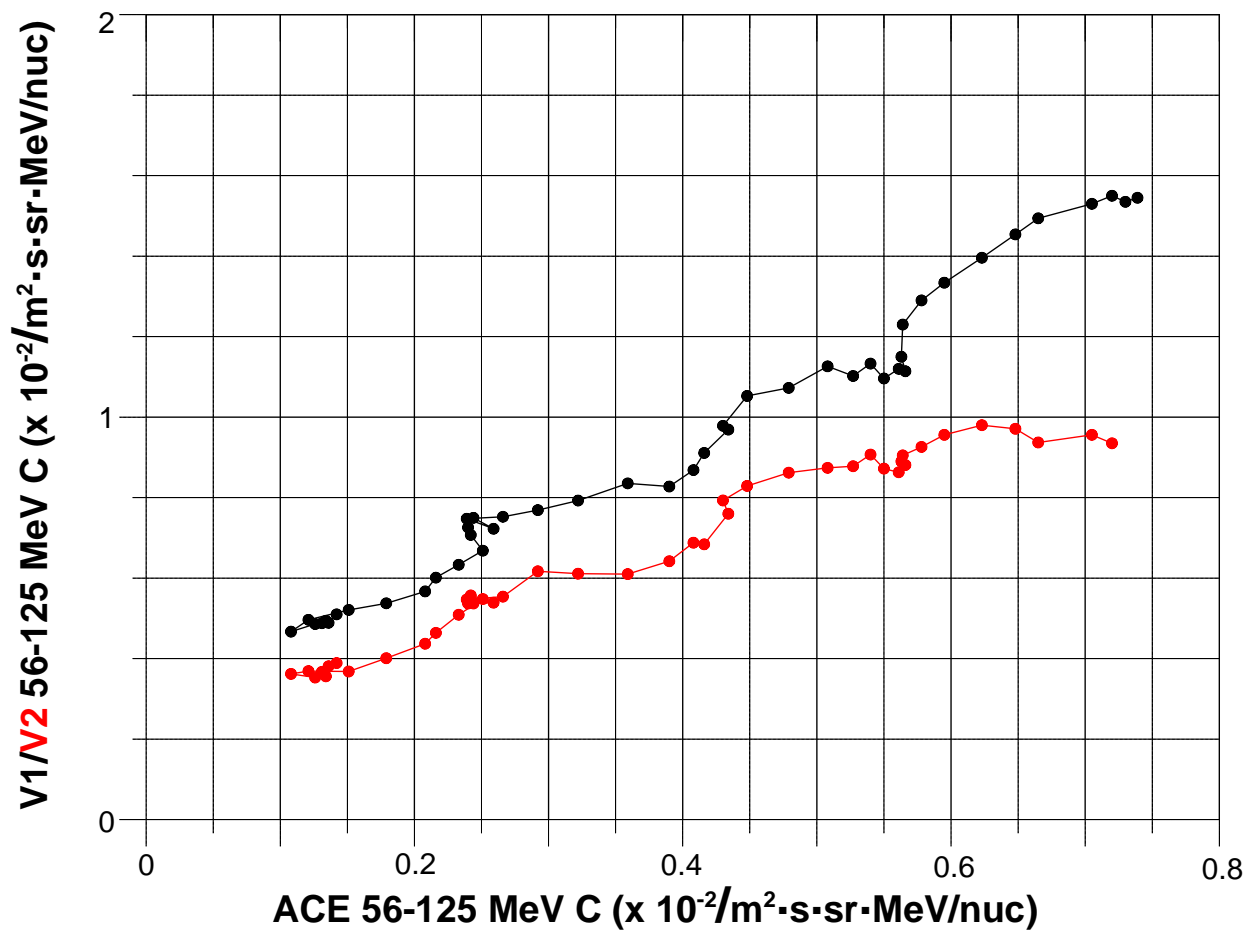


FIGURE 4A

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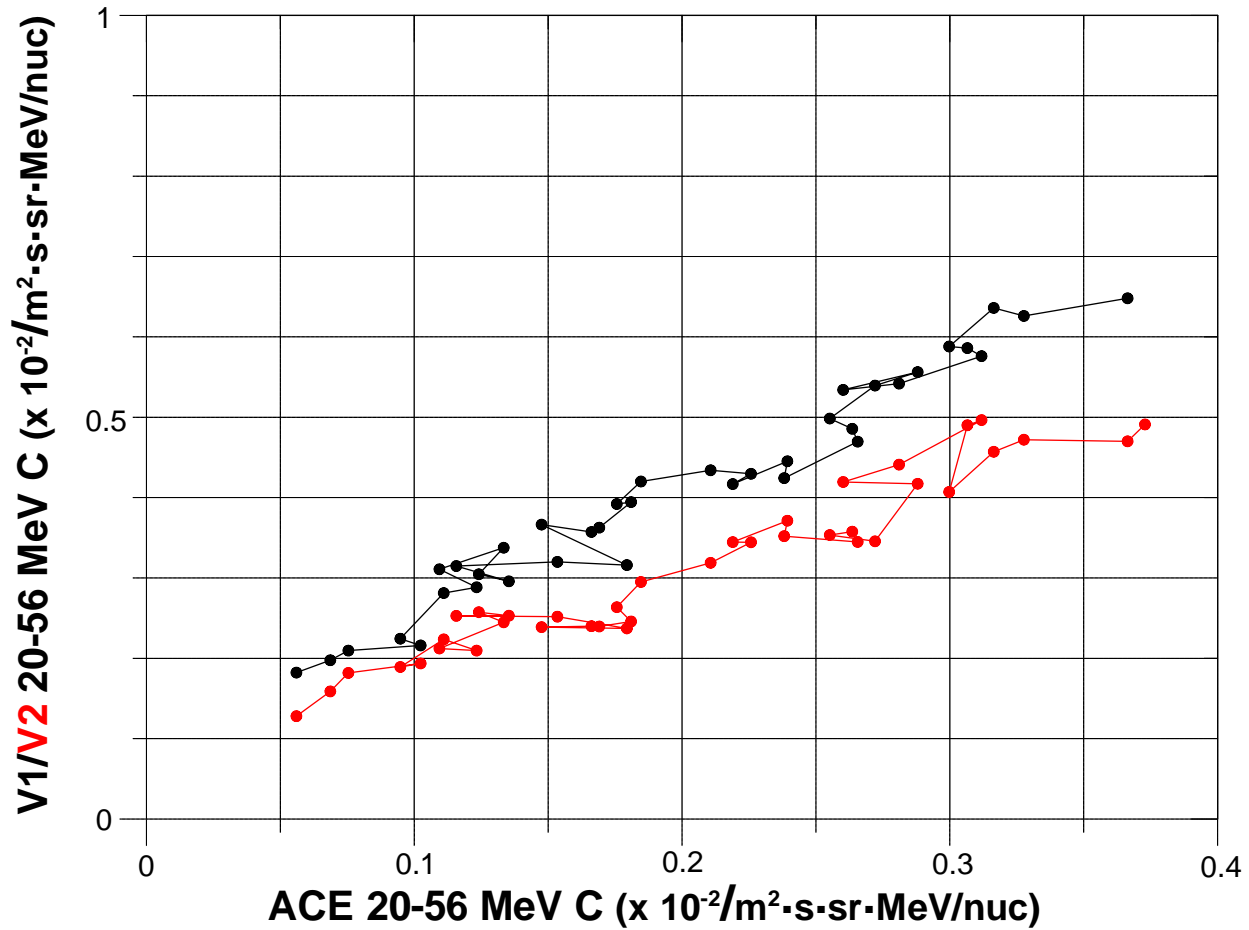


FIGURE 4B

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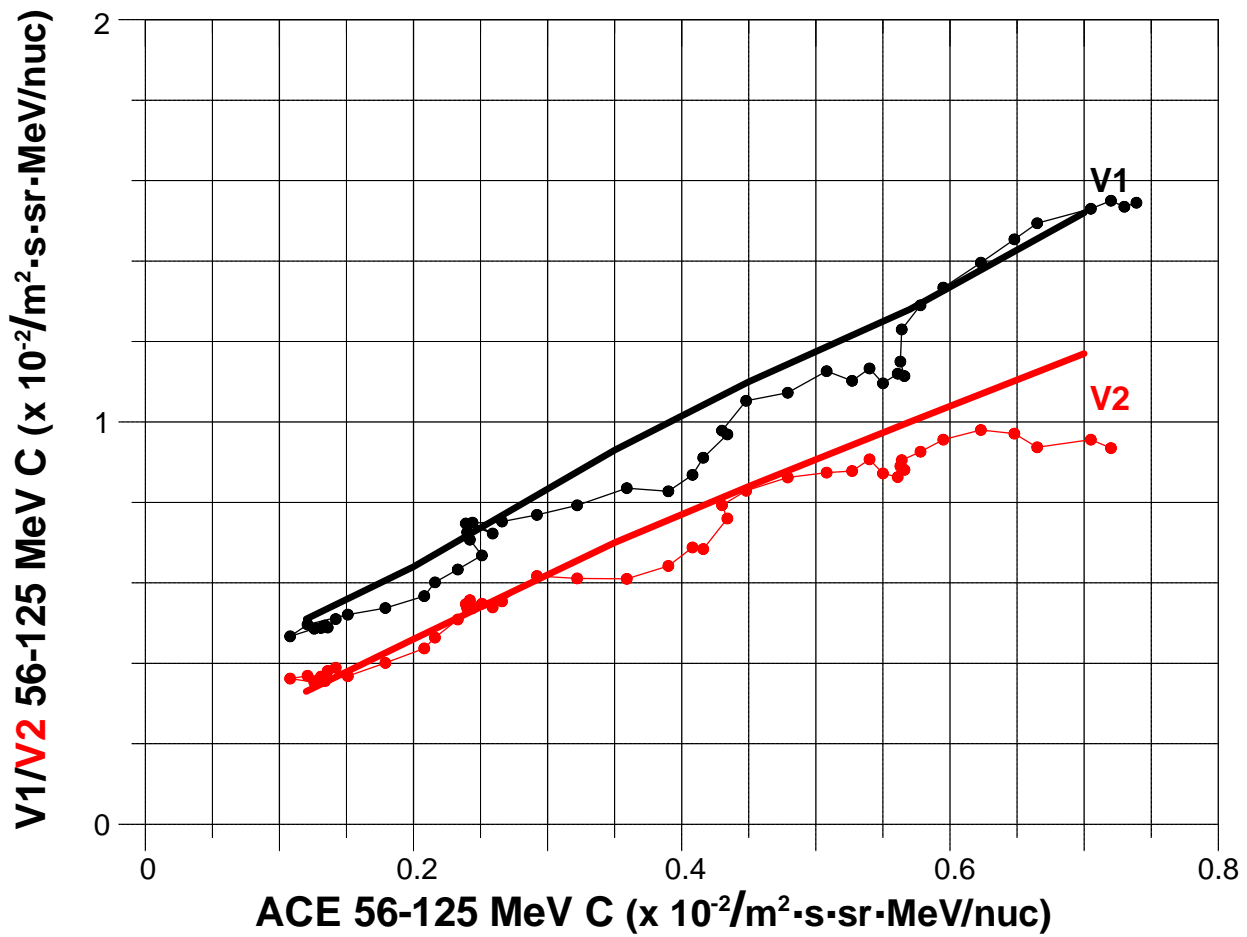


FIGURE 5A

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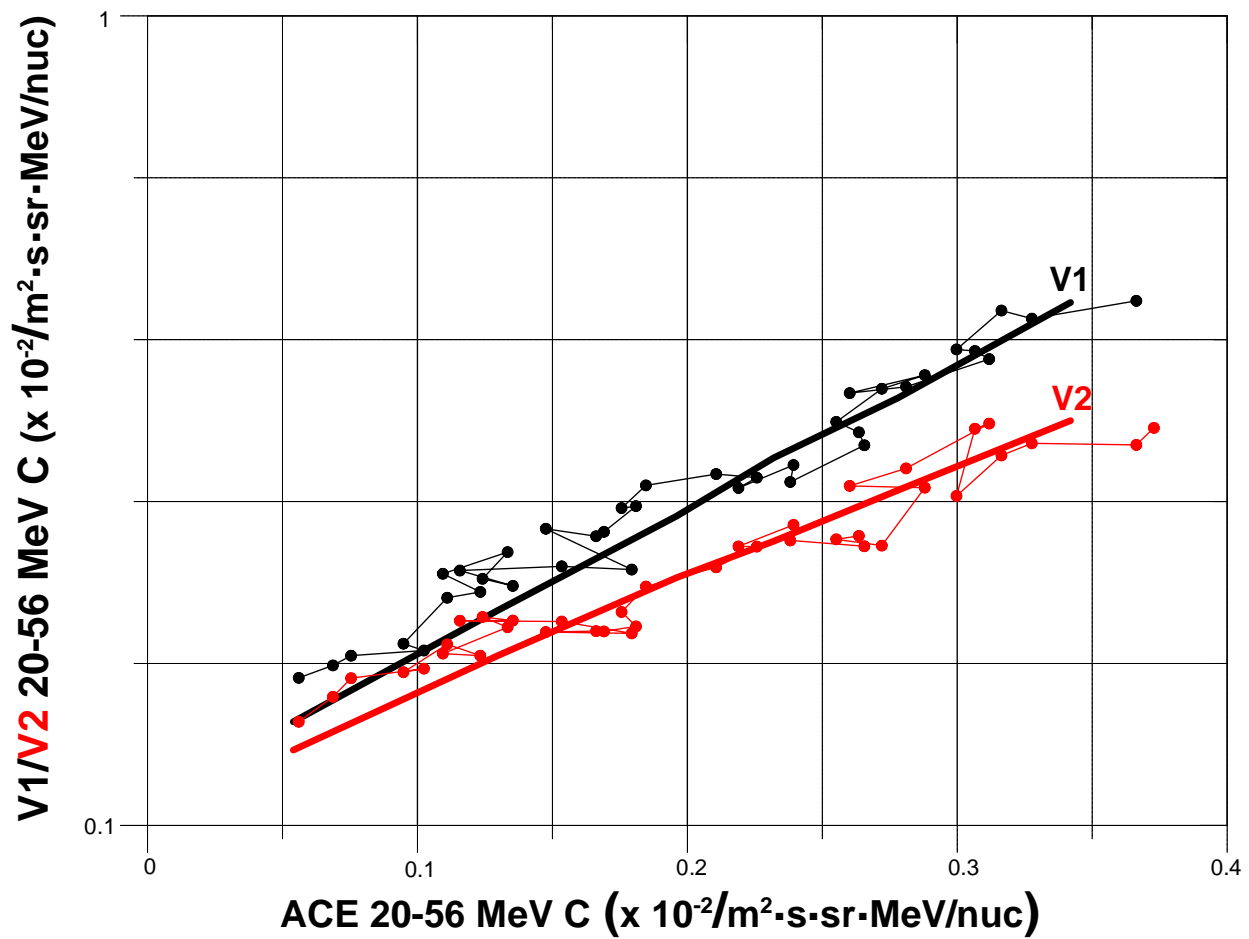


FIGURE 5B

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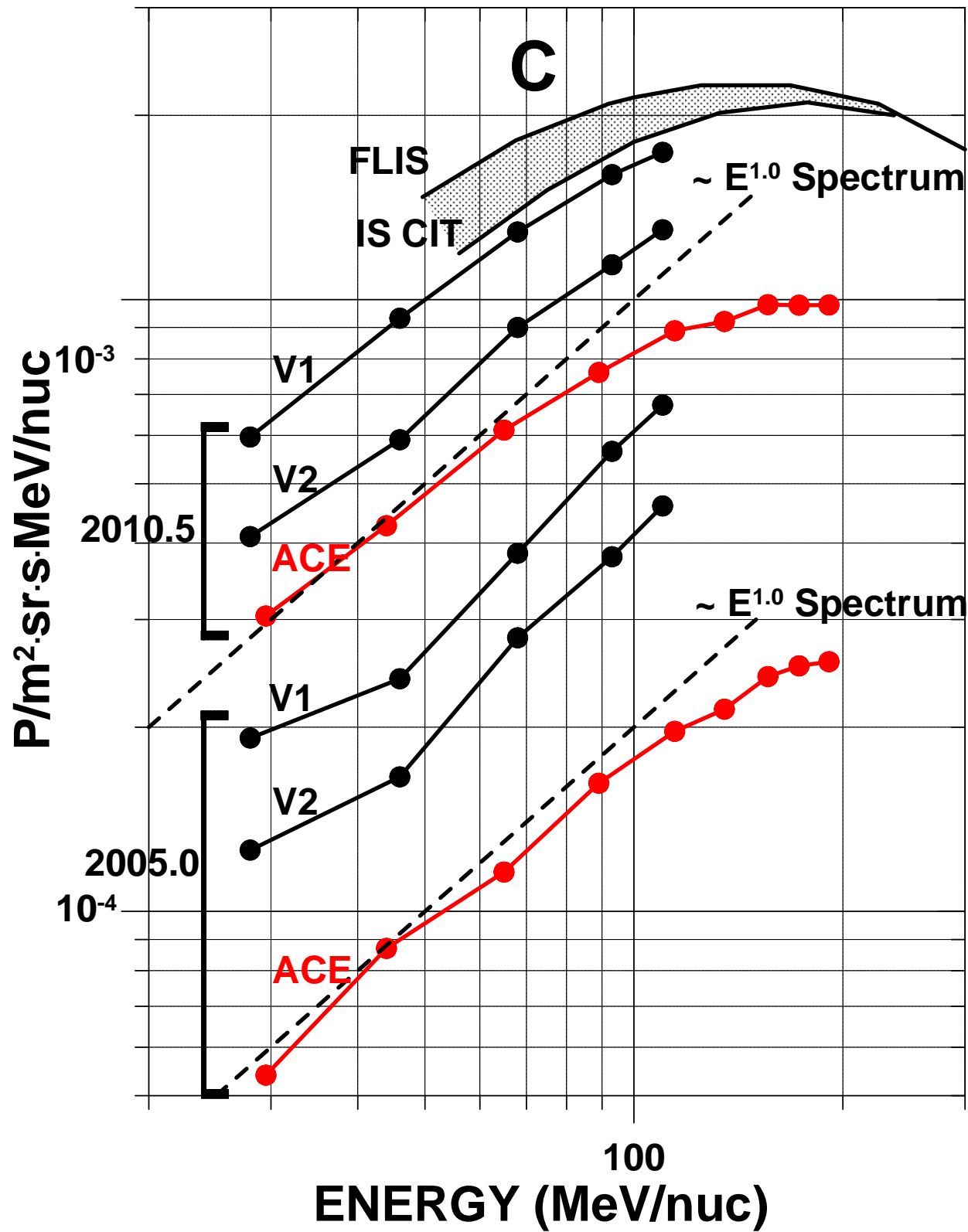
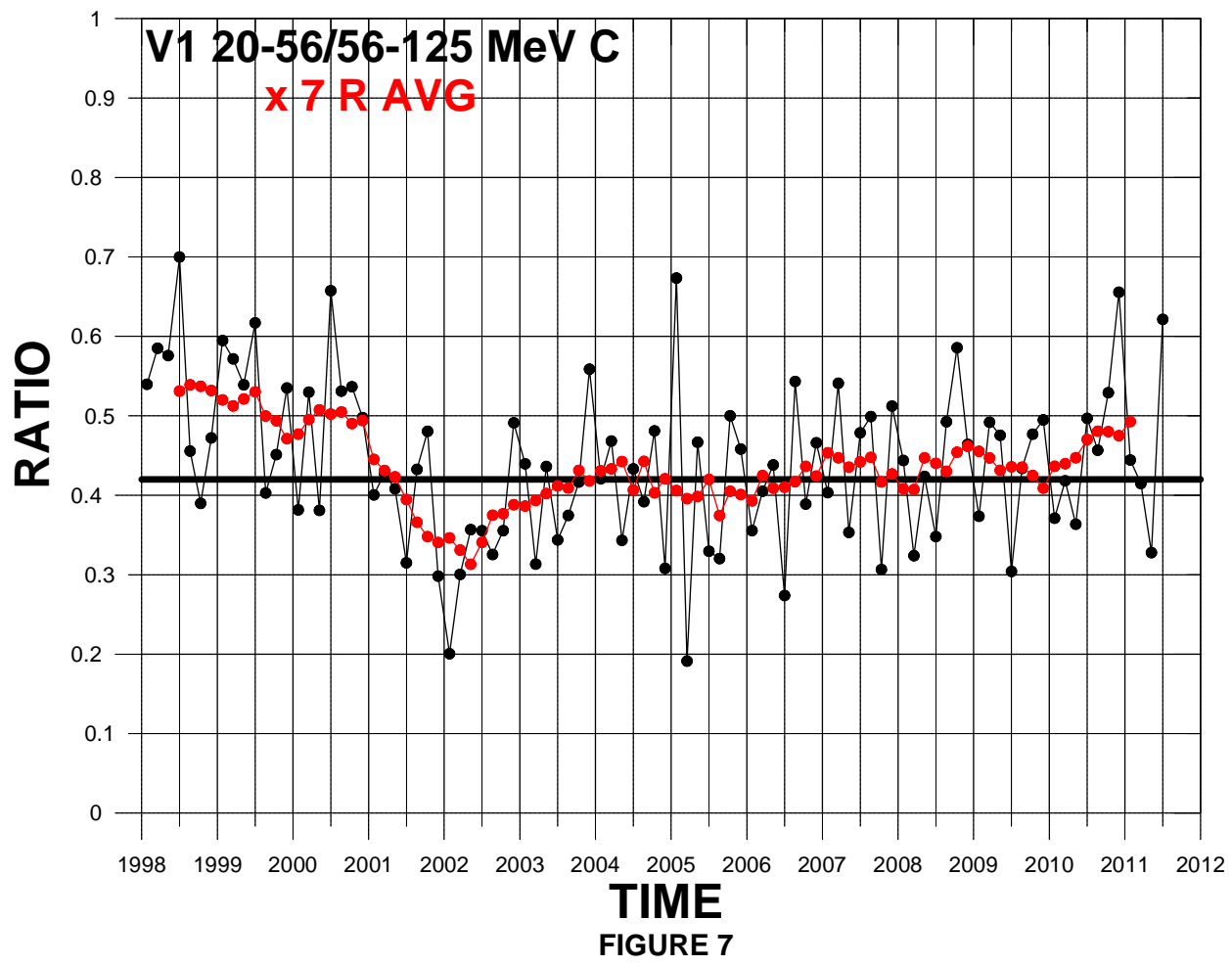


FIGURE 6

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