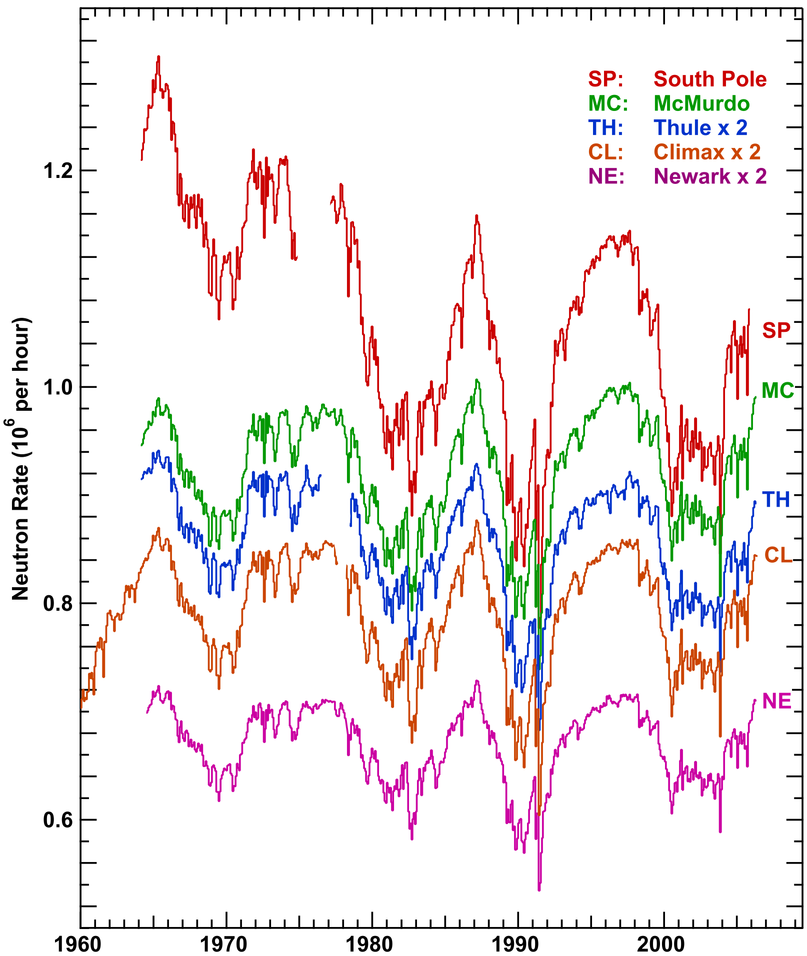

Figure 1. The count rate recorded by a neutron monitor at South Pole displays a steady long-term downtrend. To the best of our knowledge a downtrend of this magnitude has not been observed by any other neutron monitor that has been in operation over a comparable period. South Pole data are shown with the standard IGY normalization (see section 3), which may exaggerate the size of the decline. Shown are 27-d means. Statistical errors are negligible. Station information is presented in Table 1.

is both at high latitude (effectively zero geomagnetic cutoff) and at high altitude (2820 m; see Table 1 for altitudes and cutoffs of stations discussed in this article). South Pole therefore has greater sensitivity to the low end of the primary energy spectrum than a high-latitude monitor at sea level.

[8] The effect is illustrated in Figure 2, which displays the differential and integral rigidity responses at three atmospheric depths: 690 g cm^{-2}, which is representative of South Pole (red curves), 823 g cm^{-2}, which is representative of Mt. Washington (blue curves), and 1033 g cm^{-2} (black curves), which is representative of sea level (e.g., McMurdo). The integral rigidity response represents the fraction of the total neutron monitor count rate attributable to cosmic rays lower than a certain rigidity shown as the abscissa. In each case results are shown both for a Galactic cosmic ray primary spectrum under solar minimum conditions (solid lines) and under solar maximum conditions (dashed lines). Figure 2c is simply an expansion of Figure 2b with a linear abscissa. These curves were computed from response and yield functions derived by *Nagashima et al.* [1989] from a large set of available latitude surveys.

[9] The strongest differentiation between the South Pole and McMurdo energy responses occurs at the very low end of the neutron monitor energy range. As a concrete illustration, suppose the solid curves in Figure 2c are representative of 1997. If we then double the intensity of the primary spectrum below 3.4 GV, this would produce about an 8% increase in the South Pole count rate, consistent with the 1965 count rate. This same doubling would produce an approximately 4% increase at sea level in 1965 relative to 1997, and an approximately 6% increase in the Mt. Washington neutron rate.

Table 1. Altitudes and Cutoffs of Stations[a]

	Altitude, m	1965 Cutoff, GV	1995 Cutoff, GV
South Pole	2820	0.07	0.05
McMurdo	48	0.00	0.00
Thule	26	0.00	0.00
Climax	3400	3.00	2.93
Mt. Washington	1909	1.30	1.58
Newark	50	1.95	2.21

[a]The 1965 and 1995 cutoffs are from *Shea and Smart* [2001].

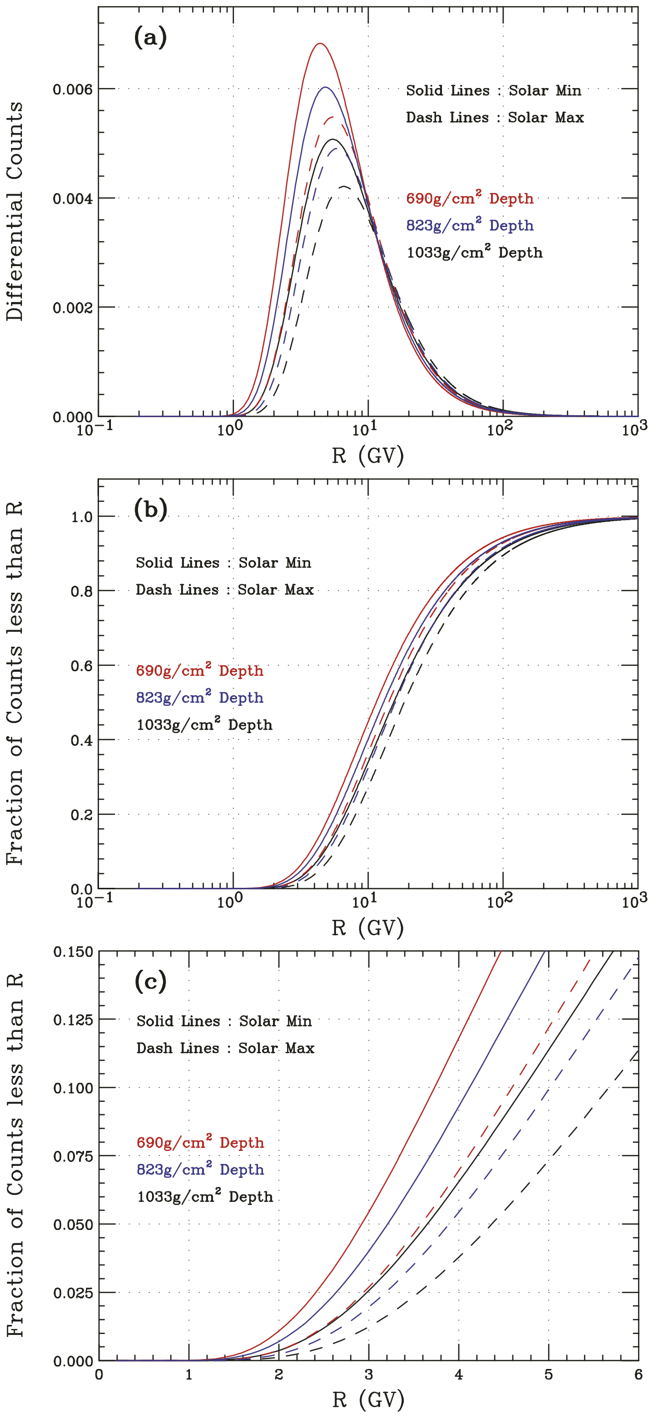

Figure 2. Owing to its high-altitude polar location, the South Pole neutron monitor has greater sensitivity to the low end of the neutron monitor energy range than a monitor at sea level. Shown are (a) the differential response as a function of rigidity, (b) the integral response as a function of rigidity, and (c) an expanded view of the integral response at low rigidities. Curves compare the responses of monitors at 690 g cm^{-2} atmospheric depth (red curves are representative of South Pole), 823 g cm^{-2} atmospheric depth (blue curves are representative of Mt. Washington), and 1033 g cm^{-2} atmospheric depth (black curves are representative of sea level). Solid and dashed lines are for solar minimum and maximum conditions, respectively.

[10] In comparison, *Stozhkov et al.* [2000] report that numerous sea level monitors display long-term changes of order -0.08% per year, which corresponds to a decline of 2.5% over 32 years. Thus this observed trend at sea level is in the same direction as the South Pole decline, but is somewhat smaller than expected (i.e., 4%) based on our computation using the *Nagashima et al.* [1989] response function.

[11] The high-altitude station on Mt. Washington presents a greater problem. It should have observed an approximately 6% decline from the 1965 cosmic ray maximum to the 1997 maximum, but instead the two maxima are at practically the same level [see *Lockwood et al.*, 2001, Figure 1]. This is all the more puzzling, in that the Mt. Washington decline of 0.02%/a is the least among 12 neutron monitors listed in the work of *Stozhkov et al.* [2000, Table 1]. One difference between South Pole and Mt. Washington is that Mt. Washington has had an IGY monitor for its entire history, whereas South Pole had an IGY only until 1974. However, workers in the field generally consider IGY and NM64 monitors to have the same energy response (up to a constant factor). Further, the two monitors display dissimilar behavior even over the period to 1974, when both were IGY types.

[12] One way to reconcile the South Pole and Mt. Washington data would be to change the neutron monitor response functions in the critical low-rigidity region, such that the response functions would show a greater differentiation between different altitudes, relative to that shown in Figure 2. We consider this a viable option (though unproven), because it is experimentally very challenging to measure the neutron monitor response in the $\sim$1–3 GV region. The reason is that neutron monitor count rates vary only slightly with geomagnetic cutoff in this region [e.g., *Clem and Dorman*, 2000], and determining the response depends upon measuring these slight variations very accurately. For instance, *Belov and Struminsky* [1997] obtained a significantly larger response than *Nagashima et al.* [1989] for energies below 0.8 GeV. On the basis of this alternative parameterization of the yield function, as reported in the work of *Clem and Dorman* [2000], we find that a doubling of the cosmic ray intensity below 3.4 GV would cause a 14% increase in the South Pole count rate, as compared to 8% expected from the *Nagashima et al.* [1989] parameterization. Clearly the uncertainties associated with response functions are considerable at these low energies.

3. IMP-7 and IMP-8 Data: Renormalization of the South Pole IGY Monitor

[13] The previous section suggests that the most likely source of the South Pole decline is a change in the cosmic ray primary spectrum in the $\sim$1–3 GV rigidity range. Fortunately, the long-running IMP-7 and IMP-8 spacecraft have cosmic ray instruments with an overlapping rigidity range [*Garcia-Munoz et al.*, 1977]. The energy channel termed HZHE measures cosmic ray heavy elements, specifically neon in the energy range 49–78 MeV/n up to iron in the range 242–417 MeV/n. The corresponding rigidity range is $\sim$0.6–1.8 GV.

[14] Figure 3 displays the IMP-7 and IMP-8 HZHE rate together with the South Pole neutron rate. Comparing solar minima (and thus cosmic ray maxima) the HZHE rate and

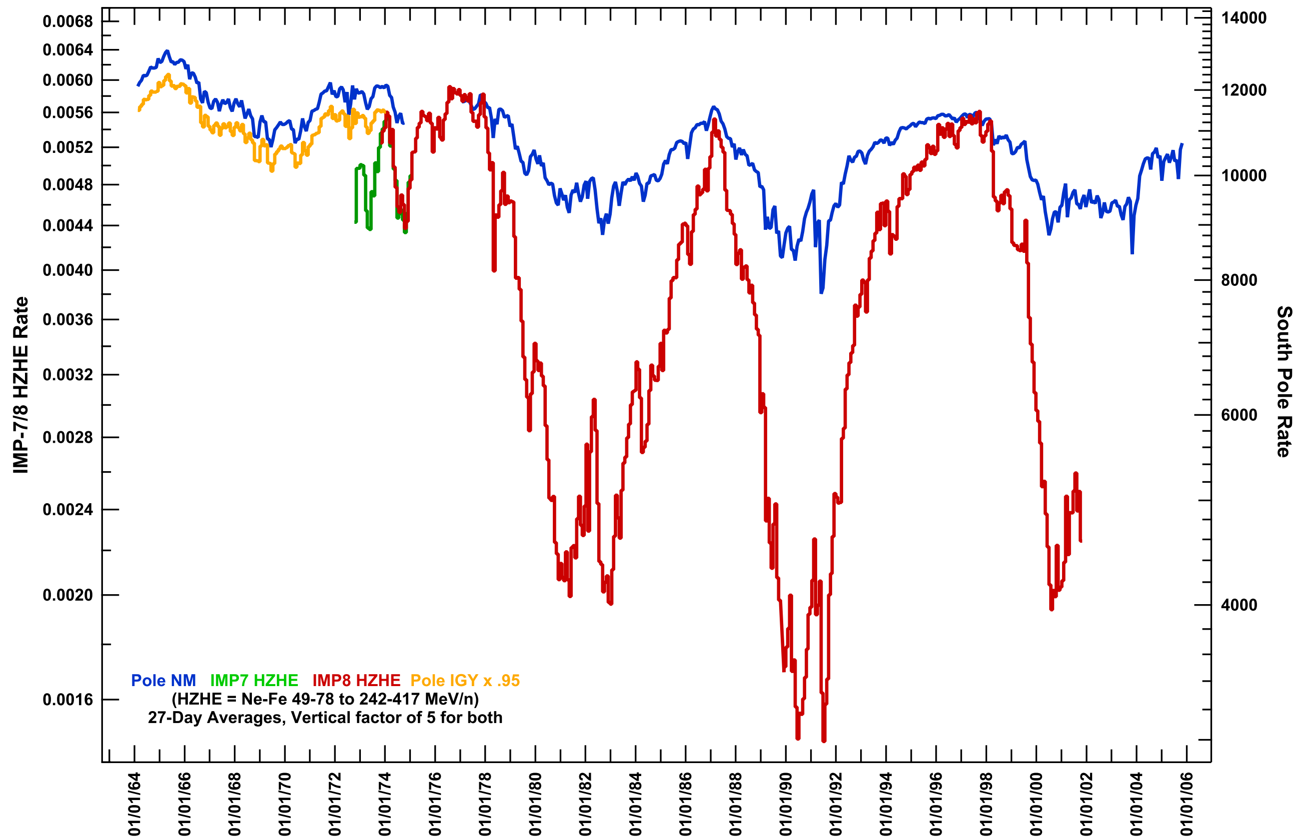

Figure 3. The IMP-7 (green curve) and IMP-8 (red curve) HZHE rate is compared with the South Pole neutron rate (blue and orange curves). The HZHE rate measures heavy cosmic rays with rigidity in the range ~0.6–1.8 GV, overlapping with the low end of the neutron monitor energy range. Blue curve shows South Pole NM64 (1977 and later) and IGY (1974 and earlier) data with the standard normalization. Orange curve shows IGY data with an alternate normalization suggested by this analysis.

South Pole neutron rate display similar downtrends. This lends confidence that the South Pole decline is real and is of extraterrestrial origin. (We do not mean to suggest that the South Pole decline is attributable to cosmic ray heavy elements. Rather, we regard HZHE as a proxy for protons and helium nuclei of similar rigidity.)

[15] The close tracking of HZHE and the South Pole neutron rate (under solar minimum conditions) provides an opportunity to reassess the normalization of the IGY monitor (1974 and earlier data) relative to the NM64 (1977 and later data). This normalization is necessary because the IGY monitor is a much smaller instrument than the NM64, with a much lower count rate per detector tube. The "standard" normalization factor we used in the past is to multiply the IGY count rate by 5.3 to make it consistent with the later NM64 data.

[16] Figure 4 displays a regression of the IMP-7 and IMP-8 HZHE rate against the South Pole NM64 rate (blue) and the IGY rate with the standard normalization (red). Although HZHE experiences a much larger amplitude of modulation than South Pole neutrons, all the NM64 data over 27 years cluster about a single regression line. While errors are not shown explicitly, they can be inferred from the amount of scatter, which, as expected, decreases during the higher-intensity periods near solar minimum.

[17] The IGY data, however, are clearly shifted off the NM64 regression line. Multiplying the (normalized) IGY data by a further factor of 0.95, as shown by the orange points, brings the IGY data onto the same regression line as the NM64 data. Consequently we adopt the hypothesis that the standard IGY data (i.e., with the standard normalization) multiplied by 0.95 provide a more reliable normalization of the IGY epoch to the NM64 epoch. (These data are archived at http://neutronm.bartol.udel.edu/. We will retain the standard (5.3X) normalization in the archived data, but will add a note suggesting that the factor of 0.95 be applied to the IGY data for long-term studies.)

[18] Figure 5 displays Bartels solar rotation averages of the South Pole neutron rate together with the McMurdo neutron rate. The IGY (pre-1975) data with the old normalization is shown by the blue curve and with the new normalization by the orange curve. Although a 5% reduction in the pre-1975 rates is substantial, this is clearly not enough to eliminate the long-term trend observed at South Pole. On the contrary, the new normalization has the effect of shifting the 1965 cosmic ray maximum onto the same trend line as the cosmic ray maxima of 1977, 1987, and 1997.

4. Could the South Pole Decline Be Instrumental?

[19] When a single neutron monitor displays a markedly different behavior than all others in the worldwide network, the concern naturally arises that the effect could be instru-

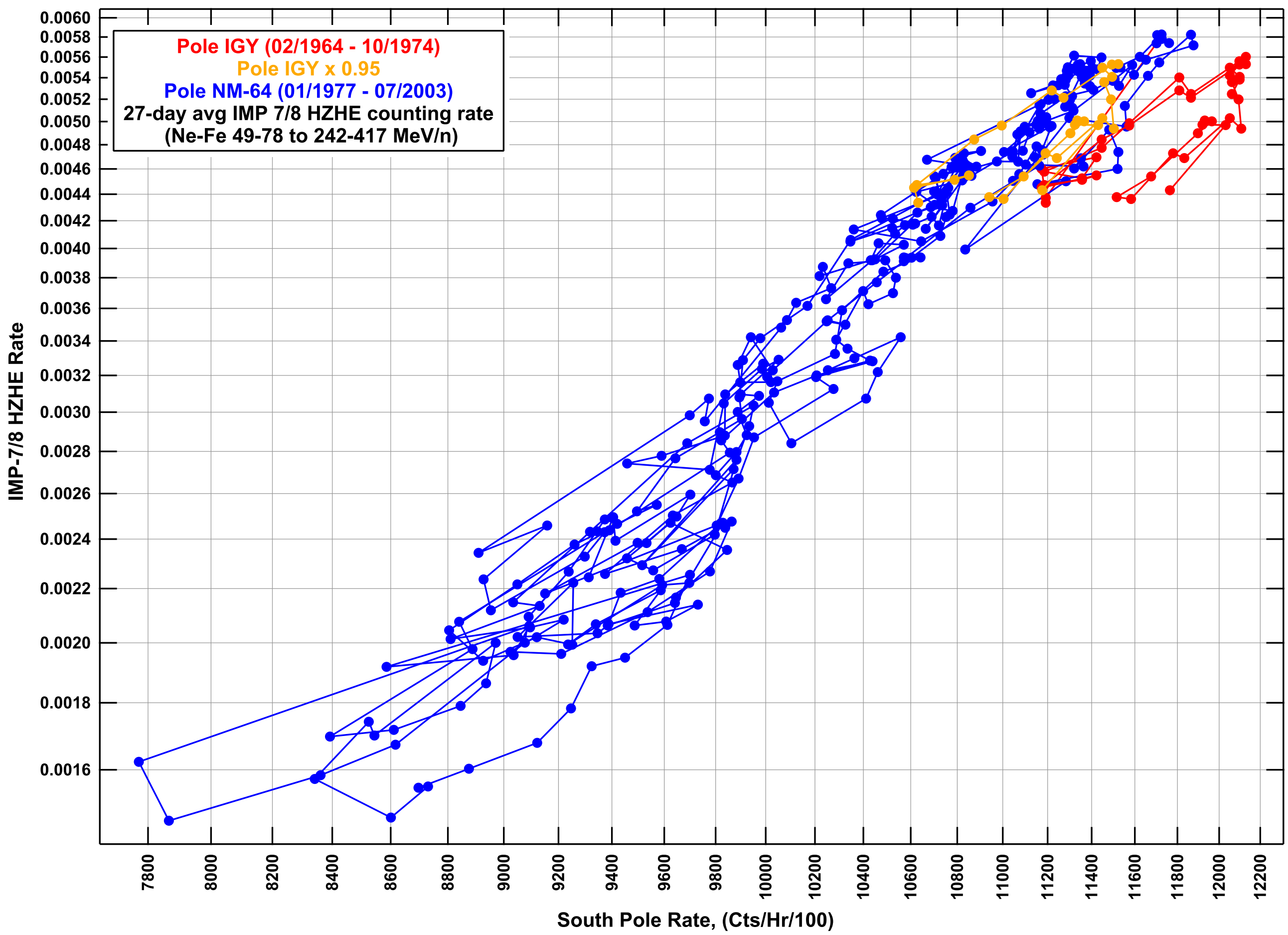

Figure 4. Regression of IMP-7 and IMP-8 HZHE rate against the South Pole neutron rate. Blue points are for NM64 measurements and red points for IGY measurements with the standard normalization. The plot suggests the South Pole IGY data with the standard normalization should be multiplied by 0.95 to be comparable with the NM64 data, as shown by the orange points.

mental in origin. This section identifies six possible instrumental artifacts and assesses their possible contribution to the South Pole decline.

4.1. Barometer Drifts

[20] Neutron monitor data must be corrected for the varying atmospheric depth through which the secondary cosmic rays propagate. This is done by using atmospheric pressure as a proxy for atmospheric depth, and correcting the data to a constant standard pressure. At South Pole the standard station pressure is 510 mm Hg, and a correction of 1% per mm Hg is applied to correct the neutron monitor data for pressure variations.

[21] If the South Pole 8% decline is to be attributed to an error in recorded pressure, the recorded barometer reading would gradually (over 32 years) have to fall by 8 mm Hg relative to the true pressure. While this is in the direction one might expect for a leaky barometer, we believe this is much larger than can be reasonably expected considering the controls we have in place. Currently these controls include multiple digital barometers that are included in the data stream and cross-checked against one another, a calibrated reference barometer that is taken annually to the station to check the primary digital barometer, and cross-checking of our barometer readings with others operated independently at the station (e.g., at the weather station). While procedures may have been different in detail at earlier times, they invariably included extensive cross-checking of barometric readings from multiple sources. Our judgment is that the accumulated barometric error would likely not exceed 1 mm Hg, and thus could not account for more than a 1% decline in the reported South Pole neutron rate over 32 years.

4.2. Changing Relative Height of Neutron Monitor and Barometer

[22] The South Pole neutron monitor is on a platform that can be periodically jacked to a higher level. This is necessary because the snow level is continually rising relative to the level of the platform. From records available to us, the platform was jacked by 10 ft in 1985 and by 8 ft in 2002. We have no records of earlier jacking, nor of the original platform height, but a platform originally 10 feet off the surface in 1977, jacked for the first time in 1985, is most probably the best assumption. The earlier IGY station was indoors.

[23] The primary data barometer, however, is located in a nearby building, and its height is not altered when the

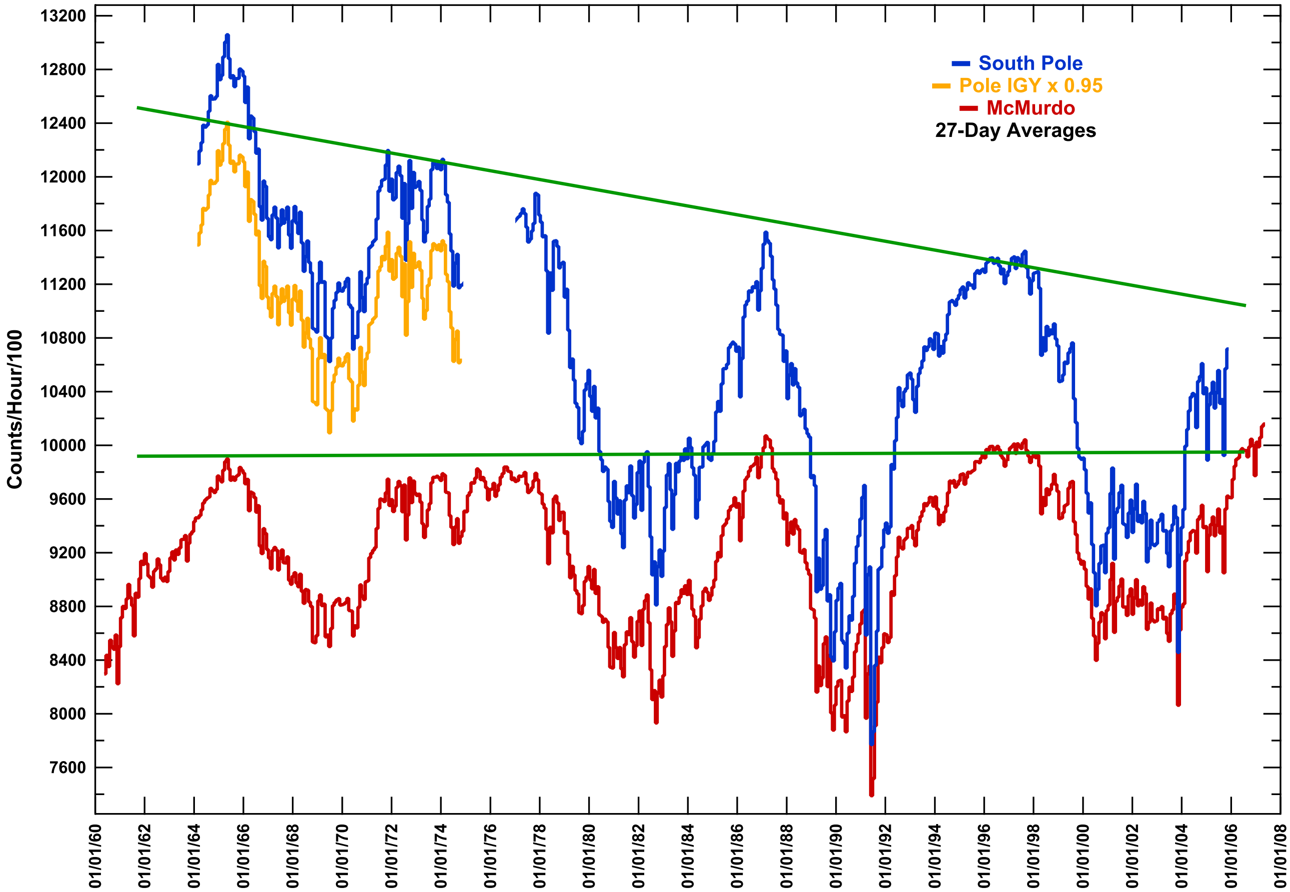

Figure 5. South Pole neutron rate compared with McMurdo neutron rate. The orange curve shows the IGY rate multiplied by 0.95, which we consider to provide a superior normalization of the IGY data than the standard normalization. Even with this reduction in the South Pole IGY rate, the downtrend in South Pole neutrons is clearly apparent.

neutron monitor platform is jacked. The effect is that the neutron monitor is continually rising relative to the barometer. However, we can eliminate this as the source of the 8% decline on two grounds. First, it is in the wrong direction. Jacking the platform will increase the monitor count rate slightly, because the actual atmospheric depth has decreased. Second, the effect is too small. An accumulated 18 ft rise in platform level (relative to the barometer) would produce only a 0.36% rise in the neutron rate.

4.3. Detector Tube Aging

[24] Another factor that separates South Pole from other neutron monitor stations is the very high count rate. Under solar minimum conditions, McMurdo records about 15.6 counts per second in each detector tube, while South Pole records (1997 epoch) about 106 counts per second per tube, a 6.8 times higher rate. If detector tubes degrade or "age" at a rate determined by the total number of counts they have recorded, this process will occur much more rapidly at South Pole than at sea level.

[25] *Qian et al.* [1998] reported on experiments on degradation of BF_3 and ^{3}He neutron detector tubes at a nuclear reactor. They tested BF_3 tubes of considerably smaller diameter than those used in neutron monitors, and found that some experienced significant degradation after recording as few as 10^{10} counts, while others remained in good condition until recording 10^{11} counts. If the Qian et al. result can be applied to the larger tubes used in neutron monitors, this implies that a tube lifetime would be ~20–200 years at McMurdo, but only ~3–30 years at South Pole. In practice we have found a variable lifetime for the tubes at Pole, with 10 years being typical.

[26] Prior to 1990 the decision to change a tube was based on comparison of the count rate of each detector with that of the other two tubes in the monitor, the so-called "channel ratios." Since 1990 we have also based the decision on an annual pulse height analysis. Figure 6 illustrates the degradation of one detector. In 1997 the new (or in this case newly refurbished) tube shows a signal distribution closely related to the physics of the neutron interaction (black curve).The detector signal results from ionization of the gas from the ^{10}B(n,α)^{7}Li reaction. This reaction can occur through two different channels in which the ^{7}Li nucleus product is either in the ground state or first excited state (480 keV). Roughly 94% of the reactions lead to an excited state with a Q value of 2.31 MeV giving 1.47 MeV to the α particle and 0.84 MeV to the ^{7}Li, while the remaining 6% lead to the ground state reaction with a Q value of 2.791 MeV. These two reaction channels are clearly identified in the pulse height distribution resulting in two distinct

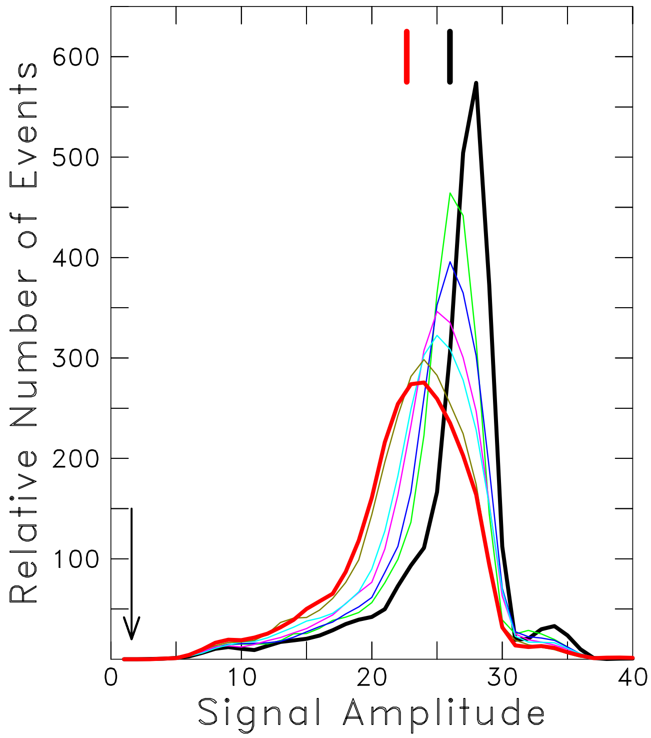

Figure 6. Degradation of a BP28 neutron detector with time. Spectra taken annually from one of the neutron detectors used at South Pole are shown from the installation of the detector in 1997 (thick black curve) to 2003 (thick red curve). The curves are normalized so that all have equal area. Despite the broadening of the resolution, the average pulse height has only been reduced by 13% over this interval (vertical lines). Because few events have pulse heights near the counting discriminator (arrow), the tube degradation has a negligible impact on count rate.

peaks. The ^{7}Li nucleus de-excites through the release of a 0.48 MeV gamma ray that generally escapes the active gas volume without detection. With a Q value of 2.31 MeV, the α particle and ^{7}Li products have a stopping-power range 1.5 cm and 0.5 cm respectively, therefore either product could hit the wall for those reactions that occur near the tube wall and some of the energy escapes detection. Thus there is a sharp edge at the maximum energy with a tail toward lower energy with a cutoff representing the 0.84 MeV ^{7}Li. In contrast, a typical muon only deposits 10 keV in the detector, allowing a discriminator setting that is almost insensitive to nonneutron background, yet nearly 100% efficient for neutrons. (The lower cutoff of the signal spectrum in the figure is an artifact of the pulse height analyzer used to take the spectrum. The setting of the counting discriminator is indicated by the arrow.) The detector is run as a proportional counter, thus each count produces a cascade in the avalanche region near the wire. Some of this ionized gas "plates out" onto the wire, increasing its effective diameter and reducing the gain locally. The process is nonuniform, and so is the gain reduction. The net result is a dramatic and progressive worsening of the resolution of the peak which evolves into the red curve by 2003. The net reduction in the average signal (shown as the short vertical lines for 1997 and 2003) is far less dramatic, being only 13%. Because so few events have pulse heights near the discriminator threshold, this reduction has a negligible effect on the count rate.

[27] Under the assumption that the signal degradation is proportional to the signal, only a few events at the low end of the curve will slip below the discriminator threshold owing to degradation at the level shown, and should have very little effect on the count rate as long as the discriminators are properly set, which we believe they are. However, BP-28 detectors typically differ in response by 1–2%, so that each time a tube is changed (we never change all at once) a new normalization factor for the station as a whole is computed on the basis of the channel ratios of the unchanged tubes to the tube removed and the new tube. If there is any evidence that the count rate of the old tube was affected, we go back in time to choose the normalization; to a point where we believe that the degradation had not begun to affect the count rate of the tube changed out.

[28] There is of course a potential trap here, because if the tubes do become systematically less efficient as they age this normalization procedure will neither detect nor correct for that. We would simply normalize the good new tube to the bad old one, and the overall reported count rate of the detector would not change. As evidence that this has not happened, we show in Figure 7 the evolution of the station normalization factor from 1985 (when our good records begin) to January 2004, when we converted the station from ^{10}B detectors to ^{3}He detectors. Most of the normalization

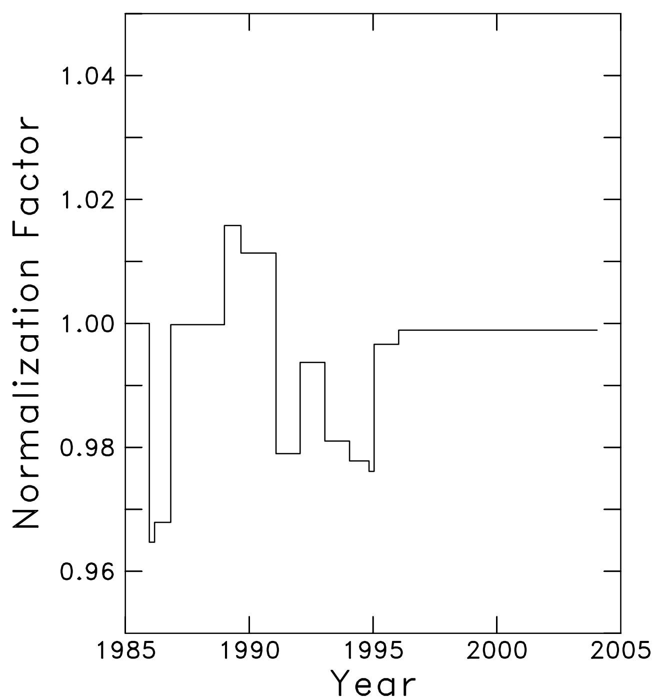

Figure 7. Normalization factor of the South Pole neutron monitor as a function of time. No systematic change is seen, indicating that there is no systematic bias in renormalizing the monitor as new detector tubes replace degraded tubes.

Figure 8. South Pole neutron monitor environment. Skylab is prominent structure at left; neutron monitor is on platform to right of Skylab; the edge of Dome is far right. Since 1977 the neutron monitor has been raised a total of 18 feet to keep it above the surface of the snow. As surrounding structures are buried, this changes the environment and potentially has a systematic influence on the count rate.

changes are related to tube changes, while a few are related to other electronics modifications. There is no trend in these data that would indicate any type of systematic bias in normalizing new detectors.

4.4. Detector Tube Operating Temperature

[29] We have recently been concerned with variations in neutron monitor count rate as a function of detector temperature. Our analysis of data from several of our stations [*Evenson et al.*, 2005] yields an estimate of the temperature coefficient of an NM64 of 4×10^{-4} per degree C. Although there may have been some uncertainty in the temperature control of our detectors, an 8% change would have required a decrease in the monitor temperature of 200C, which is not credible.

4.5. Electronic and Physical Background

[30] We have also considered the possibility that there may be a significant change in the background count rate of the station. It is of course not possible to exclude completely that some type of chronic, undetected electronic noise was present in the earlier history of the station. Then as now, the primary defense against such noise is the continuous comparison of three independent "channels" of data; separate detectors, separate discriminators, and separate counters. In our current system we have also added a second "guard" discriminator (at a lower threshold than the counting discriminator) as well as continuous sampling of the pulse height spectrum of the detectors. The only occasion on which we have resorted to serious use of this new capacity is in our continuing latitude survey on an icebreaker [*Bieber et al.*, 2003, 2004]. From time to time the icebreaking operations, and consequent vibration of the ship, induce microphonic noise into the system. Because this occurs for short periods and may be correlated among the different detectors it can create signal enhancements not readily apparent in the channel ratios. However, we find it difficult to believe that a conscientious investigator would miss continuous electronic interference at the several percent level in all channels for a period of years.

[31] We can be much more certain in excluding what we might term physical background owing to radioactive elements in the detector, air showers, etc. *Simpson* [1957] warns that there might be as much as a 4% background in an IGY type monitor from this source, but this warning applies to a sea level monitor, presumably at low latitude. A specific analysis of the situation at Pole shows the effect to be negligible there. *Simpson* [1957] quotes a typical count rate for an IGY detector, isolated in a cadmium container filled with paraffin, as one count per minute. One of us (RP) at one time routinely did this test on the Climax station detectors, with a "pass" level of two counts per minute. At Pole, near solar minimum, the count rate of an operating IGY detector is approximately 1300 per minute per tube (1965 epoch). Hence the background is at the 0.1% level and even complete elimination of the background would not influence our conclusions.

[32] Any such background in an NM64 would reduce the magnitude of the decline, but for completeness we comment on this background. We do not have a cadmium box large enough to enclose a BP-28 detector, nor do we know of such a measurement made elsewhere so we do not have an exactly comparable measurement. To obtain an upper limit on possible background, we removed one of our BP-28 detectors from its polyethylene moderator in the electronics shop in the basement of our building. The resulting count rate was 50 per minute, but pulse height analysis indicated that these counts were still predominantly due to neutrons. This is consistent with the finding of *Fowler* [1963] that the typical background due specifically to alpha particles from radionuclides in the detector itself is about 5 per minute. In the Pole monitor at solar minimum (1997 epoch), the count rate of this detector would be about 6400 per minute per tube, so background is at the 0.8% level at worst (and probably much less), which is not enough to impact our conclusions.

4.6. Environmental Change

[33] We conclude this section by commenting on a possible influence that we have not been able to quantify to any significant degree. The neutron monitor is located approximately 30 m from the iconic "dome" structure that housed the Amundsen-Scott Station and 10 m from the "Skylab" building that housed the data recording system (Figure 8). Both structures have remained in place over the lifetime of the NM64 monitor, but snow has gradually built up around them. Thus there have been two changes in the environment of the monitor, namely it has risen with respect to the structures, and large voids have developed in the snow close to the monitor. We have no specific evidence that this process is affecting the count rate of the monitor, and in fact no reason to believe that there would be such an effect on the basis of some simple simulations that we have done. We also have noticed no change in the relative count rate of the detector located on the side facing the dome with respect to that on the opposite side. In the future both structures are scheduled to be removed and the voids filled in. It is our hope that we will be able to reestablish the

monitor in its former position to see if there is any change in the count rate as a result of this operation.

5. Discussion and Summary

[34] During the 32-year span from the cosmic ray maximum of 1965 to the maximum of 1997, the neutron rate recorded at South Pole, Antarctica decreased by 8%, a much larger change than that registered by other neutron monitors in the worldwide network. The South Pole IGY count rates (pre-1975) archived at http://neutronm.bartol.udel.edu/ have already been normalized to be comparable to the count rates of the NM64 monitor that was installed in 1977, but our analysis suggests that an additional factor of 0.95 should be applied to the IGY rates. The 8% decline we report is measured after this additional factor of 0.95 is applied to the IGY data with the standard normalization. (Otherwise the decrease would be even larger.)

[35] We carefully considered factors related to the harsh South Pole environment, and were unable to identify any that could credibly cause a change in instrumental sensitivity by as much as 8%. Further, the observation of a long-term decline in the cosmic ray intensity is supported by observations recorded by balloonborne instruments and by the detectors aboard the IMP-7 and IMP-8 satellites.

[36] Owing to its unique location that is both high latitude and high altitude, the South Pole monitor has enhanced sensitivity to cosmic ray primaries at the low-energy end of the neutron monitor response. We therefore conclude that the long-term decline of the South Pole neutron rate is likely caused by a decrease in the intensity of ∼1–3 GV primary cosmic rays impacting the polar atmosphere.

[37] On the basis of neutron monitor response functions presented by *Nagashima et al.* [1989], we should have expected decreases at other neutron monitors around the world larger than what is actually observed. The lack of any decrease in Mt. Washington neutron monitor data is particularly puzzling. However, we do not regard this contrary evidence as decisive, owing to the high degree of uncertainty in the neutron monitor response at low rigidities. In addition, the behavior reported at Mt. Washington is somewhat anomalous, in that it displays the smallest rate of change in a group of 12 neutron monitors tabulated by *Stozhkov et al.* [2000].

[38] *Neher* [1967] reported that the proton differential intensity in 1965 was approximately 0.1 $(\mathrm{cm}^2\ \mathrm{s\ sr\ GeV})^{-1}$ at an energy of 1 GeV [see *Neher*, 1967, Figure 7]. Taken at face value, this is remarkably similar to the differential intensity at 1 GeV reported by the BESS collaboration for 1998 [*Sanuki et al.*, 2000, Figure 4]. However, it is hazardous to compare such measurements made with different experimental platforms. As an illustration, note that the various spectra compared in the work of *Sanuki et al.* [2000, Figure 4] range over almost a factor of 2 even at 10 GeV, where such large differences are not credible. On the other hand, *Neher* [1967] did report that ionization chambers flown aboard balloons recorded a significantly higher integral intensity of cosmic rays in 1954 than in 1965, which suggests the long-term trend reported in the present article might be extended back for at least one additional solar cycle.

[39] The origin of the decrease recorded at South Pole cannot be changes in the geomagnetic field, because the vertical cutoff at South Pole has remained below 0.1 GV for the entire period of this study [*Shea and Smart*, 2001, Table 1]. As shown in Figure 2, the South Pole monitor has negligible response to Galactic cosmic rays below about 1 GV. The South Pole energy threshold is therefore governed by the atmospheric cutoff of ∼1 GV, and changes in the geomagnetic cutoff below this threshold have no impact on the count rate.

[40] In summary, we have not been able to identify any instrumental or environmental effect that could cause the long-term decrease in the South Pole neutron rate. Unless some such cause emerges in the future, it would appear the origin of the decrease must be a change in the Sun or solar wind, with an attendant change in the strength of solar modulation of cosmic rays [*Ahluwalia and Lopate*, 2001; *Caballero-Lopez et al.*, 2004; *McCracken et al.*, 2004a, 2004b], or possibly a change in the local interstellar density of Galactic cosmic rays [*Stozhkov et al.*, 2000].

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[42] Zuyin Pu thanks two anonymous reviewers for their assistance in evaluating this paper.

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