Cosmic Ray Diffusion from the Galactic Spiral Arms, Iron Meteorites, and a Possible Climatic Connection

Nir J. Shaviv

[1]*Canadian Institute for Theoretical Astrophysics, University of Toronto, 60 St. George Street, Toronto, Ontario M5S 3H8, Canada and Racah Institute of Physics, Hebrew University, Jerusalem 91904, Israel*

We construct a Galactic cosmic ray (CR) diffusion model. The CR flux reaching the Solar System should periodically increase with each crossing of a Galactic spiral arm. We confirm this prediction in the CR exposure age record of iron meteorites. We also find that although the geological evidence for the occurrence of ice-age epochs in the past eon is not unequivocal, it appears to have a nontrivial correlation with the spiral arm crossings and the CR flux variability—agreeing in period and phase.

With the possible exception of those at extremely high energies, cosmic rays (CRs) are believed to originate from supernova (*SN*) remnants [1,2]. Moreover, most SNe in spiral galaxies like our own are those which originate from massive stars; thus, they predominantly reside in the spiral arms, where most massive stars are born and shortly thereafter explode as SNe [3].

Thus, while the Sun is crossing the Galactic spiral arms, the cosmic ray flux (CRF) is expected to be higher. To estimate the CRF variation, we construct a simple diffusion model which considers that the CR sources reside in the Galactic spiral arms. We expand the basic CR diffusion models (e.g., Ref. [2]) to include a source distribution located in the Galactic spiral arms. Namely, we replace a homogeneous disk with an arm geometry as given by Taylor and Cordes [4], and solve the time dependent diffusion problem. To take into account the "Orion spur" [5], in which the Sun currently resides, we add an arm "segment" at our present location. Since the density of HII regions in this spur is roughly half of the density in the real nearby arms [5], we assume it to have half the typical CR sources as the main arms. We integrate the CR sources assuming a diffusion coefficient of $D = 10^{28}$ cm^2/sec, which is a typical value obtained in diffusion models for the CRs [2,6,7]. We also assume a halo half-width of 2 kpc, which again is a typical value obtained in diffusion models [2], but, more importantly, we reproduce with it the ^{10}Be survival fraction [8]. Thus, the only free parameter in the model is the angular velocity $\Delta\Omega \equiv \Omega_\odot - \Omega_p$ around the Galaxy of the Solar System *relative* to the spiral arm pattern speed, which is later adopted using observations. Results of the model are depicted in Fig. 1. For the nominal values chosen in our diffusion model and the particular pattern speed which will soon be shown to fit various data, the expected CRF changes from about 25% of the current day CRF to about 135%. Moreover, the average CRF obtained in units of today's CRF is 76%. This is consistent with measurements showing that the average CRF over the period 150–700 Myr before present (BP), was about 28% lower than the current day CRF [12].

Interestingly, the temporal behavior is both skewed and lagging after the spiral arm passages. The lag arises because the CRs are emitted from SNe which on average occur roughly 15 Myr after the average ionizing photons are emitted. The skewness arises because it takes time for the CRs to diffuse after they are emitted, thereby forming a wake *after* them. This typically introduces a 10 Myr lag in the flux, totaling about 25 Myr with the *SN* delay. This lag is actually observed in the synchrotron emission from M51, which shows a peaked emission trailing the spiral arms [1].

The spiral pattern speed of the Milky Way has not yet been reasonably determined through astronomical observations. Nevertheless, a survey of the literature reveals that almost all observational determinations cluster either around $\Delta\Omega \approx 9$ to 13 (km s^{-1})/kpc [13] or around $\Delta\Omega \approx 2$ to 5 (km s^{-1})/kpc [15]. In fact, one analysis [14] revealed that both $\Delta\Omega = 5$ or 11.5 (km s^{-1})/kpc fit the data. However, if the spiral arms are a density wave [16], as is commonly believed [17], then the observations of the four-arm spiral structure in HI outside the Galactic solar orbit [18] severely constrain the pattern speed to $\Delta\Omega \gtrsim 9.1 \pm 2.4$ (km s^{-1})/kpc, since the four-arm density wave spiral cannot extend beyond the outer four to one Lindblad resonance [11]. We therefore expect the spiral pattern speed obtained to coincide with one of the two aforementioned ranges, with a strong theoretical argumentation favoring the first range.

To validate the above prediction that the CRF varied periodically, we require a direct "historic" record from which the actual time dependence of the CRF can be extracted. To find this record, we take a compilation of 74 iron meteorites which were ^{41}K/^{40}K exposure dated [19]. CRF exposure dating (which measures the duration a given meteorite was exposed to CRs) assumes that the CRF history was constant, such that a linear change in the integrated flux corresponds to a linear change in age. However, if the CRF is variable, the apparent exposure age will be distorted. Long periods during which the CRF is low would correspond to slow increases in the exposure

age. Consequently, Fe meteorites with real ages within this low CRF period would cluster together since they will not have significantly different integrated exposures. Periods with higher CRFs will have the opposite effect and spread apart the exposure ages of meteorites. To avoid real clustering in the data (due to one parent body generating many meteorites), we remove all occurrences of Fe meteorites of the same classification that are separated by less than 100 Myr and replace them by the average. This leaves us with 42 meteorites.

From inspection of Fig. 1, it appears that the meteorites cluster with a period of 143 ± 10 Myr or, equivalently, $|\Delta\Omega| = 11.0 \pm 0.8$ (km s^{-1})/kpc, which falls within the preferred range for the spiral arm pattern speed. If we fold the CR exposure ages over this period, we obtain the histogram in Fig. 2. A Kolmogorov-Smirnov (K-S) test yields a probability of 1.2% for generating this nonuniform signal from a uniform distribution. Moreover, Fig. 2 also describes the prediction from the CR diffusion model. We see that the clustering is not in phase with the spiral arm crossing, but is with the correct phase and shape predicted by the CR model using the above pattern speed. A K-S test yields a 90% probability for generating it from the CR model distribution. Thus, we safely conclude that spiral arm passages modulate the CRF with a ~ 143 Myr period.

In 1959, Ney [20] suggested that the Galactic CRF reaching Earth could be affecting the climate since the CRF governs the ionization of the lower atmosphere, to which the climate may in principle be sensitive to. If this hypothesis is correct, we may be able to see a correlation between the observed long term CRF variability and the climate record on Earth.

Interestingly, the CRF reaching Earth is also variable because of its interaction with the variable solar wind. Thus, solar activity variations will also have climatic effects *if the CRF affects the climate* (e.g., [21]). Under the assumption that it does affect climate, we can estimate how large an effect can a possible CRF-temperature relation be. This can be derived from the fact that the best fit to the global warming in the past 120 years is obtained if somewhat less than half is attributed to anthropogenic greenhouse gases and somewhat more than half to the increased activity of the Sun [22,23]. Thus, between about 1940 and 1970, the global temperature, which decreased by 0.15 K, is best explained as -0.2 K attributed to the reduced solar activity and $+0.05$ K to greenhouse gases [22,23]. A global CRF climate effect is presumably more likely to arise from CRs that can reach the troposphere and equatorial latitudes. Thus, it is reasonable to assume that a possible effect would arise from CRs that have high rigidities ($\gtrsim 10$–15 GeV/nucleon). We therefore normalize the low geomagnetic data from Haleakala, Hawaii, and Huancayo, Peru, to the higher geomagnetic data of Climax, Colorado [24] that were measured over a longer period (e.g., [25]). We find that the -0.2 K cooling correlated with a 1.5% increase in the high rigidity CRF.
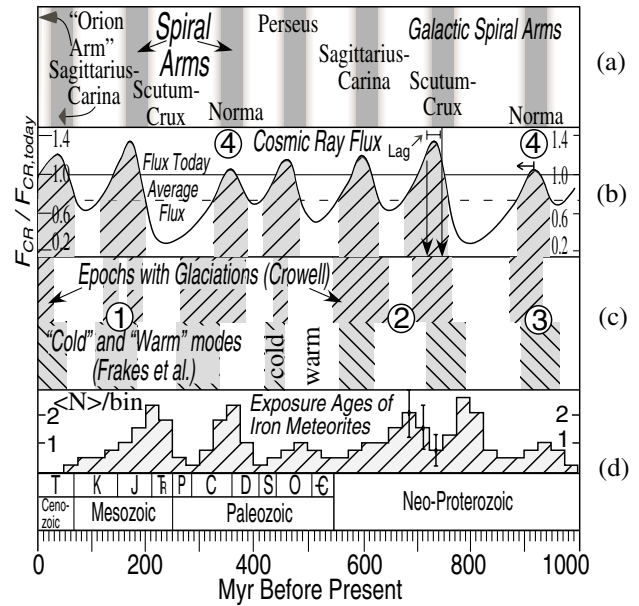

FIG. 1. The past eon: (a) Past Galactic spiral arm crossings assuming $\Delta\Omega = 10.9$ (km s^{-1})/kpc. (b) The CRF reaching the Solar System using the CR diffusion model. Note that the CRF lags behind spiral arm crossings. This is portrayed by the hatched regions, which qualitatively show the predicted occurrences of IAEs if the CRF required to trigger them is the average flux. Arrows mark the middle of the spiral crossing and the expected midglaciation point. (c) Qualitative descriptions of the geologically recorded IAEs—its top half, as summarized by Crowell [9], who concluded that the current evidence is insufficient to support a claim of periodicity, while the bottom half, as summarized by Frakes *et al.* [10], who claim a periodicity exists. By fine-tuning the observed pattern speed of the arms to best fit the IAEs, an intriguing correlation appears between the IAEs and their prediction. Note that the correlation need not be absolute since additional factors may affect the climate. Other factors that should be considered and noted in the graph are the following: (1) The mid-Mesozoic glaciations are significantly less extensive as others. (2) It is unclear to what extent the period around 700 Myr BP was warmer than the IAEs before or after. (3) The first IAE of the neo-proterozoic (if indeed distinct) is very uncertain. (4) Since Norma's crossing is an extrapolation from smaller Galactic radii, its location is uncertain. If the arm's structure at smaller radii is indeed different [11], its preferred location will lag by about 20 Myr. (d) A 1-2-1 averaged histogram of the ^{41}K/^{40}K exposure ages of Fe meteorites, which are predicted to cluster around the CRF minima. The cluster-IAE correlation further suggests an extraterrestrial trigger for the glaciations.

Thus, changing the CRF by $\pm 1\%$ would correspond to a global change of ∓ 0.13 K, *on the condition that CRs are indeed the link relating solar activity to the climate.*

For the nominal values chosen in our diffusion model, the expected CRF changes from about 25% of the current day CRF to about 135%. This corresponds to a temperature change of about $+10$ to -5 K, relative to today's temperature. This range is sufficient to markedly help or hinder Earth from entering an ice-age epoch (IAE).
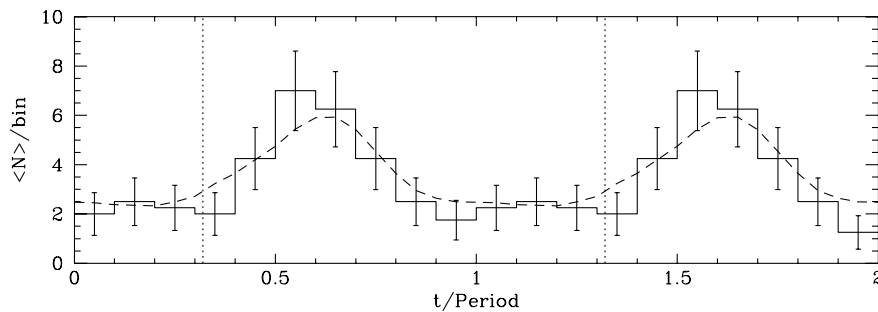
FIG. 2. A folded 1-2-1 averaged histogram (over the IAE periodicity) of the Fe meteorites' exposure ages. A statistically significant signal is obtained for a period of 143 ± 10 Myr. The dashed line is the CR diffusion model prediction. We find that the predicted phase of the cluster peaks agrees with the actual exposure age clustering. The clustering peaks 100 Myr after the spiral crossing (dotted lines), implying that it is unlikely to be a *real* age clustering peak, which should be related directly to the spiral crossing (e.g., by Oort cloud comets that are perturbed during arm crossing, that subsequently break asteroids more frequently, and that somehow affect the terrestrial climate).

Extensive summaries of IAEs on Earth can be found in Crowell [9] and Frakes *et al.* [10]. Those of the past eon are summarized in Fig. 1. The nature of some of the IAEs is well understood, while others are sketchy in detail. The main uncertainties are noted in Fig. 1. For example, it is unclear to what extent the milder mid-Mesozoic glaciations can be placed on the same footing as other IAEs, nor is it clear to what extent the period around 700 Myr BP can be called a warm period since glaciations were present, though probably not to the same extent as the periods before or after. Thus, Crowell [9] concludes that the evidence is insufficient to claim a periodicity. On the other hand, Williams [26] claimed that a periodicity may be present. This was elaborated upon by Frakes *et al.* [10].

Comparison between the CRF and the glaciations in the past 1 Gyr shows a compelling correlation (Fig. 1). To quantify this correlation, we perform a χ^2 analysis. *To be conservative,* we do so with the Crowell data which are less regular. Also, we do not consider the possible IAE around 900 Myr, though it does correlate with a spiral arm crossing. For a given pattern speed, we predict the location of the spiral arms using the model. We find that a minimum is obtained for $\Delta\Omega = 10.9 \pm 0.25$ (km s^{-1})/kpc, with $\chi^2_{\min} = 1.1$ per degree of freedom (of which there are $5 = 6 - 1$). We also repeat the analysis when we neglect the lag and again when we assume that the spiral arms are separated by 90° (as opposed to the somewhat asymmetric location obtained by Taylor and Cordes [4]). Both assumptions degrade the fit ($\chi^2_{\min} = 2.9$ with no lag, and $\chi^2_{\min} = 2.1$ with a symmetric arm location). Thus, the latter analysis assures that IAEs are more likely to be related to the spiral arms and not a more periodic phenomena, while the former helps assure that the CRs are more likely to be the cause, since they are predicted (and observed) to be lagged.

The previous analysis shows that to within the limitation of the uncertainties in the IAEs, the predictions of the CR diffusion model and the actual occurrences of IAE are consistent. To understand the significance of the result,

we should also ask what the probability is that a random distribution of IAEs could generate a χ^2 result which is as small as previously obtained. To do so, glaciation epochs were randomly chosen. To mimic the effect that nearby glaciations might appear as one epoch, we bunch together glaciations that are separated by less than 60 Myrs (which is roughly the smallest separation between observed glaciations epochs). The fraction of random configurations that surpass the χ^2 obtained for the best fit found before is of order 0.1% for *any* pattern speed. (If glaciations are not bunched, the fraction is about 100 times smaller, while it is about 5 times larger if the criterion for bunching is a separation of 100 Myrs or less). The fraction becomes roughly 6×10^{-5} (or a 4σ fluctuation), to coincidentally fit the actual period seen in the iron meteorites.

Last, before 1 Gyr BP, there are no indications for any IAEs, except for periods around 2–2.5 Gyr BP (Huronian) and 3 Gyr BP (late-Archean) [9]. This too has a good explanation within the picture presented. Different estimates to the star formation rate (SFR) in the Milky Way (and therefore also to the CR production) point to a peak around 300 Myr BP, a significant dip between 1 and 2 Gyr BP (about a third of today's SFR) and a most significant peak at 2–3 Gyr BP (about twice today's SFR) [27,28]. This would imply that at 300 Myr BP, a more prominent IAE should have occurred—explaining the large extent of the Carboniferous-Permian IAE. Between 1 and 2 Gyr BP, there should have been no glaciations, and indeed none were seen. Last, IAEs should have also occurred 2 to 3 Gyr BP, which explains the Huronian and late-Archean IAEs.

To conclude, by considering that most CR sources reside in the Galactic spiral arms, we predict a variable CRF. A record of this signal was indeed found in iron meteorites, and it nicely agrees with the observations of the Galactic spiral arm pattern speed. Next, if the apparent solar activity climate correlation is real and arises from modulation of the Galactic CRF reaching Earth, then typical variations of up to $\mathcal{O}(10 \text{ K})$ could be expected from the variable CRF. For each spiral arm crossing, the

average global temperature should reduce enough to trigger an IAE. The record of IAEs on Earth is fully consistent with the predicted and observed CRF variation—both in period and in phase. Moreover, the fit improves when the predicted lag in the IAEs after each crossing is included and when the actual asymmetric location of the arms is considered. Moreover, a random mechanism to generate the IAEs is excluded. Nevertheless, one should bear in mind that the weakest link still remains the glaciological record with its uncertainties. That is, more research on the timing and extent of glaciations is required.

The last agreement is between the eon time scale star formation activity of the Milky Way and the presence or complete absence of IAEs. Here a more detailed research on the SFR activity would be useful to strengthen (or perhaps refute) the long term correlation.

If the apparent correlation between observed CRF variations and climate on Earth is not simply a remarkable coincidence, an unavoidable question is what is the physical mechanism behind the CRF-temperature relation? Currently, there is no single *undisputed* mechanism through which cosmic rays can affect the climate. There are, however, several observational indications that such a relation could exist. For example, Forbush events during which the CRF suddenly drops on a time scale of days were found to correlate with the amount of "storminess" as encapsulated by the vorticity area index [29], or a concurrent drop in the cloud cover [30]. There were also claims that the Galactic CRF, which is modulated by the solar cycle and slightly lags behind it, correlates with the low altitude cloud cover variations [25,31]. Clearly, an in-depth study on the possible climatic effects of cosmic rays is imperative.

[1] M. S. Longair, *High Energy Astrophysics* (Cambridge University Press, Cambridge, 1994), 2nd ed., Vol. 2.

[2] V. S. Berezinskiı, S. V. Bulanov, V. A. Dogiel, V. L. Ginzburg, and V. S. Ptuskin, *Astrophysics of Cosmic Rays* (North-Holland, Amsterdam, 1990).

[3] P. M. Dragicevich, D. G. Blair, and R. R. Burman, Mon. Not. R. Astron. Soc. **302**, 693 (1999).

[4] J. H. Taylor and J. M. Cordes, Astrophys. J. **411**, 674 (1993).

[5] Y. M. Georgelin and Y. P. Georgelin, Astron. Astrophys. **49**, 57 (1976).

[6] W. Webber and A. Soutoul, Astrophys. J. **506**, 335 (1998).

[7] U. Lisenfeld, P. Alexander, G. G. Pooley, and T. Wilding, Mon. Not. R. Astron. Soc. **281**, 301 (1996).

[8] A. Lukasiak, P. Ferrando, F. B. McDonald, and W. R. Webber, Astrophys. J. **423**, 426 (1994).

[9] J. C. Crowell, *Pre-Mesozoic Ice Ages: Their Bearing on Understanding the Climate System* (Memoir Geological Society of America, Boulder, CO, 1999), Vol. 192.

[10] L. A. Frakes, J. E. Francis, and J. I. Syktus, *Climate Modes of the Phanerozoic* (Cambridge University Press, Cambridge, U.K., 1992).

[11] N. J. Shaviv (to be published).

[12] B. Lavielle, K. Marti, J. Jeannot, K. Nishiizumi, and M. Caffee, Earth Planet. Sci. Lett. **170**, 93 (1999).

[13] The first range of results for $\Delta\Omega$ includes $\sim$11.5 $(km\,s^{-1})/kpc$, C. C. Lin, C. Yuan, and F. H. Shu, Astrophys. J. 155, 721 (1969); $\sim$11.5 $(km\,s^{-1})/kpc$, C. Yuan, Astrophys. J. **158**, 871 (1969); $\sim$11.5 $(km\,s^{-1})/kpc$, C. Yuan, Astrophys. J. **158**, 889 (1969); 13.5 ± 1.5 $(km\,s^{-1})/kpc$, M. A. Gordon, Astrophys. J. **222**, 100 (1978); $\sim$11.5 $(km\,s^{-1})/kpc$ [14]; 9–13 $(km\,s^{-1})/kpc$, E. M. Grivnev, Sov. Astron. Lett. **9**, 287 (1983); and 7.5–11.5 $(km\,s^{-1})/kpc$, G. R. Ivanov, Pis'ma Astron. Zh. **9**, 200 (1983) [Sov. Astron. Lett. **9**, 107 (1983)].

[14] J. Palous, J. Ruprecht, O. Dluzhnevskaia, and T. Piskunov, Astron. Astrophys. **61**, 27 (1977).

[15] The second range of results for $\Delta\Omega$ includes 2.5 ± 1.5 $(km\,s^{-1})/kpc$, M. Creze and M. O. Mennessier, Astron. Astrophys. **27**, 281 (1973); $\sim$5 $(km\,s^{-1})/kpc$ [14]; $\sim$5 $(km\,s^{-1})/kpc$, A. H. Nelson and T. Matsuda, Mon. Not. R. Astron. Soc. **179**, 663 (1977); 1.4 ± 3.6 $(km\,s^{-1})/kpc$, I. N. Mishurov, E. D. Pavlovskaia, and A. A. Suchkov, Astron. Zh. **56**, 268 (1979); 2–4 $(km\,s^{-1})/kpc$, E. M. Grivnev, Sov. Astron. Lett. **7**, 303 (1981); and 2.3 ± 1 $(km\,s^{-1})/kpc$, L. H. Amaral and J. R. D. Lepine, Mon. Not. R. Astron. Soc. **286**, 885 (1997).

[16] C. C. Lin and F. H. Shu, Astrophys. J. **140**, 646 (1964).

[17] J. Binney and S. Tremaine, *Galactic Dynamics* (Princeton University Press, Princeton, 1988).

[18] L. Blitz, M. Fich, and S. Kulkarni, Science **220**, 1233 (1983).

[19] H. Voshage and H. Feldmann, Earth Planet. Sci. Lett. **45**, 293 (1979).

[20] E. P. Ney, Nature (London) **183**, 451 (1959).

[21] W. H. Soon, E. S. Posmentier, and S. L. Baliunas, Ann. Geophys. **18**, 583 (2000).

[22] W. H. Soon, E. S. Posmentier, and S. L. Baliunas, Astrophys. J. **472**, 891 (1996).

[23] J. Beer, W. Mende, and R. Stellmacher, Quat. Sci. Rev. **19**, 403 (2000).

[24] G. A. Bazilevskaya, Space Sci. Rev. **94**, 25 (2000).

[25] H. Svensmark, Phys. Rev. Lett. **81**, 5027 (1998).

[26] G. E. Williams, Earth Planet. Sci. Lett. **26**, 361 (1975).

[27] J. M. Scalo, in *Starbursts and Galaxy Evolution* (Editions Frontiéres, Gif-Sur-Yvette, 1987), p. 445.

[28] H. J. Rocha-Pinto, J. Scalo, W. J. Maciel, and C. Flynn, Astron. Astrophys. **358**, 869 (2000).

[29] B. A. Tinsley and G. W. Deen, J. Geophys. Res. **D12**, 22 283 (1991).

[30] M. I. Pudovkin and S. V. Veretenenko, J. Atmos. Terr. Phys. **57**, 1349 (1995).

[31] N. Marsh and H. Svensmark, Space Sci. Rev. 94, 215 (2000).