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# Critical Comment on the Article by R. Rek "The Maunder Minimum and the Sun as the Possible Source of Particles Creating Increased Abundance of the $^{14}$C Carbon Isotope"

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**Abstract** Several strong but erroneous statements were made by R. Rek in an article published in this volume of *Solar Physics*. Here we show that these misleading statements are caused by neglecting the known effects of the carbon cycle and misinterpretation of the data. In particular we show that the claim of the Maunder minimum being "the period without a significant cessation of activity" contradicts the bulk of observational evidence and is caused by the misinterpretation of proxy data.

**Keywords** Sun: activity

## 1. Introduction

A recent article by Rek (2009), called hereafter R09, presents an analysis of radiocarbon $^{14}$C data and its relation to solar activity. Several strong claims were made by R09: *i*) radiocarbon $^{14}$C is produced not by galactic cosmic rays (GCR) but mostly by particles of solar or magnetospheric origin (*e.g.*, precipitating from radiation belts) or even by auroral electrons *via* electron capture by nitrogen; *ii*) precipitation of radiocarbon from the atmosphere to the ground level and absorption by living trees takes place "very quickly," with the deposition time being "certainly less than one year"; *iii*) Maunder minimum can be interpreted "as the period without a significant cessation of activity" with "a higher level of solar activity. . .than usually is assumed." Since these statements are in strong contradiction with the modern generally accepted views, we feel it necessary to analyze the arguments used by R09 to ground such claims. Detailed analysis is presented in the subsequent sections.

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## 2. Radiocarbon Production in the Atmosphere

Radiocarbon $^{14}C$ is one of the most used cosmogenic isotopes, whose application is much wider than solar physics, forming in particular a basis for independent dating for archeology, paleoclimatology, and so on. Therefore, it is vital to know details of $^{14}C$ production in the atmosphere. This problem has been under intensive study for decades. It is presently unambiguously accepted that $^{14}C$ is a result of the capture of a thermal neutron by atmospheric nitrogen, $^{14}N(n,p)^{14}C$. Neutrons in the atmosphere are provided by the cosmic-ray-induced cascade and their flux varies in time along with the modulation of GCR flux – see, *e.g.*, Grieder (2001), Dorman (2004). We note that there are many quantitative models to compute the $^{14}C$ production rate in the atmosphere (*e.g.*, Lingenfelter, 1963; Lal and Suess, 1968; O'Brien, 1979; Castagnoli and Lal, 1980; Masarik and Reedy, 1995; Masarik and Beer, 2009). The major source of atmospheric $^{14}C$ is related to GCR with the effective energy around several GeV/nuc (Usoskin, 2008). Modulation of GCR in the Heliosphere by the variable solar magnetic activity provides the temporal variability of the $^{14}C$ production rate.

Solar energetic particles (SEP) can also produce some additional amount of $^{14}C$ during strong solar eruptive events when SEP can be accelerated up to a few GeV, *i.e.*, enough to initiate an atmospheric cascade. This effect was quantitatively evaluated by Usoskin *et al.* (2006) and shown to be negligible (less than 1% on average). Contrary to the proposition of R09, magnetospheric protons do not posses enough energy to initiate an atmospheric cascade and produce atmospheric neutrons and are not usually considered as a source of radiocarbon. The contribution of such lower energy particles directly producing $^{14}C$ without initiating a cascade was estimated by Masarik and Reedy (1995) to be about 0.01% of the production by GCR. Another process proposed by R09 to produce $^{14}C$ from $^{14}N$ *via* the electron capture (inverse $\beta$-decay $^{14}N(e,\nu_e)^{14}C$), is negligible. This is a weak interaction process with very small efficiency compared to the strong interaction of the neutron capture.

Thus, the idea that $^{14}C$ can be largely produced by low-energy particles (solar or magnetospheric) is not supported by the quantitative theory of the isotope's production, obtained as a consensus of different groups and verified by observational data. Moreover, the strongest SEP event and the largest geomagnetic storm in historical time is associated with the Carrington event of 1859 (*e.g.*, Cliver and Svalgaard, 2004; Shea *et al.*, 2006). However, no related peak is observed in annual $\Delta^{14}C$ data – see Kocharov *et al.* (1995), Stuiver, Reimer, and Braziunas (1998), contrary to the R09 expectation.

## 3. Radiocarbon Production Rate and Carbon Cycle

The conclusions of R09 are based on an analysis of the $\Delta^{14}C$ series by Kocharov *et al.* (1995). This series has large uncertainties (5 permil compared to $< 2$ permil in the Intcal series) as well as possible biases and uncontrolled large amplitude variations (Damon, Eastoe, and Mikheeva, 1999; Miyahara *et al.*, 2005). This fact is also accepted by the authors of the series (Kocharov, Ogurtsov, and Tsereteli, 2003) and other involved scientists[1] (Konstantinov *et al.*, 1997). Moreover, the tree ring samples originally used by Kocharov *et al.* (1995) were later independently re-measured in the Arizona laboratory by Damon, Eastoe, and Mikheeva (1999). The data of Kocharov *et al.* (1995) for the period 1688 – 1710 AD,

[1] Both authors of this Comment were staff members of the Kocharov's laboratory at the A.F. Ioffe Physical-Technical Institute, St. Petersburg in the 1980 – 1990's.

which forms the basis of R09 analysis, were not confirmed (see Figure 1 in Damon, Eastoe, and Mikheeva, 1999). Most of the individual high resolution $^{14}$C data series (*e.g.*, Stuiver, Reimer, and Braziunas, 1998; Miyahara *et al.*, 2004, 2008) agree well with each other and with the re-measured ones (Damon, Eastoe, and Mikheeva, 1999), but not with the original (Kocharov *et al.*, 1995) data set, particularly around the Maunder minimum. It is common to use a combined data series Intcal (Stuiver *et al.*, 1998; Reimer *et al.*, 2004), which is a result of an interlaboratory consensus calibration of different data sets with decadal resolution.

R09 equates the production rate of $^{14}$C and the $\Delta^{14}$C measured in tree rings by assuming that the residence time of $^{14}$C in the atmosphere is short, less than a year. This is not a valid assumption as discussed in the following. Soon after production radiocarbon gets oxidized to carbon dioxide $CO_2$. Because of its gaseous form, it cannot easily precipitate gravitationally, but takes part in the global carbon cycle of interrelated systems: atmosphere – biosphere – ocean. This process is presently well understood and can be modeled at different levels of precision – see, *e.g.*, Oeschger *et al.* (1974), Damon, Lerman, and Long (1978), Stuiver and Quay (1980), Bard *et al.* (1997), Stuiver and Braziunas (1998), Goslar (2001), Damon and Peristykh (2004), Naegler and Levin (2006). These models were well verified and calibrated using the bomb-effect, *i.e.*, nuclear explosions in the atmosphere producing large amount of $^{14}$C, which can be traced in the terrestrial system for decades (Damon, Lerman, and Long, 1978; Broecker *et al.*, 1985; Naegler and Levin, 2006). Thus calibrated models confirm long (several decades) residence time of $^{14}$C in the atmosphere. The carbon cycle results in attenuation and phase shift of the production signal in the measured $\Delta^{14}$C. It is incorrect to assume, as done by R09, that $\Delta^{14}$C measured in a tree ring for a particular year reflects the $^{14}$C production rate for the same year. For example, the 11-year cycle is attenuated by a factor of 100 and delayed by three years. Together with the one-year delay of a maximum GCR intensity with respect to the sunspot minimum (Usoskin *et al.*, 1998) this moves the expected maxima of $\Delta^{14}$C toward sunspot maxima, which was erroneously considered by R09 as evidence of $^{14}$C being produced by solar/magnetospheric particles. This time shift is well known and is naturally explained by the atmospheric transport of $CO_2$ as explicitly mentioned by Kocharov *et al.* (1995) and Stuiver and Braziunas (1998). The same process at the centennial time scale leads to the attenuation of a factor of 10 and the time shift of several decades (Bard *et al.*, 1997). This results in the $\Delta^{14}$C peak related to the Maunder minimum to occur at the end of the minimum, ca. 1700 AD. We note that this delayed peak was erroneously attributed by R09 to enhanced $^{14}$C production near the end of the Maunder minimum.

To illustrate this, we show in Figure 1 the correspondence between the measured data and the relative radiocarbon content $\Delta^{14}$C directly computed, using modern physics-based models, from sunspot numbers. Panel A depicts group sunspot numbers (Hoyt and Schatten, 1998), which is the best present compilation of all the available historical sunspot data (see Section 4). Since sunspots manifest the surface magnetic activity of the Sun, it is possible to compute the large-scale solar magnetic flux in the Heliosphere (Solanki, Schüssler, and Fligge, 2000; Krivova, Balmaceda, and Solanki, 2007). Using a model of GCR modulation one can evaluate, also taking into account the polarity of the interplanetary magnetic field and the heliospheric current sheet tilt, variability of the GCR flux at Earth (Alanko-Huotari *et al.*, 2007). As the next step, applying a numerical model of the atmospheric cascade and $^{14}$C production (Castagnoli and Lal, 1980), one can compute the $^{14}$C production rate $Q$ expected from GCR modulation. This is shown in Figure 1B. One can see that the production rate was high during the entire Maunder minimum from 1650 till 1700 AD. Next, applying the carbon cycle model by Usoskin and Kromer (2005), we calculated the expected $\Delta^{14}$C

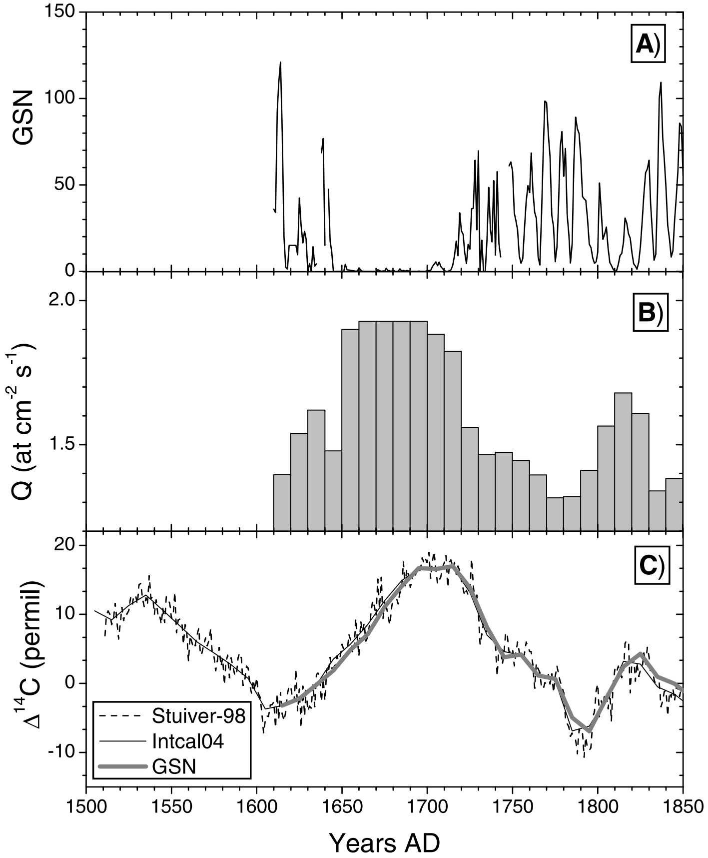


**Figure 1** Panel (A) Group sunspot numbers (Hoyt and Schatten, 1998). Panel (B) Decadal global radiocarbon production rate $Q$ computed directly from sunspot data (panel A) using the physics-based method (see text). Panel (C) $\Delta^{14}$C in tree rings: dotted and solid curves represent annual data measured by Stuiver, Reimer, and Braziunas (1998) and the decadal Intcal series (Stuiver *et al.*, 1998; Reimer *et al.*, 2004), respectively; thick gray GSN curve depicts decadal $\Delta^{14}$C straightforwardly computed from the GSN-based production rate $Q$ (see panel B) using the carbon cycle model.

in tree rings, shown as the thick gray curve in Figure 1C. For comparison we show, on the same panel, directly measured $\Delta^{14}$C – decadal Intcal04 series (Reimer *et al.*, 2004) and annual data by Stuiver, Reimer, and Braziunas (1998). One can see that the radiocarbon content directly computed via the modulated GCR flux using a set of physics-based models perfectly agrees with the real measurements. This confirms the validity of the used models and verifies the fact that $^{14}$C is produced dominantly by GCR, leaving no room for essential additional production by solar/magnetospheric particles.

## 4. Solar Activity During the Maunder Minimum

R09 stated that the Maunder minimum can be interpreted "as the period without a significant cessation of (solar) activity" based on an analysis of historical sunspot and auroral observations as well as proxy data of nitrates in polar ice and radiocarbon.

R09 studied disembodied data of sunspot observations by several individual observers. We note that all the available sunspot data, including a much larger data set than that analyzed by R09, was compiled by Hoyt and Schatten (1998) into a group sunspot number (GSN) series. The GSN series is the most complete and homogeneous index of long-term solar activity for the last centuries – see Soon and Yaskell (2003), Hathaway and Wilson (2004), Usoskin and Kovaltsov (2004), Usoskin (2008), Vaquero and Vázquez (2009). We note that sunspot records for the Maunder minimum have been intensively analyzed during the last decades (*e.g.*, Eddy, 1976, 1983; Ribes and Nesme-Ribes, 1993; Sokoloff and Nesme-Ribes, 1994; Hoyt and Schatten, 1996; Usoskin, Mursula, and Kovaltsov, 2003; Kovaltsov, Usoskin, and Mursula, 2004). It was explicitly shown that sunspot activity was extremely low during the Maunder minimum, but some submarginal cyclic activity can still be observed (Usoskin, Mursula, and Kovaltsov, 2000, 2001).

As an argument for high activity toward the end of the Maunder minimum, R09 considers a higher number of aurora-watching records in Europe in the turn of the 17th/18th centuries. These data were also extensively studied earlier (*e.g.*, Siscoe, 1980; Křivský, 1984; Silverman, 1992; Legrand *et al.*, 1991; Letfus, 2000). The increased number of reported auroras, mentioned by R09, reflects not the enhanced frequency of aurora occurrence, but rather the onset of systematic scientific observations and the foundation of special observatories, thus increasing greatly the number of nights covered by observations (Křivský, 1984). Therefore, the auroral evidence of the enhanced solar activity toward the end of the Maunder minimum is not entirely valid.

The statement of R09 that a high level of solar flare activity during the late Maunder minimum is supported by nitrate data by McCracken *et al.* (2001a, 2001b) is caused by a misunderstanding. As follows from Figure 2 of McCracken *et al.* (2001b), there were indeed solar proton events during the entire Maunder minimum, but their occurrence was much more seldom than for the normal activity.

A comparative analysis of all the available solar proxy data (sunspots, auroras, cosmogenic isotopes) for the Maunder minimum leads to a consistent scenario of the Maunder minimum – see Vitinsky, Kopecky, and Kuklin (1986), Sokoloff and Nesme-Ribes (1994), Usoskin, Mursula, and Kovaltsov (2001), Sokoloff (2004), Miyahara, Sokoloff, and Usoskin (2006), Usoskin (2008): The transition to the deep minimum occurred suddenly without any apparent precursor; sunspots nearly vanished, but a marginal 22-year cycle can be identified in sunspot occurrence during the deep minimum (1645 – 1700), with a subdominant 11-year cycle emerging toward the late phase of the Maunder minimum.

Thus, the claim of R09 on the high solar activity during the Maunder minimum is not consistent.

## 5. Conclusion

In conclusion, we argue that strong claims by R09 concerning the possible high solar activity during the Maunder minimum, dominant production of $^{14}C$ by solar/magnetospheric particles in the atmosphere, and a short residence time of $^{14}C$ in the atmosphere contradict the modern theories and are not factually supported by the available bulk of evidence. It is likely that these confusing claims were caused by neglecting important mechanisms, such as the carbon cycle, and the misunderstanding of existing theories and observational data.

## References

Alanko-Huotari, K., Usoskin, I.G., Mursula, K., Kovaltsov, G.A.: 2007, *Adv. Space Res.* **40**, 1064.

Bard, E., Raisbeck, G., Yiou, F., Jouzel, J.: 1997, *Earth Planet. Sci. Lett.* **150**, 453.
Broecker, W.S., Peng, T., Ostlund, G., Stuiver, M.: 1985, *J. Geophys. Res.* **90**, 6953.
Castagnoli, G., Lal, D.: 1980, *Radiocarbon* **22**, 133.
Cliver, E.W., Svalgaard, L.: 2004, *Solar Phys.* **224**, 407.
Damon, P.E., Peristykh, A.N.: 2004, In: Pap, J.M., Fox, P. (eds.) *Solar Variability and its Effects on Climate, Geophys. Monogr. Ser.* **141**, AGU, Washington, 237.
Damon, P., Lerman, J., Long, A.: 1978, *Ann. Rev. Earth Planet. Sci.* **6**, 457.
Damon, P., Eastoe, C., Mikheeva, I.: 1999, *Radiocarbon* **41**, 47.
Dorman, L.: 2004, *Cosmic Rays in the Earth's Atmosphere and Underground*, Kluwer Academic, Dordrecht.
Eddy, J.: 1976, *Science* **192**, 1189.
Eddy, J.: 1983, *Solar Phys.* **89**, 195.
Goslar, T.: 2001, *Radiocarbon* **43**, 743.
Grieder, P.: 2001, *Cosmic Rays at Earth*, Elsevier, Amsterdam.
Hathaway, D., Wilson, R.: 2004, *Solar Phys.* **224**, 5.
Hoyt, D., Schatten, K.: 1996, *Solar Phys.* **165**, 181.
Hoyt, D., Schatten, K.: 1998, *Solar Phys.* **179**, 189.
Kocharov, G.E., Ogurtsov, M.G., Tsereteli, S.L.: 2003, *Astron. Rep.* **47**, 1054.
Kocharov, G.E., Ostryakov, V.M., Peristykh, A.N., Vasil'ev, V.A.: 1995, *Solar Phys.* **159**, 381.
Konstantinov, A.N., Krasiljschikov, A.M., Lazarev, V.E., Mikheeva, I.B.: 1997, *Izv. Akad. Nauk, Ser. Fiz.* **61**, 1242.
Kovaltsov, G.A., Usoskin, I.G., Mursula, K.: 2004, *Solar Phys.* **224**, 95.
Krivova, N., Balmaceda, L., Solanki, S.: 2007, *Astron. Astrophys.* **467**, 335.
Křivský, L.: 1984, *Solar Phys.* **93**, 189.
Lal, D., Suess, H.: 1968, *Ann. Rev. Nucl. Sci.* **18**, 407.
Legrand, J., Le Goff, M., Mazaudier, C., Schröder, W.: 1991, *C.R. Acad. Sci. Paris, Ser. Gen. Vie Sci.* **8**, 181.
Letfus, V.: 2000, *Solar Phys.* **194**, 175.
Lingenfelter, R.: 1963, *Rev. Geophys. Space Phys.* **1**, 35.
Masarik, J., Beer, J.: 2009, *J. Geophys. Res.* **114**, D11103.
Masarik, J., Reedy, R.C.: 1995, *Earth Planet. Sci. Lett.* **136**, 381.
McCracken, K.G., Dreschhoff, G.A.M., Zeller, E.J., Smart, D.F., Shea, M.A.: 2001a, *J. Geophys. Res.* **106**, 21585.
McCracken, K.G., Dreschhoff, G.A.M., Smart, D.F., Shea, M.A.: 2001b, *J. Geophys. Res.* **106**, 21599.
Miyahara, H., Sokoloff, D., Usoskin, I.: 2006, In: Ip, W.H., Duldig, M. (eds.) *Advances in Geosciences, Vol. 2: Solar Terrestrial (ST)*, World Scientific, Singapore, 1.
Miyahara, H., Masuda, K., Muraki, Y., Furuzawa, H., Menjo, H., Nakamura, T.: 2004, *Solar Phys.* **224**, 317.
Miyahara, H., Masuda, K., Menjo, H., Kuwana, K., Muraki, Y., Nakamura, T.: 2005, In: *Proc. 29th Internat. Cosmic Ray Conf., Pune, India* **2**, 199.
Miyahara, H., Nagaya, K., Masuda, K., Muraki, Y., Kitagawa, H., Nakamura, T.: 2008, *Quat. Geochronol.* **3**, 208.
Naegler, T., Levin, I.: 2006, *J. Geophys. Res.* **111**, D12311.
O'Brien, K.: 1979, *J. Geophys. Res.* **84**, 423.
Oeschger, H., Siegenthaler, U., Schotterer, U., Gugelmann, A.: 1974, *Tellus* **27**, 168.
Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Bertrand, C.J.H., Blackwell, P.G., Buck, C.E., Burr, G.S., Cutler, K.B., *et al.*: 2004, *Radiocarbon* **46**, 1029.
Rek, R.: 2009, Solar Phys. **261**, in this issue. doi:10.1007/s11207-009-9432-8.
Ribes, J., Nesme-Ribes, E.: 1993, *Astron. Astrophys.* **276**, 549.
Shea, M., Smart, D., McCracken, K., Dreschhoff, G., Spence, H.: 2006, *Adv. Space Res.* **38**, 232.
Silverman, S.: 1992, *Rev. Geophys.* **30**, 333.
Siscoe, G.: 1980, *Rev. Geophys. Space Phys.* **18**, 647.
Sokoloff, D.: 2004, *Solar Phys.* **224**, 145.
Sokoloff, D., Nesme-Ribes, E.: 1994, *Astron. Astrophys.* **288**, 293.
Solanki, S., Schüssler, M., Fligge, M.: 2000, *Nature* **408**, 445.
Soon, W.H., Yaskell, S.: 2003, *The Maunder Minimum and the Variable Sun – Earth Connection*, World Scientific, Singapore.
Stuiver, M., Braziunas, T.F.: 1998, *Geophys. Res. Lett.* **25**, 329.
Stuiver, M., Quay, P.: 1980, *Science* **207**, 11.
Stuiver, M., Reimer, P., Braziunas, T.: 1998, *Radiocarbon* **40**, 1127.
Stuiver, M., Reimer, P.J., Bard, E., Burr, G.S., Hughen, K.A., Kromer, B., McCormac, G., van der Plicht, J., Spurk, M.: 1998, *Radiocarbon* **40**(3), 1041.
Usoskin, I.G.: 2008, *Living Rev. Solar Phys.* **5**, 3. http://www.livingreviews.org/lrsp-2008-3.
Usoskin, I.G., Kovaltsov, G.A.: 2004, *Solar Phys.* **224**, 37.

Usoskin, I.G., Kromer, B.: 2005, *Radiocarbon* **47**, 31.
Usoskin, I.G., Mursula, K., Kovaltsov, G.A.: 2000, *Astron. Astrophys.* **354**, L33.
Usoskin, I.G., Mursula, K., Kovaltsov, G.A.: 2001, *J. Geophys. Res.* **106**, 16039.
Usoskin, I.G., Mursula, K., Kovaltsov, G.A.: 2003, *Solar Phys.* **218**, 295.
Usoskin, I.G., Kananen, H., Mursula, K., Tanskanen, P., Kovaltsov, G.A.: 1998, *J. Geophys. Res.* **103**, 9567.
Usoskin, I.G., Solanki, S.K., Kovaltsov, G.A., Beer, J., Kromer, B.: 2006, *Geophys. Res. Lett.* **33**, L08107.
Vaquero, J., Vázquez, M.: 2009, *The Sun Recorded Through History*, *Astrophys. Space Sci. Lib.* **361**, Springer, Dordrecht.
Vitinsky, Y.I., Kopecky, M., Kuklin, G.V.: 1986, *Statistics of Sunspot Activity*, Nauka, Moscow (in Russian).