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Imprint of Galactic dynamics on Earth's climate

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A connection between climate and the Solar system's motion perpendicular to the Galactic plane during the last 200 Myr years is studied. An imprint of galactic dynamics is found in a long-term record of the Earth's climate that is consistent with variations in the Solar system oscillation around the Galactic midplane. From small modulations in the oscillation frequency of Earth's climate the following features of the Galaxy along the Solar circle can be determined: 1) the mass distribution, 2) the timing of two spiral arm crossings (31 Myr and 142 Myr) 3) Spiral arm/interarm density ratio ($\rho_{\rm arm}/\rho_{\rm interarm} \approx$ 1.5–1.8), and finally, using current knowledge of spiral arm positions, a pattern speed of $\Omega_{\rm P}$ = 13.6 ± 1.4 km s^{-1} kpc^{-1} is determined.

1 Introduction

The Solar system circles the galactic center of the Milky Way with a period of approximately 240 Myr at a distance of ≈ 8.5 kpc. During this journey the Solar system passes through dense and less dense regions associated with the spiral structure of the Milky Way. The spiral arms are believed to be density waves that the stars and gas, i.e., the entire galaxy, are participating in. In connection with the passage through a spiral arm, an increase of cosmic ray flux is expected The spiral arms are regions of star formation, and therefore also regions where large short lived stars can occur that end in a supernova explosion. Except for the rare very high energetic particles, all cosmic rays are believed to be accelerated in the shock fronts associated with supernova explosions. Cosmic rays (CR) are mainly protons that fill interstellar space at an energy density of ≈ 1 eV/cm^3. As a consequence, the Earth's atmosphere is bombarded with CR particles. These generate a very large number of secondary particles that are responsible for nearly all of the ionization in the lower part of Earth's atmosphere. There are now many studies which demonstrate the remarkable correlation between cosmic ray variations and climate variations (Carslaw, Harrison & Kirkby 2002). These studies suggest that cosmic ray ionization is influencing the Earth's climate. One possible link is between atmospheric ionization and Earth's cloud cover (Svensmark & Friis-Christensen 1997, 1998; Marsh & Svensmark 2000). The evidence suggests that an increase in cosmic ray flux results in an increase in the formation of low clouds, reducing the amount of sunlight reaching the Earth's surface, which leads to a colder climate. Recently, a microphysical mechanism has been identified experimentally that links ionization generated from CR secondary particles in the lower part of the Earth's atmosphere and aerosol formation (Svensmark et al. 2006a), which may be the fundamental link between cosmic rays, clouds, and climate.

It has been shown that cold periods (glaciations) in Earth's history correlate with spiral arm passages, with a period of ≈ 140 Myr (Shaviv 2002, 2003; Shaviv & Veizer 2003). Even a construction of the cosmic ray flux over the entire 4.6 Gyr history of the solar system correlates well with the known climate history of the Earth (Svensmark 2004, 2006). Although it is not suggested to be the only influence on climate, cosmic rays, surprisingly, seem to have a significant impact on Earth's climate.

This paper deals with the connection between cosmic rays, climate and the solar systems oscillation perpendicular to the galactic plane. As described above, the idea is based on variations in the cosmic ray flux. When the solar system is at the Galactic midplane a higher cosmic ray flux is expected than when at a maximum distance (≈ 100 pc) from the plane. The expectation is, therefore, that climate on Earth is colder when at the Galactic midplane than at the maximum distance. In the following it will be shown that an imprint of galactic dynamics in the Earth's climate during the last 200 Myr reflects variations in the Solar systems oscillation around the Galactic midplane. Remarkably, this imprint reflects variations in the Galactic mass density which the solar systems experiences, during its journey around the Galactic center.

2 Dynamics of solar system perpendicular to the Galactic plane

First a formulation of the dynamics of the solar system is necessary. Figure 1 shows the Milky Way based on the Tay-

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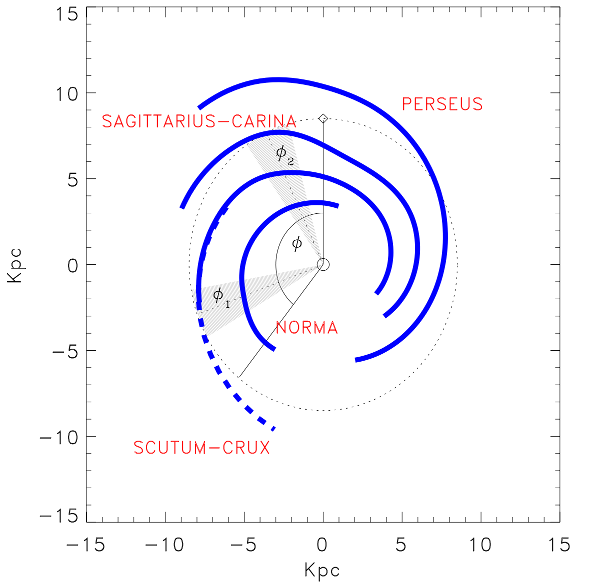

Fig. 1 Overview of the Milky Way. The known parts of the 4 spiral arms are shown as the thick blue lines. The solar system is shown with the diamond symbol. ϕ_1 and ϕ_2 are the angles at which the solar system crosses the spiral arms, and the grey areas are the estimated uncertainty. The semi-circle is the angle the solar system has traveled *relative* to the spiral arms during the last 200 Myr (see text).

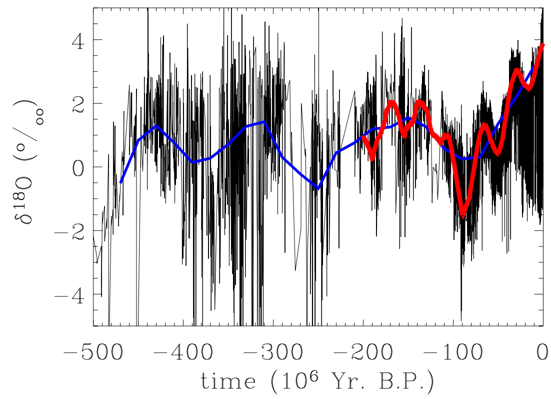

Fig. 2 δ^{18}O proxy data from the phanerozoic database showing variations in Earth's climate during the last 500 Myr. The blue curve is a 60 Myr low pass filtered data. The red curve is low passed filtered, 1/20 Myr, this curve is also shown in Fig. 3. These proxy data reflect changes in temperature of the Oceans (1 ‰ $\approx$ 2°C).

lor and Cordes (1993) model of free electrons, where the current position of the spiral arms are indicated. The position of the solar system is in cylindrical coordinates given by (R, ϕ, z). The dynamics of the solar system relative to the galaxy is simplified in the epicycle approximation (Binney & Tremaine 1987),

$$(\,\xi(t), \eta(t), z(t)\,) = (R(t) - R_{\rm g}, \phi(t) - \\ -\Omega_0 t - \phi_0, z(t))\,, \tag{1}$$

with its motion described relative to the guiding center of the solar system with coordinates $(\,R_{\rm g}, \Omega_0 t + \phi_0, 0\,)$, and where $R_{\rm g}$= 8.5 kpc and $\Omega_0 = 25.9 \pm 4$ km s^{-1} kpc^{-1}. As a further simplification, the effects of the spiral arms and the epicyclic motion of the solar system in the $[R, \phi]$ plane are ignored, i.e. $(\,\xi(t), \eta(t)\,) = (\,0, 0\,)$. The only equation remaining describes the vertical motion which is given by

$$\ddot{z} = -\nu^2(\rho) z\,. \tag{2}$$

Here, z is the vertical deviation from the galactic mid-plane, and the oscillation frequency, ν, which depends on the local mass density, ρ, is given by

$$\nu^2(\rho) \equiv \left(\frac{\partial^2 \Phi_{\rm e}}{\partial z^2}\right)_{(R=R_{\rm g}, z=0)} = 4\pi G\rho\,. \tag{3}$$

The second derivative is of the effective galactic potential, $\Phi_{\rm e}$, at the radius $R_{\rm g}$, i.e., the distance from the galactic center to the guiding center of the solar system, and at the galactic mid-plane $z = 0$, and G is the gravitational constant. Via Poisson's equation the oscillation frequency is related to the local mass density ρ. If the mass density was constant and known, the motion would be a simple harmonic oscillation with frequency $(4\pi G\rho)^{1/2}$. However, the density is not constant due to the non-axisymmetric structure of the Milky Way; i.e. the spiral structure, and variations in the vertical oscillation frequency is expected as the solar system circles the galactic center. The reason being that the spiral pattern is rotating at a smaller angular frequency, $\Omega_{\rm P}$, and the solar system therefore moves in and out of the spiral arms with the relative angular frequency $\Delta\Omega = \Omega_0 - \Omega_{\rm P}$. The equation of motion then becomes

$$\ddot{z} = -4\pi G\rho\,(\,R_{\rm g}, \Delta\Omega t, 0\,)\,z\,. \tag{4}$$

This relates the solar system's vertical motion to the mass density at the solar radius, however the function $\rho\,(\,R_{\rm g}, \Delta\Omega t, 0\,)$ is general not known. In the following the density variations at the solar radius are modeled by the following function

$$\rho\,(\,t\,) = \frac{\pi}{GP(t)^2} \approx 678 \left(\frac{P(t)}{\rm Myr}\right)^{-2} M_\odot\,{\rm pc}^{-3}, \tag{5}$$

where $P(t)$ is defined as

$$P(t) = p_0 + \sum_{i=1}^{2} p_i \exp\left[\frac{t - t_i}{2\sigma_i}\right]^2. \tag{6}$$

For a pattern speed $\Omega_{\rm P}$ in the range 5–25 km s^{-1} kpc^{-1} the Solar system is only expected to have passed at most two spiral arms during the 200 Myr period ($\Delta\phi \approx$ 70–230 deg in Fig. 1. The index i is therefore limited to 2. There are seven parameters in the fit (see Table 1).

2.1 Effect on Earth's temperature

Due to a midplane symmetry of cosmic rays the effect on climate is not expected to depend on the sign of the devi-

Table 1 Determined parameters of the period function $P(t)$ of Eq. (6). The bottom line is the one sigma uncertainty. The units are Myr.

p_0	p_1	t_1	σ_1	p_2	t_2	σ_2
84.0	−26.7	−141.7	18.02	−25.1	−30.7	14.1
0.38	1.1	4.4	1.1	3.4	6.4	2.7

ation z. Therefore, to the lowest order, the relationship between Earth's climate and the Solar systems position, z, relative to the Galactic midplane can be written as

$$T(z) = a + b\,(z/z_0)^2\,, \tag{7}$$

where a, b are constants, and z_0 is a characteristic amplitude of z variation.

2.2 Data and model procedure

The δ^{18}O proxy data of Earth's temperature from the Phanerozoic database covering the last 500 Myr (Veizer et al. 1999) are shown in Fig. 2. The blue curve is obtained by box-car filtering the raw data to isolate frequencies longer than 1/60 Myr. Note the ≈ 140 Myr period that has already been connected to passing of spiral arms of the milky way (Shaviv 2002; Shaviv & Veizer 2003). The red curve in Fig. 2 is also a band-pass but with a cutoff frequency of 1/20 Myr. Note that now a ≈ 30 Myr period is visible.

It has already been demonstrated by Prokoph & Veizer (1999) that there is an approximately 32 Myr variation in the geological proxy data that could be related to the crossing of the Galactic plane. This can be seen directly in the raw data of Fig. 2 over the most recent 100 Myr. One ‰ (per mille) corresponds to change in temperature of ≈ 2°C (Veizer, Godderis & Francois 2000).

Although geological data are available over a 500 Myr period the study will be restricted to the last 200 Myr, due to the high data density and lack of large gaps over this period. The filtered data are shown as the red curve in the top panel of Fig 3. This figure shows an oscillation in δ^{18}O with a clearly visible change in frequency over the 200 Myr range.

This ≈ 30 Myr oscillation will now be studied in more detail. First the data of Fig. 2 are band-passed with a simple boxcar filter function to isolate frequencies in the range from 1/60 to 1/20 Myr. The result is shown as the red curve in the top panel of Fig. 3.

In order to link this temperature oscillation to the dynamics of the solar system around the Galactic midplane the following procedure used is: (a) Eq. (4) is solved numerically using a density trial function defined in Eq. (5) and (6), (b) the solution in inserted into Eq. (7) (using $a = -0.5$ and $b = 1$, z_0= 75 pc), and finally (c) the parameters in the trial function Eq. (6) are fitted by minimizing the least square deviation from the proxy data. A constrain is the present known position of the solar system z coordinate: 9 ± 4 pc. To estimate the robustness of the fitted parameters a Monte Carlo simulation is performed where at random 37% of the proxy climate data are replaced with normal distributed noise. Monte Carlo simulations where also performed so the amplitude of the noise simulated the relative data variance.

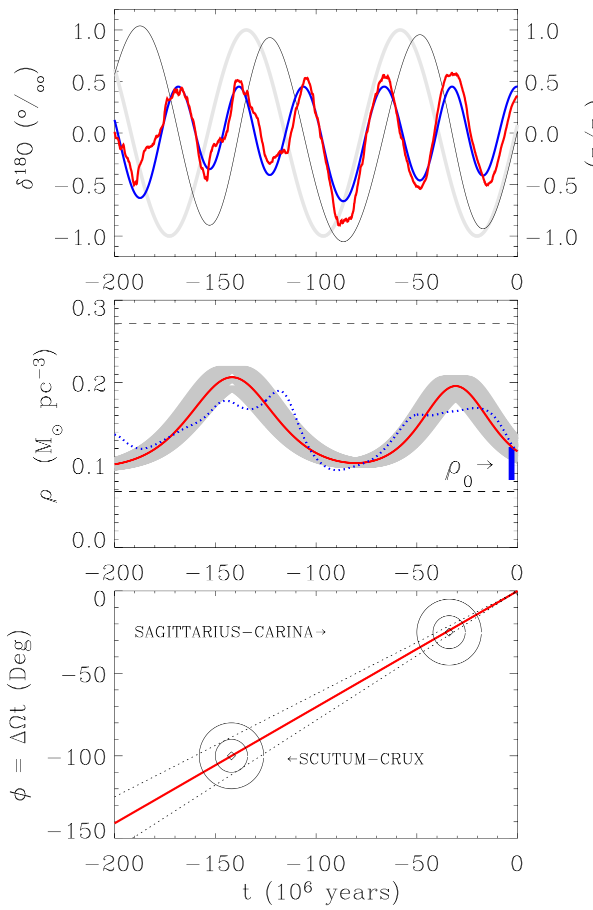

Fig. 3 *Top panel*: red curve bandpass-filtered climate data (δ^{18}O) as a function of time. Thin solid line, motion of solar system in z plane including variations in density. Thin grey line, motion of solar system for a constant local density. Blue curve, T(z) given by Eq. (7). *Middle panel*: red curve, the average density as a function of time. Grey area one sigma uncertainty. Blue line two sigma uncertainty of local mass density. Dotted lines, see text. *Bottom panel*: location of spiral arm crossings in (t, ϕ) coordinates. The circles are one and two sigma uncertainties . Red curve is the best fit of relative pattern speed $\Delta\Omega = 12.3\,\mathrm{s}^{-1}\,\mathrm{kpc}^{-1}$, and the dashed lines are the one sigma uncertainty.

2.3 Climate record and Galactic properties

Figure 3, (top panel) shows the solution determined by statistically averaging over 10^3 Monte Carlo realizations. The blue line is the climate signal given by Eq. (4) constructed by the statistical procedure described above (units of δ^{18}O). The solid thin black curve shows the oscillation of the solar system with respect to the Galactic midplane normalized to

z_0. For comparison a solution to the solar motion assuming a constant density is shown, grey curve. It is seen that this solution replicates the data poorly, e.g. the phase in this is off by 90 degree.

The middle panel of Fig. 3 shows the associated density distribution, and the grey area indicates the one sigma uncertainty range, (see also Table 1 for the determined parameters). The two dotted horizontal lines in the figure are the boundaries of possible density variations set by the bandpass filtering. ($\rho(\max / \min) \approx 678 / T(\min / \max)^2$ where T is in Myr, and ρ in $M_\odot$ pc^{-3})

To further test the robustness of the above result pseudo proxy climate data sets were constructed by taking the inverse Fourier transform of the climate data, scrambling the phases with a random uniform distribution between 0 and 2π, and Fourier transforming back. This procedure gives pseudo climate series whose statistical properties are close to the original. Fitting, using the above described procedure, to these data gave on average a constant density distribution, of which the individual fits only very rarely gave a double peaked distribution similar to the above. Note that the fitting procedure does not restrict the peaks of the gaussian to be within the 200 Myr period. Finally a fitting procedure was also tested where there was no restriction on the functional form of Eq. (6). For an initial density profile the dynamics of the solar system is calculated and the least square deviation between Eq. (7) and the filtered proxy data is determined. If a new density profile has a smaller least square deviation the new profile is accepted or else rejected. This procedure is continued until it converges. The resulting density profile is shown in Fig. 3 middle panel, blue curve. Therefore there is confidence in the robustness and general features of the obtained distribution.

Figure 3 (middle panel) indicates two density maximums at 142 Myr and at 31 Myr ago. The present local mass density is found $\rho_{\rm local}$ = 0.115 $M_\odot$ pc^{-3}. This value should be compared with the local density $\rho_{\rm local}$ = 0.105 $M_\odot$ pc^{-3} determined using Hipparcos data (Holm & Flynn 2004). The local density based on Hipparcos data is plotted as the blue line (two sigma) in the middle panel of figure (3). The two density maximums are 0.20 and 0.19 $M_\odot$ pc^{-3} , and the minimum between the two peeks is 0.115 $M_\odot$ pc^{-3}, giving a density spiral arm/interarm ratio $\rho_{\rm arm}/\rho_{\rm interarm} \approx$ 1.8. For the unconstrained density profile this density ratio is found to be 1.5. This arm/interarm ratio for the Milky Way is within the range 1.5–3 found in spiral galaxies with a grand design (Rix & Zaritsky 1995). A resent estimate on the Milky Way gave 1.8 at the solar circle (Drimmel & Spergel 2001). The with of the spiral arms is determined as

$$W_i = R_0 \Delta\Omega 2\sigma_i / \sin(11^\circ) = 0.36 \text{ kpc and } 0.28 \text{ kpc}, \quad (8)$$

where the angle between the solar motion and the spiral is 11°. This width is in good agreement with the width of 0.3 kpc used in the model of Taylor and Cordes (1993).

Finally a consistency test of the above results with the known spiral structure of the Milky Way shown in Fig. 1.

Table 2 Parameters of the Milky Way derived from the present study, the last two are derived from the Taylor and Cordes model of the spiral structure (see Fig. 1). The arm/interarm ratio is 1.5 for the unconstrained density function.

$\rho_{\rm local}$	0.115 ± 0.1 $M_\odot$ pc^{-3}
$\overline{\rho}$	0.145 ± 0.1 $M_\odot$ pc^{-3}
$\rho_{\rm arm}/\rho_{\rm interarm}$	≈ 1.8 (1.5)
$\Delta\Omega$	12.3 ± 1.4 km s^{-1} kpc^{-1}
$\Omega_{\rm P}$	13.6 ± 1.4 km s^{-1} kpc^{-1}
t_1 (Scrutum-Crux)	142 ± 8 Myr
W_1	0.36 kpc
t_2 (Sag-Car)	34 ± 6 Myr
W_2	0.28 kpc
ϕ_1	25 ± 10 (deg)
ϕ_2	100 ± 10 (deg)

In this figure the angles ϕ where the path of the solar system crosses the Sagitatius-Carina and Scrutum-Crux spiral arms are shown as dotted lines, the grey areas are one sigma variations due to the uncertainty in the exact locations of the arms. The two angles are related to the relative pattern speed as, $\phi(t) = \Delta\Omega t = (\Omega_0 - \Omega_{\rm P})t$. The pattern speed at the solar radius is not known with a high accuracy and values range from 5–20 km s^{-1} kpc^{-1}. Figure 3 (bottom panel) shows the relative phase angle $\phi(t)$ as function of time. On the plot are two points determining the position of the spiral arms crossings. On the coordinates on the ϕ-axis ϕ_1 and ϕ_2 are determined as mentioned above, and the coordinates on the time-axis are given by the positions, t_1 and t_2, of two maximums in the density function. The two circles are one and two sigma uncertainties. The relative pattern speed that is consistent with the points (t_1, ϕ_1) and (t_2, ϕ_2) is shown in the Fig 3 bottom panel as the red curve and found to be $\Delta\Omega = \Omega_0 - \Omega_{\rm P}$ = 12.3 ± 1.4 km s^{-1} kpc^{-1}. This result is consistent with resent estimates (Shaviv 2003a; Gies & Helsel 2005). Parameters determined in this study are listed in Table 2.

3 Cosmic ray variation perpendicular to the Galactic plane

Although there is an internal consistency in the above there is one remaining problem. The variation in δ^{18}O in Fig. 3, is of the order 1 ‰, or ≈ 2°C. Using a climate sensitivity of cosmic rays of 1% CR change ≈ 0.06 ± 0.035° C (Shaviv 2003), suggest that the cosmic ray variation should be of the order of 30^{+40}_{-10} %. Estimates of the galactic cosmic ray pressure variation are only of the order 10–30% at distance ≈ 100 pc. The large variation is obtained by Boulares & Cox (1990) where they assume that the cosmic diffusion constant increases with distance from the Galactic plane. Apart from the cosmic ray variation the gas density decreases with about 30 % at 100 pc which, due to a pressure balance between the ISM and the heliosphere, will result in a larger heliosphere. A larger heliosphere will screen better against the cosmic rays, adding to the CR variation. There are however large uncertainties in the actual cosmic ray distribution, and future work must determine the cosmic ray distribution with respect to the Galactic midplane (Boulares & Cox 1990).

4 Conclusion

A possible connection between climate and the Solar system's motion perpendicular to the Galactic plane during the last 200 Myr has been found. In δ^{18}O proxy data of Earth's climate from the Phanerozoic database an approximately 30 Myr period is identified. From small frequency modulations of this period the following features of the Galaxy along the Solar circle can be determined: 1) the mass distribution, 2) the timing of two spiral arm crossings (31 Myr and 142 Myr) 3) Spiral arm/interarm ratio ($\rho_{\rm arm}/\rho_{\rm interarm} \approx 1.5 - 1.8$), and finally, using current knowledge of spiral arm positions, a pattern speed of $\Omega_{\rm P} = 13.6 \pm 1.4\,{\rm km\,s^{-1}\,kpc^{-1}}$ is found.

It is important to note that the present study is fundamentally different from the previous ones in one respect. It determines several features of two most recent spiral arm passages from climate data restricted to modulation of time scales between 20–60 Myr, much shorter than the characteristic time for spiral passage $\approx$ 140 Myr. The results obtained are consistent with previously reported properties of the Milky Way and give further confidence in the significance of cosmic ray variations and importance in climate changes.

The possibility that detailed information of the Milky Way along the solar circle is stored in the Earth's climate is remarkable.

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