A Galactic Theory of Climate

Steven Wickson, Astrophysicist
srwickso@ucalgary.ca kozmoklimate@gmail.com 1-403-734-2118
P.O. Box 279, Gleichen, Alberta, Canada, T0J 1N0

Abstract

Based on mathematical analysis of Earth's glacial history and the record of mass extinctions over the Phanerozoic Era, past and recent theories have explored possible connections between geological history and the solar system's motion in the galaxy. Building on new evidence for these claims, this paper proposes a new mechanism for galactic influences on terrestrial climate: the moderation of galactic cosmic ray flux by the expanding and contracting Oort cloud under the influence of the galactic tidal field. This paper describes a model for the sun's orbit in the galaxy that can be tested against astronomical observations of the galaxy and paleoclimate studies from around the world.

Keywords: ice age, mass extinction, galaxy, cycle

1. Introduction

Over the last 600 million years, the Earth has experienced some remarkable changes, some of which are told through the archives of the geological record. The story of Earth's climate through the Phanerozoic Eon includes a number of episodes of continental glaciations (Frakes et al. 1992), as well as prolonged periods when polar regions supported subtropical rainforests (Clarke and Jenkyns 1999). Over the last one hundred years a number of authors have attributed these large-scale variations in global climate to the solar system's motion in the galaxy. Early theories on this subject pointed to the Sun's 200-300 million year orbit around the center of the galaxy and the somewhat periodic occurrences of glacial epochs (Steiner and Grillmair 1973). Raup and Sepkoski (1984) proposed a link between the solar system's motion with respect to the plane of the galaxy and a 26 Myr periodicity of mass extinctions in the fossil record. Veizer & Shaviv (2003) proposed a correlation between Earth's climate and galactic cosmic rays according to an analysis of cosmogenic isotopes in ancient meteorites that was compared with the most complete reconstruction of the paleoclimatic record that was available. Svensmark (2007) describes the Earth's climate system responding to its galactic environment through a varying external cosmic ray flux, balanced against the varying activity of the solar wind. The recent experimental support that this theory has encountered with the cloud chamber experiment of Marsh and Svensmark (2000) and the close correlation between cosmic ray activity and low cloud cover observations makes this one of the most exciting new areas of research in twenty-first century climate science.

This paper aims to provide support for the theory of galactically driven climate change through an analysis of recent reconstructions of Phanerozoic paleoclimate in a mathematical framework. It demonstrates the strength of the galactic theory in explaining climatic variations over timescales of millions of years, and then describe the current scientific understanding of exogenic mechanisms that influence climate conditions for planets in the solar system. It also examines some of the shortcomings of the models of Shaviv (2002) and Svensmark, such as the large uncertainty in the Milky Way

Galaxy's spiral arm pattern speed. Finally, it presents some possibilities for other galactic mechanisms that may influence climate in addition to cosmic ray variation.

2. Archives of Climate History

The Earth can tell us information about past environmental conditions in numerous ways. Traditionally, one of the most-studied souces has been the Earth's glacial record, which is summarized in Table 1 and Figure 1 based on the work of Frakes et al. (1992) and Crowell (1999). Glacial tillite was observed in Pennsylvanian aged rocks in the late 1800s. There is a remarkable absence of glacial tillites in 185 million years of Mesozoic rocks, although evidence from Antarctica and Australia suggests a brief cool interval in the late Jurassic and early Cretaceous (Frakes et al. 1992). Evidence for glaciation also appears in Ordovician strata from Africa and a very intense glacial period in the late Proterozoic called the Marinoan/Varangian glaciation, popularly referred to as Snowball Earth (Hoffman et al. 1998). These glacial deposits provided the first clues for dramatic alterations in the Earth's climate over long timescales and were considered by some to exhibit periodic behaviour. Galactic influences were proposed to account for glacial episodes as early as the 1920s. In 1973, Steiner and Grillmair proposed that glacial episodes were linked to the Sun's eccentric orbit in the galaxy and the solar system's response to a varying interstellar medium. In more recent papers, Shaviv and Svensmark attribute megayear scale glacial epochs to the solar system's passage through spiral arms of the galaxy as a result of an increased galactic cosmic ray flux. The glacial record provides a first draft for the Earth's climate history through geological interpretation of the fundamental thermodynamic properties of water.

Midpoint of Ice Age Epochs			Perigalacticon Passages
Frakes 1992	Crowell 1999	Veizer 2000	Wickson 2007
< 28	< 15	~ 30	~ -10
~ 144	~ 155	~ 180	~ 140
~ 293	~ 325	~ 310	~ 290
~ 440	~ 450	~ 450	~ 440
~ 588	~ 595		~ 590
~ 765	~ 730		~ 740
~ 940	~ 900		~ 890

Table 1. Ice Ages over Phanerozoic time from Crowell 1999, Frakes 1992 and Veizer 2000 and perigalacticon passages defined by the new model of the solar system's motion in the galaxy.

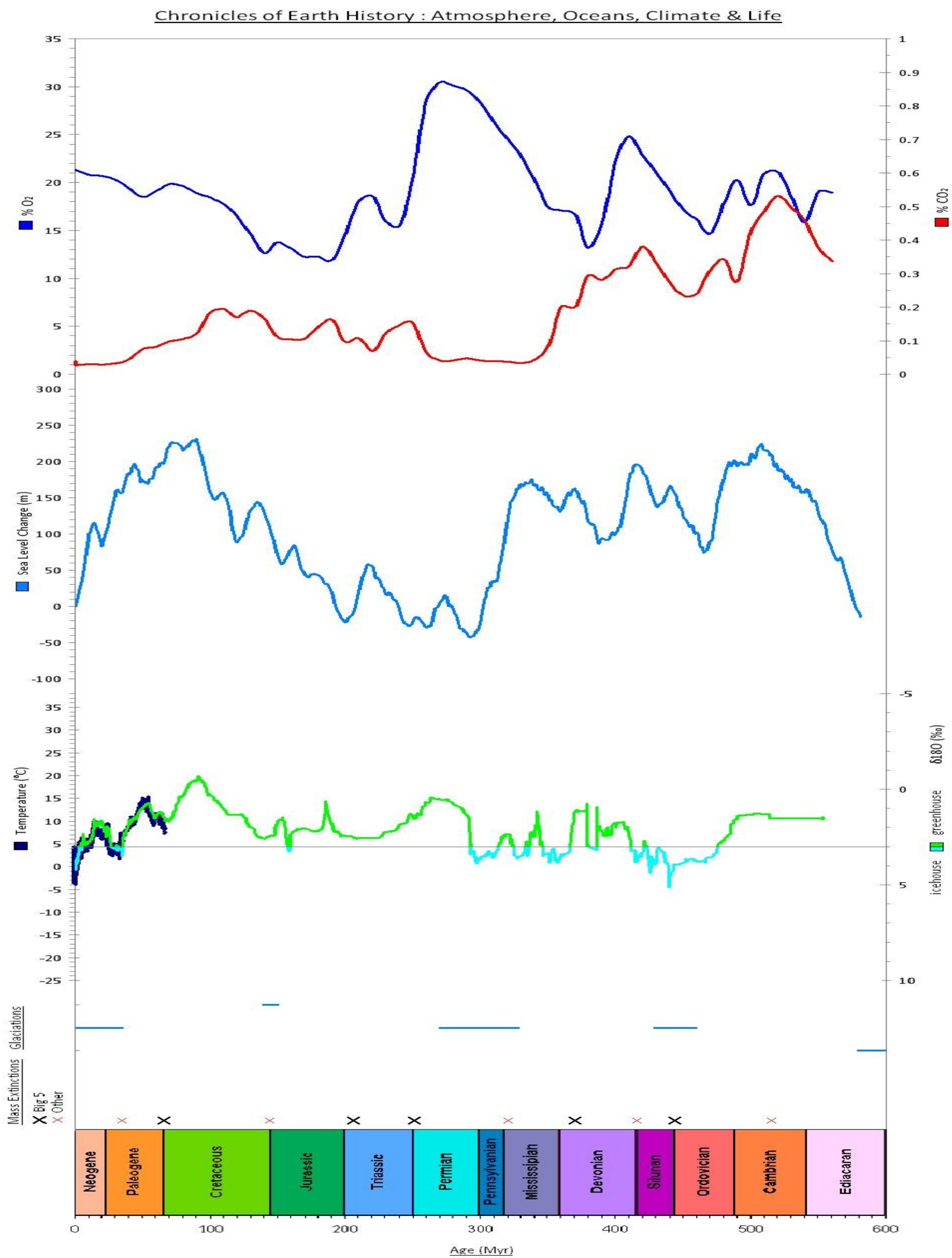

Fig. 1. Concentration of atmospheric O2 and CO2, sea level, temperature, glaciations and extinction events over Phanerozoic time, using the ICS Geological Timescale 2004.

A more detailed paleoclimatic record is available through analysis of isotopes that act as paleotemperature proxies. The most extensive record presently available is from Veizer et al. (2004), who compiled data using oxygen isotope measurements of a variety of different shelled fossil organisms, shown in the lower portion of Figure 1. Veizer's original Phanerozoic curve showed very low $\delta^{18}O$ values for the early Paleozoic, suggesting sea temperatures of around 50°C. The corrected paleotemperature curve, displayed in Figure 1 and smoothed with a 30 Myr gaussian weighted moving average, shows a climate history that more clearly represents the events in the glacial record and fossil record and more closely resembles the traditional paleoclimatic history of the last 600 million years.

Also plotted in Figure 1 is a Phanerozoic sea level reconstruction from Exxon, (1988). Sea level appears to have an interesting correlation with paleotemperature except in one interval, from the Mississipian to the Jurassic. The noticeably low sea levels at this time are believed to be a result of the formation of the supercontinent of Pangea (Hallam 1992), suggesting Earthly factors have a large role in determining the planet's environmental properties. Carbon dioxide concentration in the atmosphere is believed by some to be the driver of climate on all timescales (Royer et al. 2004), although this is questioned in Veizer et al. (2000). The volcanically corrected atmospheric CO_2 reconstruction shown in Figure 1 is from Berner (2006). A clear correlation is claimed by a few scientists, but some point to the Ordovician glaciation of 440 million years ago occurring when the atmosphere contained at least five times the level of CO_2 in today's atmosphere as a reason to search for other drivers of terrestrial climate change on this scale.

Other interesting records that can shed light on the Earth's past environmental conditions are extinctions in the fossil record. Mass extinctions such as the K-T extinction that wiped out the dinosaurs 65 million years ago can serve to indicate times of environmental stress that had biological consequences. The most dramatic mass extinction events in the Phanerozoic were nicknamed the "Big Five" by the paleontologist Jack Sepkoski (1994). These are identified in Figure 1 along with other important extinction events defined in Muller and Rohde's analysis of the fossil record (2005). Some mass extinction events are suggested to be the result of bollide impacts (Alvarez et al. 1980) or major volcanic eruptions (Wignall 2001), but the causes of the different extinction events of the Phanerozoic are still hotly debated in scientific circles. The mass extinction record may be able to relay some additional information to us following an analysis of the climate record.

3. The Sun's orbit in the Galaxy

Climate varies on a multitude of different timescales, often in cyclical patterns. The main oscillations in hemispherical and global environmental conditions are linked in some way to astronomical cycles. The most pronounced of these cycles are the 24 hour daily cycle and the seasons of the year, which are driven by the rotation of the Earth and the revolution of the Earth around the Sun. On decadal and centurial timescales there are a number of cyclical climatic variations that have been described as following Sunspot cycles (Friis-Christensen and Lassen 1991). An apparent 2400 year climatic cycle of is attributed by some to the Sun's motion with respect to the center of mass of the solar system (Charvatova 2000). On even larger timescales, the Milankovitch orbital theory is used to explain the advance and retreat of continental glaciers over the last two million years (Berger 1988). Given this progression, it is only natural to believe that large scale variations in climate over the Phanerozoic would be linked to some astronomical forcing, although that would lead us to searching outside of the solar system. As long as the pattern is at least somewhat periodic, we have reason to believe that the ebb and flow of icehouse conditions over the last 600 million years may have its root in the solar system's motion in the galaxy.

The Sun is one of many millions of stars that orbits around the galactic center. Like most stars in the galaxy's disk, the Sun revolves in a rosette-shaped precessing elliptical orbit like the one shown in Figure 2, which illustrates one model for the Sun's orbit. The standard values for the Sun's galactocentric radius and circular velocity, 8.5 kpc and 220 kms-1 (Bash 1986), which places the Sun's circular period at approximately 237 million years. This defines the local standard of rest, which is the average velocity of stars in the stellar neighbourhood. In addition to the Sun's circular motion, it oscillates in the radial direction as a result of its slightly elliptical orbit with an eccentricity of 0.07 (Bash 1986). The Sun is currently approaching perigalacticon, which will occur in approximately 15 million years (Bash 1986). Perigalacticon represents the closest point in a star's orbit to the galactic center, and so our galactocentric radius is now decreasing. Stars like the Sun also exhibit vertical sinusoidal motion with respect to the galactic plane, as they are constantly accelerated towards the regions with increased density. The orbits displayed in Figure 3 are based on the work of Bash, 1986 [24], where the Sun last passed through the galactic plane 2.1 million years ago and travels with a vertical oscillation half-period of approximately 33 million years.

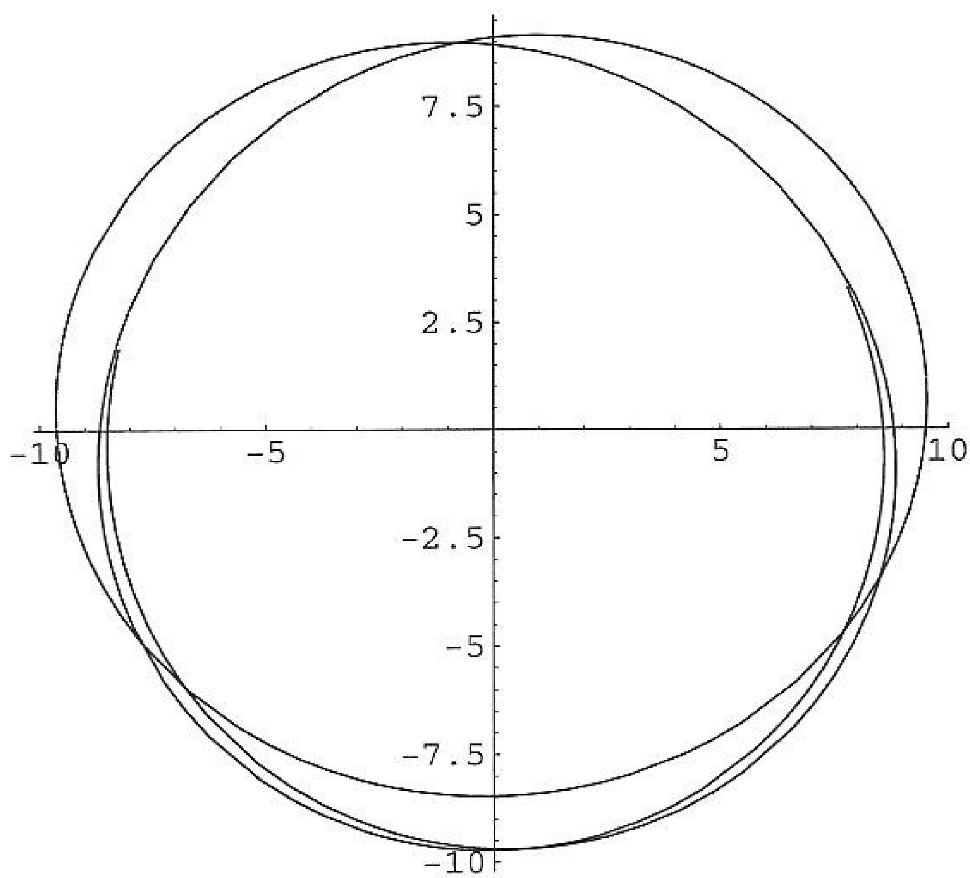

Fig.2 . The solar system's motion in the plane of the galaxy from 601 million years ago to 15 million years into the future, measured in kiloparsecs.

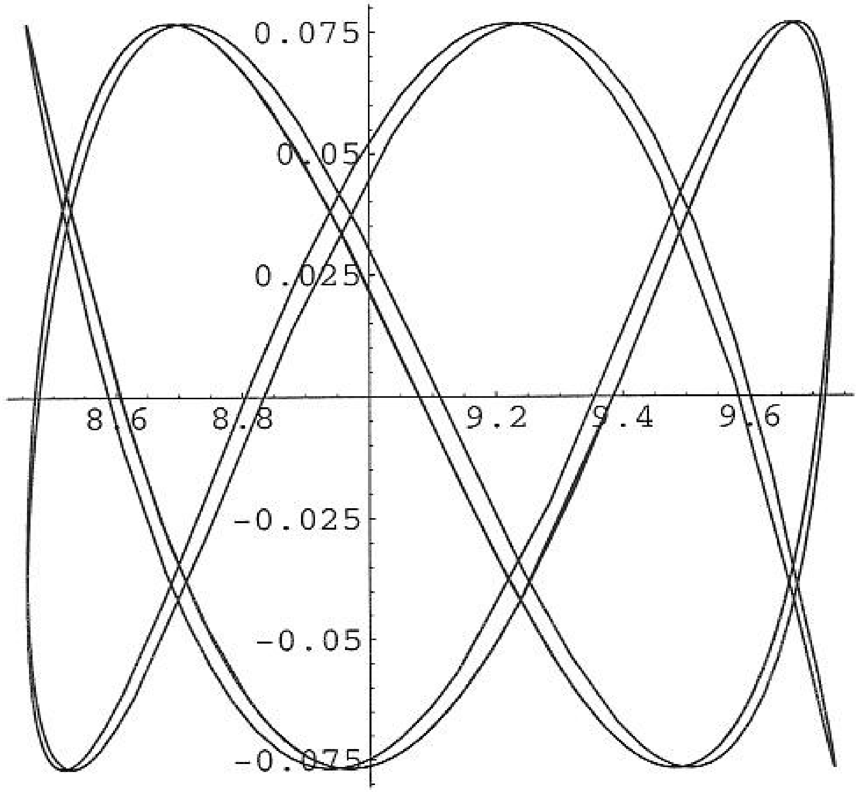

Fig. 3. The solar system's motion in the R-Z plane from 601 million years ago to 15 million years into the future, measured in kiloparsecs.

The galactic cycle that has received the most attention in recent literature is the solar system's periodic passages through the spiral arms of the galaxy. However, the current scientific understanding of spiral structure and dynamics is severely limited and there is a wide range of uncertainty for the pattern speed of the spiral arms [25]. This has allowed many authors to simply pick whatever pattern speed they need to satisfy their model of galactically induced climate change, without any tests to verify their conclusions. Although spiral arm passages are crucial events for the Sun's orbit in the galaxy, this paper aims to use an alternative approach to viewing the problem and will reserve discussion of the spiral arm free parameter until other galactic cycles have been examined in detail.

Another cyclical process that may be of interest is the orbit of the Magellanic cloud galaxies around the Milky Way. This is described in a recent paper by Shaviv (2003), suggesting that the proximity of the Large Magellanic Cloud to the galactic plane may cause additional cosmic ray flux. The orbit of these satellite galaxies has been reconstructed through recent astronomical observations (Lin and Lynden-Bell 1982), so it is worth examining for potential impacts on the galactic climate change hypothesis.

4. Climate in a Galactic Context

We can now compare the long term geological record to the solar system's motion in the galaxy and see if there is any correlation between the two. First, we will begin by comparing the highest frequency galactic cycle, vertical oscillation, to the most well resolved portion of the Phanerozoic paleotemperature curve, the last 100 million years. The Sun undergoes vertical oscillation according to an approximately sinusoidal function, with a half period of 33 million years, which represents the period of time between galactic plane crossings. The last time the solar system passed through the plane of the galaxy was 2.1 million years, representing the last vertical minimum. Using this information, a function that approximates the Sun's local galactic density is plotted in Figure 4 alongside Veizer's paleotemperature record of the last 100 million years (Figure 5). This displays the most convincing evidence that exists for the Sun's orbit in the galaxy influencing environmental conditions on Earth. The paleotemperature record appears to exhibit oscillation with roughly the same period and phase of the Sun's vertical motion in the galaxy. The local minimums in the temperature data appear to occur near the dates of the galactic plane crossings and the local maximums appear to be centered at the crests of the vertical oscillation wave pattern.

In addition to an oscillation of about 33 million years, the temperature record exhibits an overall downward trend over the last 100 million years. This is observed in the geological record with the evolution from a worldwide tropical paradise in the mid Cretaceous to an icehouse world that supported extensive continental glaciations for most of the Pleistocene. This is perhaps a reflection of the Sun's motion towards perigalacticon over the Cenozoic Era. Astronomical observations suggest the Sun will reach perigalacticon within the next 15 million years, although the value for the anomalistic period of the Sun's orbit, representing the period of time between two successive perigalacticon passages, is much less ambiguous. The current best estimate for the Sun's anomalistic period are in the range 170+/-10 Myr (Gies and Helsel 2005). Although based on certain elements of the geological record, a value closer to 150 Myr seems more appropriate. The trend of gradual cooling over the Cenozoic based on the solar system's motion towards perigalacticon is consistent with the idea that local temperature minimums occur near galactic plane crossings because both events relate to an increased density in the local galactic environment and hence an increased exposure to galactic cosmic rays. The models of Shaviv and Svensmark for the Sun's orbit do not include radial oscillation and assume a more or less circular orbit in the galaxy. These authors posit periodic glaciations to the solar system's passage through spiral arms of the galaxy because cosmic ray flux is greater in spiral arms than the rest of the interstellar medium.

Shaviv suggests a 140 Myr cycle of cosmic ray activity that reflects the periodicity of spiral arm passages and this is roughly consistent with the conventional dates for glacial periods over the Phanerozoic, although there are a number of criticisms to this hypothesis.

Firstly, measurements of the Milky Way's spiral arm pattern speed have a wide range of values from 12 to 25 $kms^{-1}kpc^{-1}$ (Martos 2004), placing the period between spiral arm passages in a four armed system in the range of uncertainty between 110 Myr and 1.7 Gyr. This allows selection of the relatively ambiguous parameter from a wide range of values.

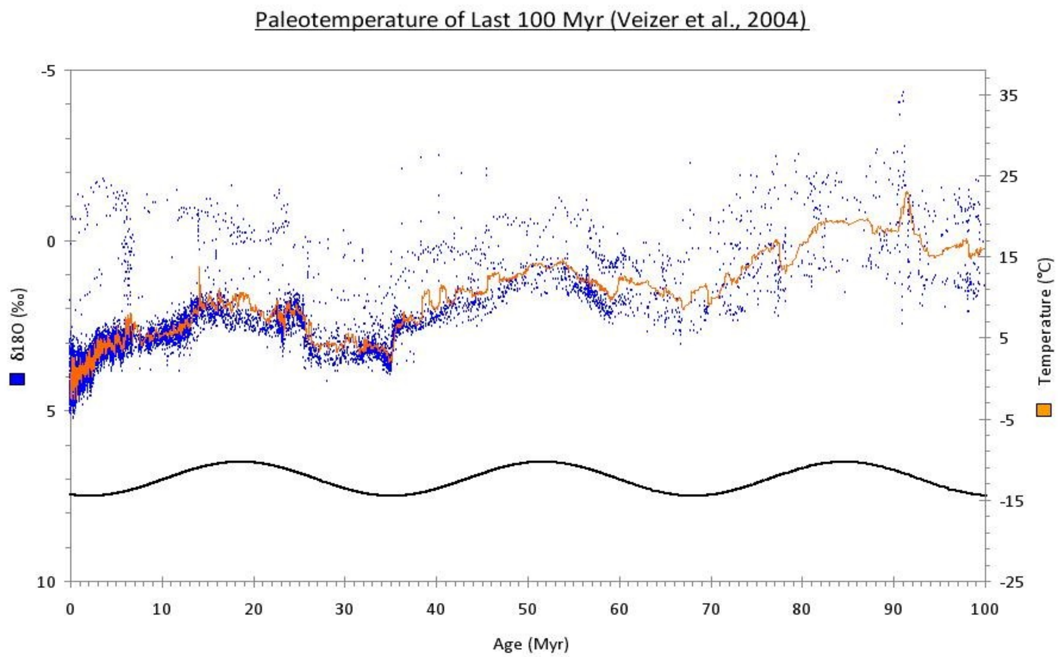

Fig. 4. Oxygen isotope paleotemperature of the last 100 Myr compared with the solar system's motion perpendicular to the galactic plane.

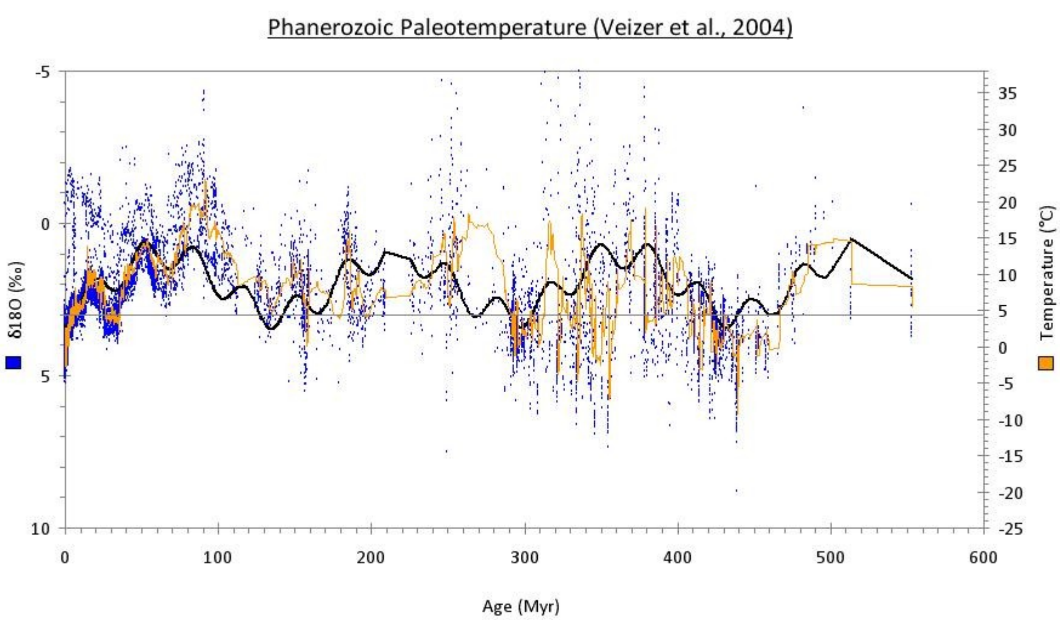

Fig. 5. Oxygen isotope paleotemperature of the last 600 Myr compared with the solar system's radial and vertical motion in the galaxy.

The second major criticism of the Shaviv model is that the Earth is experiencing icehouse conditions today, but it is not located near any of the major spiral arms. To mend this, Shaviv points to the solar system's recent passage through the Orion spur, which is a spiral arm fragment. It does not make sense, as the relatively minor icehouse conditions in the early Cretaceous period 150 mya and the Oligocene 35 mya are being attributed to passages through the very prominent Scutum-Crux and Sagittarius-Carina arms, whereas the vastly more extensive current glaciation is being attributed to the proximity to a feature that would not be discernable to observers that weren't in its immediate vicinity. The late Cenozoic icehouse is more satisfactorily explained by a combination of the Sun's recent passage through the galactic plane and its proximity to perigalacticon in its orbit, and possibly Earthly factors as well.

Another important point to mention is that spiral arm passages are relatively short and far between. If glacial episodes were indeed linked to spiral arm passages then we would expect to see a rapid descent into glacial conditions when the solar system enters the spiral arm followed by a sharp increase in temperature back to average conditions a few million years later as the solar system exits the vicinity of the spiral arm. In other words, if Shaviv's hypothesis were correct, we would expect the low frequency paleoclimate signal to look more or less like a flat line with dips every 150 Myr, instead of the wave like pattern we see in Figure 4 or in Shaviv's own publications. The Sun's radial oscillation in the galaxy offers an alternative mechanism for the occurrence of periodic glaciations over Phanerozoic time that is more consistent with the paleoclimatic record.

5. Mechanisms

Nearly all theories concerning galactically induced climatic change are concerned with the solar system's response to varying conditions in the local interstellar medium. The first mention of a link between Earth's climate and galactic position in scientific literature is found in Shapley (1921), which proposed that solar luminosity varied as a result of its changing galactic environment. Forbes (1931) and Umbgrove (1942) proposed that the main driver of large scale climatic variation was interstellar dust that prevented solar radiation from reaching the Earth to varying degrees. Lungershausen (1957) remarked that the Sun's orbit in the galaxy was eccentric and "cosmic winters" were the result of the Sun travelling through the outer, less dense regions of the galaxy. In contrast to this hypothesis, Tamrazyan (1959) proposed ice ages were caused by the Sun's passage through dust clouds and nebulae in the galactic plane. In the 1970s, the galactic theory broadened and a number of hypotheses were explored by Williams (1975), McCrea (1975) and (Steiner and Grillmair 1973). He suggested that the changing galactocentric distance in the Sun's orbit affected the value of the gravitational constant, which in turn has an influence on tectonic, stratigraphic, geomagnetic and biological aspects of the planet. A set of conferences in the mid 1980s produced the book entitled The Galaxy and the Solar System, a collection of papers exploring various avenues of galaxy-solar system interactions, although paleoclimate had faded from the forefront in favour of bollide induced extinction events.
The galactic theory of climate was revived in recent years by geologist Jan Veizer and astrophysicist Nir Shaviv with a new mechanism: high energy cosmic rays bombarding the solar system from the rest of the galaxy. In the most recent rendition of this hypothesis, the Earth's magnetic field, the solar wind and the external influence of the galaxy are described as being in a delicate balance. This hypothesis has been strengthened by a number of recent experimental successes. The contributors of this theory appear to have produced a theory that genuinely explains a connection between the Earth's climate and

its local galactic environment, and it may be the culmination of nearly a century of daring scientists searching for an extraterrestrial mechanism to describe the patterns in the geological record. New research in this field will hopefully provide us with more insight into the interaction of the solar system and the galaxy, and will most likely generate some surprises and additional questions along the way.

Another mechanism that may be of interest to the galactic theory of climate is the interaction between the outer regions of the solar system and the galactic tidal field, leading to alterations in solar system geometry. The strength of the local galactic tidal field varies as the Sun orbits the galactic center and is at a high during perigalacticon, galactic plane crossings and passages through the spiral arms. This has been proposed to have a major influence on the activity of comets in the Oort cloud (Heisler and Tremaine 1986, Matese and Whitman 1992). When the solar system travels through a part of the galaxy where the tidal field is stronger, we expect the Oort cloud to be perturbed a little farther from the center of the solar system. On the contrary, when the local galactic tidal field strength is at a minimum, the solar system will be more tightly bound together, and the gravitational perturbations from the giant planets on the Oort cloud will be stronger. As a result, this may increase the probability of Oort cloud objects being pulled into the inner solar system, and increased comet activity or “comet showers” may occur near the Sun’s apogalacticon, or vertical maximums above and below the plane of the galaxy.

There are a few ways that comet activity may influence life on Earth or other planets. Firstly, there is the possibility that cometary impacts may be the important factor behind some of the mass extinctions observed in the fossil record (Rampino and Stothers 1984), (Davis et al. 1984), (Morris and Muller 1986), although many scientists believe most mass extinctions are explained completely through endogenic factors. The second possibility is that comets may deliver the “seeds of life” to newborn planets and perhaps may have been what caused life to originate on our planet (Hoyle and Wickramasinghe 1999), (Greenberg and Mendoza-Gomez 1992). Finally, there is the possibility that comet activity may influence climate and life on Earth by moderating the amount of galactic cosmic rays that enter the solar system.

In this case the Oort cloud acts a shield, absorbing some of the galactic cosmic rays that are solar system bound. Most Oort cloud objects are small icy bodies with an approximately spherical distribution around the solar system. When the galactic tide is high, the Oort cloud expands and the average separation between the particles in the outer solar system increases. This makes the solar system less opaque to the influence of external galactic cosmic rays. At low tide the Oort cloud is more condensed. This means the Earth becomes more opaque to the influence of external galactic cosmic rays.

6. New model of the Sun’s Orbit

This paper presents a new model of the solar system’s motion in the galaxy based on a mathematical analysis of the geological record. The Wickson model of the Sun’s orbit was also designed to make predictions in the paleoclimate record and the fossil record to further test the reality of galactic influences on Earth’s climate. It is described by three cycles that are regular and repeating. The first cycle is the vertical oscillation of the Sun’s orbit with respect to the galactic plane, which has a period of roughly 33 million years and a phase such that the last galactic plane passage occurred approximately 2.1 million years ago. This cycle affects global temperature based on the level of cosmic

ray activity in the solar system and predicts that local minimums in the temperature record will be centered around galactic plane crossings.
The second cycle is the Sun's radial oscillation in the galaxy, representing the solar system's motion from apastron to periastron in its orbit around the galactic center. I suggest this to have a periodicity of roughly 150 million years, and having a phase such that the next perigalacticon passage occurs approximately 10 million years into the future. Here, I speculate that the Sun's radial motion produces a lower frequency oscillation in the climate record as the amount of cosmic rays entering the solar system varies with local galactic density and the strength of the galactic tidal field. We expect to see ice ages in the geological record centered around perigalacticon passages, as suggested in Figure 4. Interestingly, we can also look for markers of apogalacticon passages, where the last three occur at the dates 65 mya, 215 mya and 365 mya. Therefore, the three previous galactic tidal minimums in the 150 Myr radial oscillation cycle in the new model of the Sun's orbit occur close to three of the Big Five mass extinctions.

The third galactic cycle that is important is the solar system's occasional passage through spiral arms in the galaxy, related to the Sun's angular velocity and the pattern speed of the galactic spiral arms. This cycle has a wide range of possibilities between 110 Myr and 1.7 Gyr, making it somewhat of a free parameter. I suggest a value of 185 Myr for the approximate period of the cycle, with the last spiral arm passage occurring around 65 million years ago, which is the date of the K-T extinction, which is similar to the hypothesis proposed by Goncharov and Orlov (2003). This proposition suggests spiral arm passages may be the main factor behind some mass extinction events in the fossil record, and is consistent with the P-T mass extinction event and the O-S mass extinction event occurring close to 250 mya and 435 mya. If this is the case then the new model for the Sun's orbit accounts for all of the Big Five mass extinctions with spiral arm crossings and apogalacticon passages, as displayed in Table 2.

Mass extinction episode	% extinction of species	Age, Myr	Apogalacticon Passages	Spiral Arm Passages
Cretaceous (K-T)	76	65	~ 65	~ 65
Triassic	76	208	~ 215	
Permian	96	245		~ 250
Devonian	82	367	~ 365	
Ordovician	85	439		~ 435

Table 2. The Big Five mass extinction events in the Phanerozoic marine fossil record and their intensities as defined in Jablonski 1991, compared with apogalacticon passages and spiral arm crossings defined by the new model of the solar system's motion in the galaxy.

7. Conclusion

The predictions of the new model for the Sun's orbit can be tested against both astronomical observations of the galaxy and the large scale geological record. Thus, we expect a better resolved and more complete climate record to exhibit statistically significant correlations with the long term trends suggested by the frequencies and phases of the sun's motion in the galaxy. Future studies in this field will hopefully produce more complete climate histories that fill in some of the gaps in the record and are more in harmony with paleovegetation and the glacial record.

If the results of these tests appear to suggest even a minor connection between the Sun's orbit in the galaxy and environmental conditions on Earth, the implications are extensive. Biological systems respond to alterations in environmental conditions. Therefore if the galaxy has an effect on terrestrial climate, does it not have an effect upon the evolution of life on our planet as well?
Finally, if this hypothesis is correct, we may be able to use the geological record to learn information about our galaxy that we cannot see with our eyes and our telescopes. Most of what we know about our galaxy has been deduced from astronomical observations over the last few centuries. However, on its journey through the cosmos, the Earth's climatic record acts as a flight recorder for the spaceship, preserving vital information about our planet's path through the galaxy. In this case, the geological record is a vast and invaluable resource, a tape that has been running for millions and billions of years that may shed light on things that have so far been hidden from view.

Acknowledgements

I would like to thank Phillip Langill, my undergraduate supervisor, for his assistance and encouragement, and Jan Veizer and Christoph Korte for their information on paleoclimate reconstructions. I would also like to thank any other people who were willing to provide me with information and all the people who took the time to help edit this article.

References

1. L.A.Frakes, J.E.Francis, J.I.Syktus, Climate Modes of the Phanerozoic, Cambridge University Press (1992)
2. L.J.Clarke, H.C.Jenkyns, New oxygen isotopic evidence for long-term Cretaceous climatic change in the Southern Hemisphere, Geology 27 (1999) 699-702
3. J.Steiner, E.Grillmair, Possible Causes for Periodic and Episodic Glaciations, Geol. Soc. America Bull. 84 (1973) 1003-1018
4. D.M.Raup, J.Sepkoski, Periodicity of Extinctions in the Geologic Past, Proceedings of the National Academy of Sciences 81 (1984) 801-805
5. N.Shaviv, J.Veizer, Celestial Driver of Phanerozoic Climate? Geol. Soc. America (July 2003) 4-10
6. H.Svensmark, Imprint of Galactic dynamics on Earth's climate, Astron. Nachr., 327 (2006) 866-870
7. H.Svensmark, Cosmoclimatology: a New Theory Emerges, Astronomy & Geophysics 48 (2007), 18-24
8. N.D.Marsh, H.Svensmark, Low Cloud Properties Influences by Cosmic Rays, Phys. Rev. Lett. 85 (2000) 5004-5007
9. N.Shaviv, Cosmic Ray Diffusion from Galactic Spiral Arms, Iron Meteorites and a Possible Climatic Connection, Phys. Rev. Lett. 89 (July 2002)
10. J.C.Crowell, Pre-Mesozoic Ice Ages: Their Bearing on Understanding the Climate System, Geological Survey of America (1999)
11. P.F.Hoffman, A.J.Kaufman, G.P.Halverson, D.P.Schrag, A Neoproterozoic Snowball Earth, Science, 281 (August 1998) 1342-1346
12. J.Veizer et al., Online database: http://www.science.uottawa.ca/geology/isotope_data/ (2004)
13. Haq et al. (1987), Ross & Ross (1987), Ross & Ross (1988), Online database: http://hydro.geosc.psu.edu/Sed_html/strata_front_page.html
14. A.Hallam, Phanerozoic Sea Level Changes, Columbia University Press (1992)
15. D.L.Royer, R.A.Berner, I.P.Montanez, N.J.Tabor, D.J.Beerling, CO_2 as a primary driver of Phanerozoic climate, Geol. Soc. America Today 14 (July 2004) 4-10

16. J.Veizer, Y.Godderis, L.M.Francois, Evidence for Decoupling of atmospheric CO2 and global climate during the Phanerozoic Eon, Nature, 408 (2000) 651-652
17. R.A.Berner, Inclusion of the Weathering of Volcanic Rocks in the GEOCARBSULF model, American Journal of Science, 306 (May 2006) 295-302
18. J.J.Sepkoski , Extinction and the fossil record, Geotimes 39 (1994) 15-17
19. R.A.Rohde, R.A.Muller, Cycles in Fossil Diversity, Nature 434 (2005) 208-210
20. L.W.Alvarez, W.Alvarez, F.Asaro, H.V.Michel, Extraterrestrial Cause for the Cretaceous-Tertiary Extinction, Science, 208 (June 1980) 1095-1108
21. P.B.Wignall, Large igneous provinces and mass extinctions, Earth Science Reviews, 53 (2001) 1-33
22. E.Friis-Christensen, K.Lassen, Length of the Solar Cycle: An Indicator of Solar Activity Closely Associated with Climate, Science 254 (November 1991) 698-700
23. I.Charvatova, Can origin of the 2400 year cycle of solar activity be caused by solar inertial motion? Annales Geophysicae 18 (April 2000) 399-405
24. A.Berger, Milankovitch theory and climate, Reviews of Geophysics 26 (November 1988) 624-657
25. F.Bash, The Present, Past and Future Velocity of Nearby Stars: The Path of the Sun in 10^8 Years, in The Galaxy and the Solar System, ed. R.Smoluchowski, J.N.Bachall, M.S.Matthews (1986) 35-46
26. M.Martos, X.Hernandez, M.Yanez, E.Moreno, B.Pichardo, A plausible Galactic spiral pattern and its rotation speed, Mon. Not. R. Astr. Soc. 350 (2004)
27. N.Shaviv, The spiral structure of the Milky Way, cosmic rays, and ice age epochs on Earth, New Astronomy 8 (2003) 39-77
28. D.N.C.Lin, D.Lynden-Bell, On the proper motion of the Magellanic Clouds and the halo mass of our Galaxy, Mon. Not. R. Astr. Soc. 198 (1982) 707-721
29. D.R.Gies, J.W.Helsel, Ice Age Epochs and the Sun's Path Through the Galaxy, The Astrophysical Journal 626 (2005) 844-848
30. H.Shapley, Note on a possible factor in changes of geological climate, J. Geology 29 (1921) 502-504
31. W.T.M.Forbes, The great glacial cycle, Science 74 (1931) 294-295
32. J.H.F.Umbgrove, The Pulse of the Earth, The Hague (1942)
33. G.F.Lungershausen, Periodic changes in climate and the major glaciations of theglobe (some problems of historical palaeogeography and absolute chronology), Sovetskaya Geologiya 59 (1957) 88-115
34. G.P.Tamrazyan, Intermediate and deep focus earthquakes in connection with the Earth's cosmic space conditions, Izvestia Geofizika 4 (1959) 598-603
35. G.E.Williams, Possible relation between periodic glaciation and the flexure of the Galaxy, Earth and Planetary Science Letters 26 (1975) 361-369
36. W.H.McCrea, Ice ages and the Galaxy, Nature 255 (1975) 607-609
37. R.Smoluchowski, J.N.Bahcall, M.S.Matthews, The Galaxy and the Solar System, University of Arizona Press (1987)
38. J.Heisler, S.Tremaine, The Influence of the Galactic Tidal Field on the Oort Comet Cloud, Icarus 65 (1986) 13-26
39. J.J.Matese, P.G.Whitman, A Model of the Galactic Tidal Interaction with the Oort Comet Cloud, Celestial Mechanics and Dynamical Astronomy 54 (1992) 13-35
40. M.R.Rampino, R.B.Stothers, Terrestrial mass extinctions, cometary impacts and the Sun's motion perpendicular to the galactic plane, Nature 308 (April 1984) 709-712
41. M.Davis, P.Hut, R.A.Muller, Extinction of species by periodic comet showers, Nature 308 (1984) 715-717
42. D.E.Morris, R.A.Muller, Tidal gravitational forces- The infall of 'new' comets and comet showers, Icarus 65 (1986) 1-12
43. F.Hoyle, N.C.Wickramasinghe, Comets – A Vehicle for Panspermia, Astrophysics and Space Science 268 (1999) 333-341
44. J.M.Greenberg, C.X.Mendoza-Gomez, The seeding of life by comets, Adv. Space Res. 12 (1992) 169-80,.
45. G.N.Goncharov, V.V.Orlov, Global repeating events in the history of the Earth and the motion of the Sun in the Galaxy, Astronomy Reports 47 (November 2003) 925-933
46. F.M.Gradstein et al., A Geologic Time Scale 2004, Cambridge University Press (2004)
47. C.Korte, T.Jasper, H.W.Kozur, J.Veizer, δ18O and δ13C of Permian brachiopods: A record of seawater evolution and continental glaciation, Palaeogeography, Palaeoclimatology, Palaeoecology 224 (2005) 333-351
48. C.Korte, H.W.Kozur, J.Veizer, δ18O and δ13C of Triassic brachiopods and carbonate rocks as proxies for coeval seawater and paleotemperature, Palaeogeography, Palaeoclimatology, Palaeoecology 226 (2005) 287-306
49. D.Jablonski, Extinctions: A Paleontological Perspective, Science 253 (1991) 754-757

