Mapping the location of terrestrial impacts and extinctions onto the spiral arm structure of the Milky Way

Running head: Location of events in the spiral arms

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Abstract

High density regions within the spiral arms are expected to have profound effects on passing stars. Understanding of the potential effects on the Earth and our Solar System is dependent on a sufficient dynamic model of arm passage. Using a novel combination of data we derive a model of the timings of the Solar System through the spiral arms and the relationship to arm tracers such as methanol masers. This reveals that asteroid/comet impacts are significantly clustered near the spiral arms and within specific locations of an average arm structure. The end-Permian and end-Cretaceous extinctions are shown to be located within a small star formation region in two different arms. The start of the Solar System greater than 4.5 Ga occurs in the same region in a third arm. The model complements geo-chemical data in determining the relative importance of extra-Solar events in the diversification and extinction of life on Earth.

keywords: spiral arm, impact craters, extinctions, superchrons, star formation, density wave theory

Introduction

Density wave theory provides predictions of structuring of spiral galaxies with sequences of star formation, gas/dust and different aged stars through the arms (Pour-Imani *et al*. 2016; Vallée 2017a). Detailed studies of our own galaxy (Wu *et al.* 2014; Choi *et al.* 2014; Hachisuka *et al.* 2015) and others (Foyle *et al.* 2010; Schinnerer *et al.* 2017) empirically show increased rates of star formation in and around spiral arm structures. What are the consequences for our Solar System and life on Earth as we pass through the spiral arms of the Milky Way? The potential importance of passage through the spiral arms was noted in the late 1970s and early 1980s (Napier & Clube 1979; Clube & Napier 1984, Raup & Sepkoski 1984) and receives occasional scrutiny, especially with respect to its effect on climate and glaciation (Gies & Helsel 2005; Overholt et al. 2009; Svensmark 2012; Brink 2015), the timings of extinctions (Leitch & Vasisht 1998, Gillman & Erenler 2008; Filopović et al. 2013) and the role of gravitational perturbation during passage through regions of dense matter (Yabushita & Allen 1989; Kataoka *et al.* 2014; Nimura *et al.* 2016). Other studies and critiques of periodicity in impact cratering, extinctions and climate have focussed on shorter period events potentially related to oscillations through the galactic midplane (Rampino & Stothers 1984, Yabushita 2002, Rohde and Muller 2005, Lieberman & Melott 2007, Shaviv et al. 2014, Meier & Holm-Alwmark 2017).

Evidence on Earth for the galactic journey of the Solar System is expected to be found in the stratigraphic record of biological, geophysical and chemical changes. This includes events believed to be associated with passage through the arms, e.g. high iridium-cobalt ratios suggested as being indicative of encounters with molecular clouds (Nimura *et al.* 2016), superchrons as potential markers of inter-arm passage (Wendler 2004) and increased impact cratering (Clube & Napier 1984). Increasing accuracy of event ages (high-precision records), longer and more complete sets of environmental proxy data, and a more detailed understanding of the structure of the Milky Way (e.g. Bland-Hawthorn & Gerhard 2016; Urquhart *et al.* 2014; Vallée 2016, 2017a,b) collectively enhance opportunities for an interdisciplinary investigation of the potential effect of the galactic cycle of the Solar System. Clarifying the timings and mechanisms during galactic cycles is important for determining the extent to which Earth processes, at given points in time, can be viewed in isolation, or coupled to Solar System (e.g. Milankovitch) processes and extra-Solar drivers. If this can be achieved, then the galactic cycle may provide a unified theory of extinction and origination of life on Earth (Barash 2016).

The model presented here describes the possible relationship of Earth and Solar system events to the structure and substructure of the spiral arms of the Milky Way.

Methods

A four-arm structure is assumed, with arms modelled as logarithmic spirals with the same pitch of 13^{o} (median value for all arms; Tables 4 and 5, Vallée 2015). The galactic radius of the Solar System was set at 8.0 kpc (Vallée 2017b). The model uses Vallée's notation of ^{12}CO as the arm centre with more negative distances further from the galactic centre, corresponding to younger ages with passage through the arms (Vallée 2016). It is these arm centres that are modelled as logarithmic spirals. The publications of Vallée cited here present summaries and meta-analyses of many studies of the structure of the Milky Way.

The distances between the four arm centre spirals and the ^{12}CO marker locations given in Vallée 2016 (his Table 5, illustrated in our Figure 1, details in Appendix 1) were minimised by manipulating parameter *a* of the logarithmic spiral; radius is ae^{bt}, b = tan (pitch angle). For Sagittarius-Carina and Scutum-Crux-Centaurus the spiral was fitted between the two observed values (also agreeing with the start of Sagittarius but not fitted to that). The shortest Euclidean distance was found for a resolution of *t* to the nearest 0.0001.The distance between arm tracer galactic coordinates and the corresponding ^{12}CO coordinates was also determined (as used by Vallée), independent of the fitted spirals.

The model assumes a constant relative motion of our Solar System to the spiral arms and therefore that the galactic orbit angle is proportional to age, which can be determined once the galactic period, defined here as the time for the Solar System to pass through all arms and return to its original location, is known. The galactic period is constrained by estimates of the angular velocities of the Solar System and the spiral arms. Taking the weighted mean of 228 km/s for the Solar System (LSR, Table 1, Vallée 2017b) and values between 200 and 160 km/s for the spiral pattern (Table 2, Vallée 2017b) gives a range of galactic periods from 1750 to 720 Myr. This can be constrained further by considering superchrons as markers of inter-arm passage (Wendler 2004). In particular we assume that the superchrons end at a fixed distance (and therefore time) before the arms. The difference between the times of the last two superchrons (265 and 83.07 Ma, Belica *et al.* 2017, Wang *et al.* 2016) is therefore equivalent to the difference between the angles of the ^{12}CO centres of the two most recent arms (84.01 degrees), giving a galactic period of 779.58 Myr. Note that while the galactic period is fixed, the passage time between the arms can vary according to the structure in Figure 1. The higher Solar System velocity relative to spiral arm pattern is consistent with the assumption that the Solar System is below co-rotation radius and therefore predicted to pass through the arms of the Milky Way (Vallée 2017a). The process of velocity dispersion (Wielen 1977), which arises due to local fluctuations in the gravitational field of the galaxy and alters the individual orbits of stars in the galaxy, is a potential source of time-dependent variation in our estimate of the galactic period. Current estimates put the local stellar velocity dispersion near the Sun at 25 km/s (Rix & Bovy 2013), which is an order of magnitude less than the circular orbital velocity. The review of Bland-Hawthorn and Gerhard (2016) notes the difficulty of reliably modelling the velocity dispersion of a stellar population. We also note that there is no obvious time-dependent shift in the locations of the events considered here with respect to the locations of the spiral arms.

Based on a circular orbit of radius 8 kpc and a known galactic period, an event of a given age has a location whose distance from the modelled ^{12}CO arm centre can be determined. The shortest Euclidean distance was found by altering the value of t in the log spiral equation (to the nearest

0.0001). We contrast the distance of events from the modelled arm centre with the distance between the observed ^{12}CO location and arm tracers, including methanol masers, H I, H II, 870 μm dust and old stars (Vallée 2016, Tables 6-10 – our results differ from some of those presented in Table 3 of Vallee as we use different averaged values, see Appendix 1).

Earth and Solar System events considered in the results (Appendix 2) comprise the largest and most accurately-aged impacts (crater diameter greater than 20 km, age error ≤ 4 Myr), the top three most ecologically or taxonomically severe extinctions (four extinctions in total, McGhee *et al.* 2013), superchron ages over the last 2 Ga (Driscoll & Evans 2016, Wang *et al.* 2016, Belica *et al.* 2017), the earliest age of the Solar System (calcium-aluminium – rich inclusions, CAIs, Connelly *et al.* 2012; Connelly *et al.* 2017) and the origin of the Earth-moon system from a giant impact (Connelly & Bizzarro 2016). The extinctions may be viewed as solely Earth-based events or an inter-play of external events (e.g., impacts, molecular clouds) and Earth-based processes. Stratigraphic boundary ages and names follow Cohen *et al.* (2013) unless stated otherwise. The aim is to consider the relationship of galactic structure and arm sub-structure to a set of key events as a template for future work and to provide a broad base for discussion of potential mechanisms.

Three types of statistical analyses were employed. First, clustering of impacts or superchrons around the galactic orbit was tested against a Poisson distribution null model in which the probability of 0, 1, 2 … n events within an angle window is e^{-m}, me^{-m}, $(m^2/2!)e^{-m}$ … $(m^n/n!)e^{-m}$, where m is the density of events (per angle window). Superchron midpoints are assumed to be samples of the same event if less than the average duration of superchrons (details in Appendix 3). The location of clusters (mean and SE of angle) was then compared with the independently derived locations of arm centres. Second, we determine whether Earth-Solar System events are located within one standard error of the independently derived arm tracer locations and, finally, whether the fraction of events within a given range of arm tracers is significantly different from expected (likelihood ratio test).

Times/ages are reported to the nearest 0.1 Myr and distances to the nearest pc. In considering these differences it should be noted that a change of 0.1° galactic longitude equates to an average of 12 pc difference, which in turn relates to about 0.8 Myr near the arm centre.

Results

The last four arm-centre (^{12}CO) interceptions are predicted to have occurred at 57.9 Ma (Carina), 239.8 Ma (Crux-Centaurus), 478.8 Ma (Norma) and 659.3 Ma (Perseus). Thirteen of the 16 impacts occur in two significant clusters around the Carina and Crux-Centaurus arms (Figure 1), with six impacts from 6.8° to 35.2° (taking 0° as vertical with larger angle corresponding to earlier age) and seven impacts from 89.5 to 134.0° ($P<0.01$ for 29° and 45° windows respectively). The two impacts at 214.2° and 224.2° around the Norma arm have a probability of 0.07 (11° window). The means and SEs of the first two clusters of angles (24.1° ± 4.4 and 110.4° ± 6.7) overlap with the ^{12}CO arm centre angles for Carina and Crux-Centaurus (26.7° and 110.7° respectively). The third pair of impacts with a mean of 219.2° is within two degrees of the Norma centre (221.1°). Five of the superchron midpoints occur in two significant clusters at midpoints of 134.9° ($P<10^{-4}$, 3 superchrons) and 236.4° ($P<0.01$), 24.2° and 15.3° prior to the arm midpoints of Crux-Centaurus and Norma. A third cluster of two superchrons at 37.1° and 10.4° before the Carina arm is marginally non-significant ($P=0.08$). The earliest Solar System and Earth-Moon system precede the Perseus and Norma arms by 4.7° and 20.7° (midpoint).

Entry into the arms occurs at about 400 pc (first marker at 440 pc, superchron end at 374 pc), with passage through the methanol maser and 870 μm dust regions, followed by HI after the ^{12}CO centre (Figure 2, combining data across all four arms). The observed HII and old star regions are much wider (Figure 2); the range of the methanol maser, HI and 870 μm dust tracers are 248 pc, 138 pc and 179 pc respectively, compared with 828 pc and 600 pc for the HII and old star tracers (the SEs in Figure 2 are approximately 1/6 of the full range, details of tracer locations in Appendix 1).

Thirteen of the 16 impacts occur within the widest arm regions from 440 to -660 pc (Figure 2) equivalent to 77 Myr. The observed duration of these impacts including errors is from 76.5 Ma to the equivalent of 192.7 Ma (10.8 Ma), i.e., 65.7 Myr. Taking the arm tracer range as an extrinsic (and more conservative) hypothesis, the probability of 13 out of 16 events occurring in 0.395 of the time, i.e., (4 x 77)/779.6, is P=0.0006 (G=11.72, likelihood ratio test). Two impacts prior to the earliest arm tracer in the Crux-Centaurus arm (286 and 1849 Ma) overlap with the location of the Earth-Moon system in the Norma arm (4426-4411 Ma).

The arms include the four most severe extinctions, in terms of either taxonomic ranking (end-Permian, end-Triassic and end-Ordovician) or ecological ranking (end-Permian, end-Cretaceous and end-Triassic). The end-Permian (178 pc, Crux-Centaurus) and end-Cretaceous (119 pc, Carina) extinctions are within 1 SE of the methanol maser average (mean 156 ± 1 SE from 118 – 195 pc, Figure 2). The midpoint location of the two extinctions (149 pc) is very close to the earliest Solar System value (148 pc) in the Perseus arm and within 10 pc of the methanol maser average. The end-Ordovician and end-Triassic extinctions are located at -473 and -536 pc in the Norma and Crux-Centaurus arms, with separation similar to that of the end-Permian and end-Cretaceous.

Discussion

A significant fraction of the largest impacts and the top three most ecologically or taxonomically severe extinctions are located within the spiral arms according to the model presented here. A notable example is the end-Cretaceous extinction, well-known as the final demise of the dinosaurs set against a backdrop of fluctuating global climate (Bowman *et al.* 2014, Thibault *et al.* 2016). The proximal triggers for this extinction are debated but have centred mostly on the Chicxulub impact (Renne *et al.* 2013) and the Deccan traps (Parisio *et al.* 2016). Nimura *et al.* (2016) use the iridium-cobalt ratio as an extraterrestrial index to hypothesise interactions with a giant molecular cloud from about 71 to 65 Ma (using 66 Ma as the end-Cretaceous age), overlapping with intermittent cooling from about 71.6 to 66.4 Ma (Thibault *et al.* 2016). This timing is consistent with the methanol maser mean location ± 1 SE (Figure 2), equivalent to 71.1 to 66.0 Ma. The geological study of Nimura *et al.* (2016), combined with insights into the possible effects of molecular clouds (Yabushita & Allen 1989, Kataoka *et al.* 2014), complements the galactic model presented here. The end-Permian extinction, the most severe both taxonomically and ecologically (McGhee *et al.* 2013), is predicted to occur in the Crux-Centaurus arm, at an approximately equal distance from the methanol maser average as the end-Cretaceous extinction.

Methanol masers are indicative of regions of high star formation (Fontani *et al.* 2010). Indeed, the current model places the earliest age of our own Solar System (CAIs) within 10 pc of the methanol maser average in the Perseus arm. The CAIs formed from heating and rapid cooling of dust approximately 1-2 Myr after gravitational collapse within a molecular cloud (Amelin & Ireland 2013). Passage through high mass/density regions offers various possibilities for mechanisms underpinning proximal extinction triggers, including rapid climate change (possibly due to enhanced Milankovitch effects), higher frequency of asteroid/comet impacts including extrasolar induced gravitational scattering events of minor planets (Malmberg *et al.* 2011; Goździewski *et al.* 2010) and orbital perturbation of Oort cloud objects (Collins & Sari 2010; Kenyon & Bromley 2004), increased magmatic activity (altered Earth tides) and higher cosmic ray incidence (Benyamin *et al.* 2016). Regions of high star formation are also linked to supernovae which, along with possibly related gamma ray bursts, have been suggested as causes of extinctions (Russell & Tucker 1971; Ellis & Schramm 1995; Melott *et al.* 2004).

Evidence from our own Solar System (Batygin & Brown 2016; Bromley & Kenyon 2016) and many recently discovered exoplanets implies gravitational scattering events are common during the dynamic evolution of planetary systems (Bromley & Kenyon 2016; Ford 2014; Bromley & Kenyon 2011; Chatterjee *et al.* 2008; Ford & Rasio 2008; Weidenschilling & Marzari et al. 1996). Furthermore, large gas giants that undergo gravitational scattering are likely to lose their moons when located $> 0.1\ R_{hill}$ from a giant gas planet (Hong *et al.* 2018). Consequently, gravitational scattering of large planets can cause a cascade of minor planets to become de-stabilised, leading to a rise in planetary impacts. The recent discovery of the interstellar asteroid 1I/2017 U1 in the solar system and analysis of its orbital energy point to an extrasolar scattering (Wright 2017).

An exciting outcome of the present study is that passage through star formation regions may underpin the largest extinctions and cross-reference to the location of the origin of our Solar System. A dynamic model of the galactic journey of our Solar System offers the possibility of determining the degree to which the galactic journey contributes to the stratigraphic pattern of geological change. Conversely, while the predictions of this model are clearly dependent on a set of assumptions about the dynamics and structure of the Milky Way, the increasingly accurate multi-proxy stratigraphic record may provide further checks of those assumptions. Finally, there is the opportunity to investigate the extent to which models of spiral arm passage relate to suggested shorter (quasi)periodic cycles of extinctions, impacts and climate.

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Figure legends

Figure 1. Logarithmic spiral model of the Milky Way showing ^{12}CO central lines and ^{12}CO markers (x) with arm labels. Both the spiral pattern and our Solar System (located at the top, on a radius of 8 kpc, dashed circle) move clockwise, the Solar System at a faster velocity and therefore passing through the arms. The locations of impacts (diamonds), superchron cluster midpoints (squares) and early Solar System (open circle) are shown on the Solar System orbit.

Figure 2. Relationship of impacts (diamond), extinctions (circles) and early Solar System (+) to arm tracer locations during passage through the spiral arms. The labels on the impacts, extinctions and Solar System events are absolute ages (Ma, to nearest 0.1 Myr). Ages relate to different arm passage as follows: Carina (76 to 14 Ma), Crux-Centaurus (254 to 193 Ma, 1849 Ma), Norma (485 to 445 Ma, 4420 Ma) and Perseus (4567 Ma). The impacts are divided into greater and less than 50 km diameter craters (upper and lower lines respectively). The error bars on the arm tracers are 1 SE (across all arms, multiple markers within one arm are themselves averaged). The two crosses indicate the first

and last arm markers. The vertical dashed line indicates the end of the last two superchrons (used in calculation of the galactic period and assumed to be an equal distance from the arm centre).