

From the grain to galactic scale; Milky Way neutral hydrogen and terrestrial zircon oxygen support coupling of astrophysical and geological processes over deep-time

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Neutral hydrogen (HI) is fundamental for tracing spiral structure in galaxies, including the Milky Way, through its 21-cm emission line, revealing features otherwise obscured by dust and gas. However, much of the Milky Way remains poorly resolved due to the Solar System's embedded location within the galactic disk. Here, we present the first direct comparison between zircon oxygen isotope kurtosis, a terrestrial deep time record, and spatial variations in HI density along the Solar System's galactic orbit. Significant correlations between Earth's magmatic zircon oxygen isotope kurtosis and HI density in spiral arms suggest astrophysical influences on Earth's crustal evolution. Peaks in HI density near the Scutum-Centaurus and Perseus spiral arms are consistent with the hypothesis that periodic disruptions of the Oort cloud during galactic arm crossings increased impact rates on Earth. These periods of elevated impact flux may have contributed substantial thermal energy, leading to more variable magmatic petrogenesis. This variability is recorded by zircon oxygen isotopes, a proxy sensitive to the depth of crustal melting and the degree of interaction with surface-derived water. These results provide new insights into the interplay between galactic-scale processes and Earth's geological history, arguing for consideration of astrophysical drivers of planetary evolution.

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I. INTRODUCTION

Neutral hydrogen (HI) consists of hydrogen atoms where a single proton is orbited by a single electron, resulting in a neutral, nonionized atom. HI is the most abundant form of hydrogen in the universe and is widely used to reconstruct spiral galaxies due to the significant fraction of it comprising the interstellar medium (ISM) [1]. HI can be detected through its characteristic emission at a wavelength of 21 cm (1420.4 MHz), within the radio region of the electromagnetic spectrum [2]. The longer wavelength of radio waves than visible light means that these waves are not scattered by the ISM, enabling them to penetrate dense dust and gas that would otherwise obscure large regions of galaxies from observation [3]. Hence, radio-based observations offer advantages over optical telescopes for mapping of spiral galaxies, especially the Milky Way, since our Solar System is situated within the plane of the galactic disk [4].

Despite the penetrative ability of radio waves, parts of the Milky Way remain difficult to observe from within our Solar System due to the high stellar density and intervening material in the central bulge and bar, located close to Sagittarius A*, the supermassive black hole at the Galactic Center. Therefore, approximately 17%, or about one-sixth,

of the environment in which the Solar System orbits within the Milky Way remains uncharted and cannot be determined through normal astrophysical observations. However, if the deep time terrestrial isotopic record of Earth, in some way, is influenced by the impact flux on the inner Solar System, and this can be unscrambled from other terrestrial processes, then it has been proposed that long-lived geological archives may offer a window into reconstructing environmental conditions experienced by the Solar System during galactic transit, particularly those obscured from direct observation [5].

How could this work? According to density wave theory, spiral arms are regions of higher density that propagate through the galactic disk at non-Keplerian velocities (orbits in which Kepler's laws lack predictive and descriptive power; [6]). These density waves compress the ISM leading to an increased concentration of HI within the spiral arms, which also drives the gravitational instability of molecular clouds and subsequent star formation [7–9]. Consequently, higher measured intensities of HI are expected to spatially correlate with spiral arms. This relationship has been confirmed by the study of many spiral galaxies that are thought to be analogous to our own galaxy [10]. Since HI can be used as a tracer for spiral arms, it is worth exploring whether variations in HI density, used here as a proxy for spiral arm architecture, coincide with geochemical records that may in some way reflect crustal or surface responses to varying impact flux.

Perturbations, from periodic gravitational changes, on the local Solar System environment (e.g., galactic tide and multiple close approaches of other stellar bodies) have been modeled to drive destabilization of Oort cloud comets, a vast distant region of icy bodies that surrounds the Sun at the outermost reaches of the Solar System. Such destabilization would

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send comets inward into the inner Solar System, potentially increasing the impact flux on the rocky planets [11]. In more extreme cases, bodies can be ejected from solar systems due to a combination of perturbations that lead to gravitational scattering of the smaller body, resulting in free-floating interstellar objects [12].

The orbital velocity of the Solar System around the Milky Way's center is commonly cited as approximately 220–240 km/s, depending on the model and measurement method. Here, we take 240 km/s as a reasonable and commonly used value, supported by various studies (including Ref. [13]). Density wave theory suggests that the spiral arms of galaxies like the Milky Way are not fixed structures of stars but rather regions of enhanced density moving through the galactic disk, with stars and gas moving in and out of these arms. According to Ref. [14], the orbital velocity of the density wave structure in the Milky Way is slower, at around 210 km/s, than the Sun's orbital velocity (240 km/s), consistent with the idea that stars, including the Sun, move in and out of spiral arms over time.

The difference in velocity between stars and the spiral density wave depends on distance from the Galactic Center, as stellar orbital speeds vary with radius while the spiral pattern moves at a nearly constant rate. This results in stars and gas moving through the spiral arms except at the corotation radius, where their speeds match. Gas compression and star formation are most effective away from the corotation radius, where relative motion between the material and the density wave leads to the accumulation and compression of interstellar gas [15,16]. This difference (slightly slower speed of the density wave compared to the solar orbital speed) is crucial for maintaining the spiral structure over time without it winding up too tightly [17]. Many images of spiral galaxies support this concept of star formation within density waves and the movement of young stars away from the arm structure.

Even without defining a spiral arm model for the Milky Way galaxy, the following astrophysical consensus views enable us to conclude that the Solar System follows an orbitlike path around the Galactic Center. This path can then be mapped onto the spatial distribution of HI within the galactic plane. The Milky Way is a disk like spiral galaxy [18]. The Solar System is located within the disk of the galaxy [19]. Unlike elliptical galaxies, the disk component of spiral galaxies is not “kinematically hot” ($V/\sigma < 1$), meaning their rotational velocities (V) are much greater than their velocity dispersion (σ) [20]. For example, the Milky Way exhibits tangential isotropy with a ratio of rotational-to-velocity dispersion of $V/\sigma \approx 7.3$. The rotational velocity of spiral galaxies is related to their mass or intrinsic luminosity through the Tully-Fisher relation [21], which supports the link between rotational velocities and the intrinsic properties of spiral galaxies [22].

Deep time isotopic records help track processes related to crust production, albeit blurred by selective preservation. These time-resolved isotopic datasets serve as some of the longest time series of terrestrial processes [23] and may represent a rare archive for evaluating potential astrophysical influences on Earth, which have long orbit or repetition frequencies [5]. Specifically, oxygen isotopes in zircon provide an informative record of our planet's source of magmatism related to the depth of melting over geological time [24]. Light

oxygen isotope signals are generally rather unusual on our planet and reflect the influence (at some stage) of shallow processes in the crust where there is interaction with the hydrological cycle. This signature is imprinted via water-rock interaction or direct melting of altered rock [25]. A greater proportion of isotopically lighter oxygen is recognized in >3.9 Ga zircon crystals, although there is some nuance to this observation. Specifically, earlier magmas do not equate to average lighter signals but rather a greater tail toward isotopically light values; in short, the population structure of zircon oxygen isotopes is variable through time [26]. Most magmas are within the mantle range of $5.3 \pm 0.6\text{‰}$ [24]. Values much greater than the mantle typically reflect the involvement of supracrustal material, as frequently associated with subduction [27,28].

Recent studies suggest that Earth's geological record may preserve signatures of the crustal responses to astrophysical forcing [5,29–31]. Specifically, previous works have highlighted that the zircon oxygen time series holds important information in its population structure over time [24]. For example, the evolution of bimodality, normality, and other statistical parameters have been related to the dominant geodynamic process on the planet and potentially carry information on the impact flux over favorable temporal intervals when a more modern style of subduction may not have dominated [26]. Here, we expand on this approach and move beyond model-based comparisons [5] to directly test for correspondence between measured galactic hydrogen density and terrestrial zircon oxygen isotope variability, over time. We formulate hypotheses regarding the underlying physical processes from the relationships of these variables.

II. METHODS

A. Astrophysical dataset

To compare geological data with the local intensity of neutral hydrogen in the Milky Way, we need to recast both datasets to timeseries with a common unit (see the Supplemental Material). As the Solar System orbits the galactic center, we utilize the map of neutral hydrogen (HI) in the Milky Way provided by Oort, Kerr, and Westerhout [32]. By interpolating along a simplified circular orbit, taking a 50 Ma moving bin, from the current position of the Sun, at a rate of approximately $2^\circ/\text{Ma}$, corresponding to a galactic period of roughly 748 Ma, we assess variations in HI intensity. Given that neutral hydrogen in the Milky Way spatially correlates with the spiral arms [33–35], analyzing the relative intensity of HI along the Sun's orbit in conjunction with geological features may yield valuable insights into regions of the Milky Way that are currently unobservable through traditional astrophysical methods.

The galactic orbital period, which is the time it takes for the Solar System to complete one full orbit relative to the quasi static spiral arm structure, is derived from previous models [5,31] based on the observed velocities of the Solar System (~ 240 km/s) relative to the slower rate of ~ 210 km/s for the spiral arm structure [36]. These velocities are based on the current distance of the Sun from the Galactic Center (~ 8 kpc). According to this consensus model of the Milky Way,

the time between the Solar System's transits of each spiral arm is approximately 187 Ma.

The biggest caveat to this approach is that the movement of stars, and by extension, all other matter in the galactic disk of a spiral galaxy, does not orbit the center with a constant angular velocity. Stars, like the Sun, take more elliptical orbits, introducing a radial component to their movement as they orbit the Galactic Center. This results in a radial oscillation, known as epicyclic motion, with a period or frequency of radial oscillation estimated at approximately 150 million years [37]. This radial motion causes the Sun to oscillate inward and outward within the galactic disk, leading to fluctuations in its azimuthal or angular velocity, around the Galactic Center. These variations in radial position and azimuthal velocity inevitably affect the timing of the Sun's entry into and exit from the spiral arms. Observational data confirm this, showing a galactocentric radial velocity of $V_r \sim -10$ km/s for the Sun, indicating that it is not on a circular orbit (where $V_r = 0$) [36]. Additionally, the Sun's radial velocity component, like its angular velocity, is expected to vary approximately sinusoidally with a period related to the epicyclic frequency of approximately 150 million years [37]. We evaluated this radial movement and its effect on the timing of spiral arm entry and exit, using published values for epicyclic frequency and radial amplitude [37]. Taking an elliptical orbit around the galactic center for the Sun, varying its radial position between 7.9 and 8.9 kpc, we find that the uncertainty in timing for the entry and exit to the spiral arms is on the order of a million years, accounting for a potential error of $\pm 3\%$ in the azimuthal position across any given arm (dataset S1 in the Supplemental Material [38]). This uncertainty is represented in our model as an extended shaded region surrounding the density profile of the spiral arms (Fig. 1).

While orbital angular velocity varies around the galactic center, it also oscillates about the mean motion position of the orbit, where the mean motion is given as $n = 2\pi/T$ and T denotes the galactic period. The mean motion remains constant regardless of the orbit's eccentricity since the orbital period is independent of eccentricity. Therefore, over a galactic year (T), significant differences in the timing of spiral arm passages on a geological timescale are not expected.

When a galactic period of 748 Ma is used to iterate around the orbit of the Solar System in the HI map, we find it to be in good agreement with the local mass density model for a four-arm spiral as a normal probability function as previously employed [5,31], further confirming the usefulness of HI as a tracer for spiral arms, as is already well established for spiral galaxies [39,40].

B. Geological dataset

We calculate the kurtosis of $\delta^{18}\text{O}$ (standard mean oceanic water) ‰ values in dated magmatic zircon crystals, on a running 50 Ma bin and perform cross-correlation analysis on the zircon $\delta^{18}\text{O}$ kurtosis (hereafter "Oxygen") and the local intensity of neutral hydrogen within the Solar System's orbit (hereafter "Hydrogen") time series. For this procedure, we detrend the Oxygen time series with a simple moving average (centered 150 Ma) to remove nonstationarity. Following detrending, we verify that both time series are stationary

using the augmented Dickey-Fuller (ADF) and Kwiatkowski-Phillips-Schmidt-Shin (KPSS) tests [41].

Cross-correlation provides a measure of the similarity between the time series as a function of a time lag applied to one of them. This helps in identifying the time shift at which the two series are most closely aligned. The cross-correlation function (CCF) is calculated for a range of lags. For each lag, the CCF is computed as the covariance of the two series divided by the product of their standard deviations [42]. Cross-correlation is computed between the detrended Oxygen and Hydrogen time series with a maximum lag of 10, corresponding to ± 500 Ma. We plot the cross-correlation coefficient at different lags (in million years) with positive lags indicating Hydrogen leading the Oxygen timeseries.

To further explore the relationships between Oxygen and Hydrogen, we use a multiple rolling window correlation [43]. This approach can deal with nonstationarity in the time series and also evaluate the stability of any correlation over time. In this method, we do not detrend either time series. Each time series is sampled on a regular 50 Ma bin, and we design a function to calculate Spearman's rank correlations across expanding window sizes. The window is expanded by adding one bin to both the front and end of the window through each pass through the time series (3–27 bins, incremented by 2 bins). Our function only calculates a correlation value if the entire window contains finite values, hence the pyramid shape of the plot. We use permutation to help in estimating the significance of the observed correlations, given the well-understood multiple testing problem for calculations such as this [44]. We calculate the rolling correlation for the original data and then compare it to correlations from data with the Oxygen values shuffled 1000 times.

III. RESULTS

A. Space and time

The HI density time series, derived from direct measurement of galactic neutral hydrogen, shows generally good correlation with a four-arm spiral model of the Milky Way (dataset S1 in the Supplemental Material [38]), with significant density peaks at approximately 4000–3950, 3750, and 3600–3500 Ma, with repetitions every ca. 190 Ma. These HI peaks correspond to the Scutum-Centaurus, Sagittarius, and Perseus arms, respectively. The Norma arm appears within the occluded section of the timeseries. Zircon oxygen isotope kurtosis, when averaged across multiple orbital reconstructions, exhibits peak values that frequently overlap with HI-rich intervals, highlighting alignment between geological variance and astrophysical measurements, beyond orbit-model-based inferences.

Kurtosis in zircon oxygen isotopes over time, measured in 50 Ma bins, exhibits significant variability and distinct patterns. A plot of this timeseries reveals fluctuations with several pronounced peaks, suggesting changes in the distribution's shape across different geological periods. The kurtosis values range widely, with a mean of approximately 23.57 (normalized on a scale from 0 to 100) and a standard deviation of 18.42, indicating a skewed distribution and considerable variability. Notable peaks in the time series are observed at

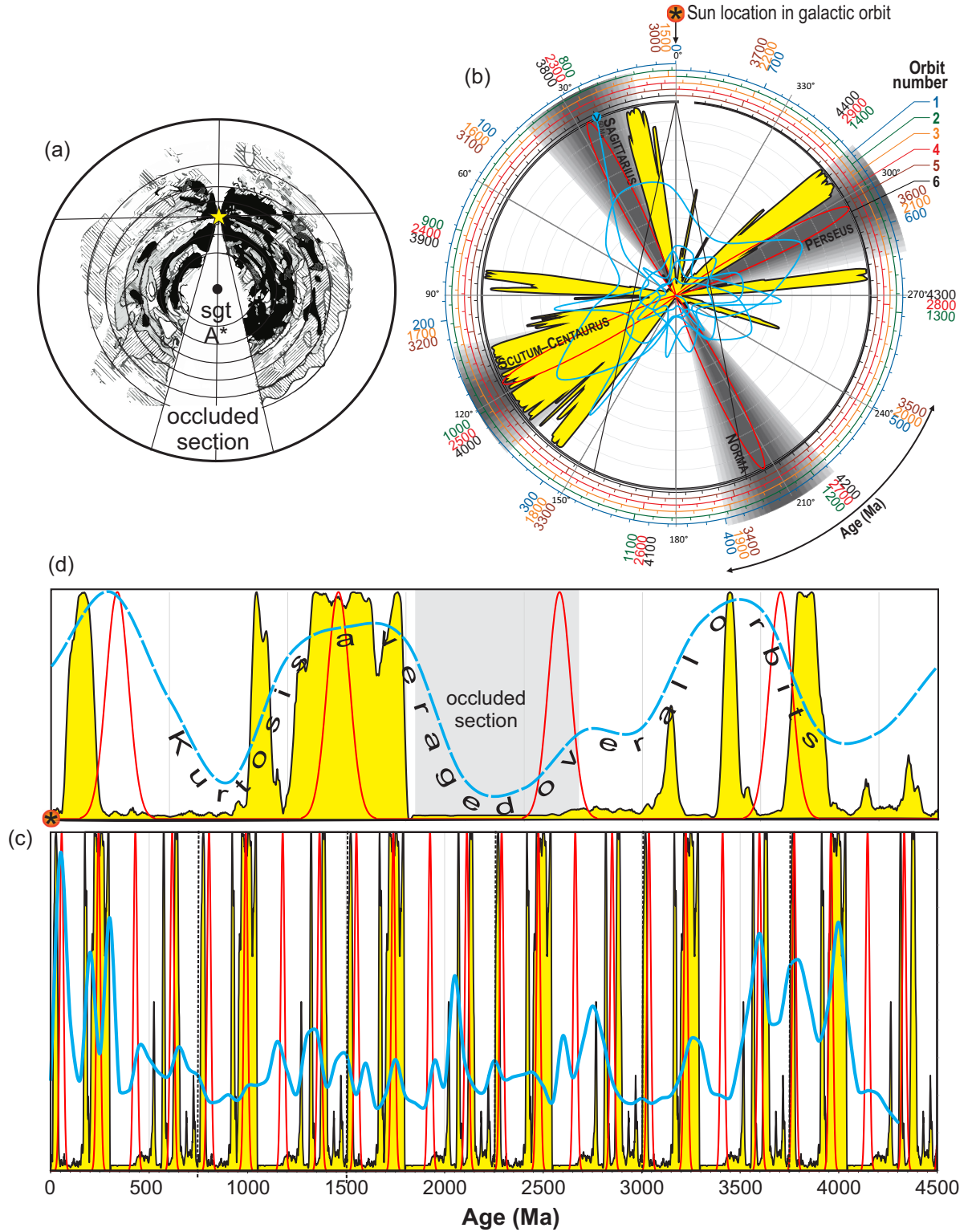


FIG. 1. (a) Radio map of the galaxy by Oort, Kerr, and Westerhout [32] from which the HI time series is extracted. (b) Probability plot of zircon oxygen kurtosis (blue line) and Milky Way HI (yellow fill) rescaled to orbital positions about Sagittarius A*. Red line denotes four armed Milky Way model. Deflections on the radial axes toward the bezel denote higher probability. Orbits and age are color coded according to the bezel. (c) Milky Way HI (yellow fill) from panel (a) recast as a time series, shown along with the four-arm Milky Way model (red line) and zircon oxygen kurtosis (blue line). Black vertical dashed lines are approximately one orbit of the Solar System about the central black hole. (d) One orbit through all the spiral arms with zircon oxygen kurtosis averaged over all six orbits (blue dashed line). Current location of the Sun is denoted with a star symbol.

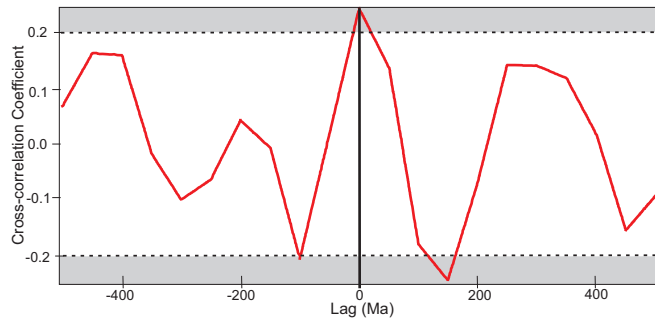


FIG. 2. Cross-correlation plot of zircon oxygen isotope kurtosis and Milky Way atomic hydrogen for leads and lags of up to 500 Ma. The black dash lines represent the 95% confidence level. Cross-correlation coefficients outside these lines are considered statistically significant.

50 Ma (kurtosis of 100), 200 Ma (63), 300 Ma (76), 2050 Ma (54), 3600 Ma (70), and 4000 Ma (74), possibly corresponding to periods of abnormal environmental conditions. However, a linear regression through the data, reveals only a slight, statistically insignificant positive slope. This suggests that there is no strong evidence for a consistent long-term trend in kurtosis over the entire period, suggesting that while localized peaks reflect significant changes, the overall trend remains relatively stable. Specifically, this implies that the Oxygen time series has a greater signal from individual events than general secular change.

B. Cross and rolling correlation

Based on the results from the ADF and KPSS tests, both the Oxygen and Hydrogen time series are stationary, meaning that statistical results from cross-correlation analysis may be meaningful.

At lag 0, there is a significant positive correlation, indicating simultaneous changes in both Oxygen and Hydrogen time series toward greater oxygen kurtosis (indicates heavier tails and a more peaked $d^{18}O$ distribution) and higher relative HI density (Fig. 2). At lags, in both directions, of approximately 100 Ma, there are significant negative correlations, suggesting inverse relationships at these points in time. Such relationship is consistent with an out of phase relationship at approximately the midpoint on the Solar System's transit between each spiral arm. Other lags do not show significant correlations, indicating no strong relationship at those points.

The rolling window investigation provides both a detailed view of the time series and a high-level overview (Fig. 3). There are 60 statistically significant correlations ($P < 0.05$) in the dataset (on windows from 150 to 1350 Ma): 2 are negative correlations, whereas 58 are positive correlations. Statistically significant correlations are primarily concentrated around 1700–2200 Ma, especially around 1750–2100 Ma. There are also significant positive correlations in other isolated time points like 1400, 3050, and 3500–3650 Ma.

IV. DISCUSSION

Disruption of the Oort cloud has been considered via three mechanisms. When stars pass relatively close to the Oort

cloud, their gravitational influence can disturb the orbits of Oort material toward the inner Solar System. The gravitational forces exerted by the Milky Way galaxy itself in the radial and vertical directions, known as galactic tides, can also perturb the orbits of Oort cloud comets over long timescales. Occasionally, the Solar System may encounter interstellar objects or debris, and their gravitational interactions with the Oort cloud could disrupt cometary orbits. Although this is a less common mechanism, it could contribute to sending comets toward Earth-crossing orbits. These disruption processes must be considered long-period operating over a vastly longer time frame from the current crater record, which reflects the impact of meteorites derived from the asteroid belt [45,46]. Specifically, the terrestrial crater record is demonstrably biased to recent impacts and principally reflects preservation bias [47], which is unsurprising given the mean age of oceanic crust is 64 Ma and supercontinent aggregation and dispersal will ensure a spatially uneven sampling through deep time [48].

Adding to the challenge, the fossil record, key to studying biodiversity shifts in relation to external or internal drivers, is short compared to arm transits [49] and has been widely debated in terms of interpreting diversity patterns [50]. Arguments for and against exogenic drivers within the fossil record have been made [51–55]. A significant challenge arises from the spatial and temporal incompleteness of the fossil record, which means that apparent “global” diversity estimates reflect aggregated diversity across geographically and environmentally distinct regions [49]. Moreover, detailed records extend only as far as about 500 Ma, which is too short to relate to longer period drivers.

Zircon oxygen isotopes reflect the magmas source and interaction with (near-) surface environments [56]. Various arguments have been made to indicate that the long-term pattern in oxygen isotopes, and more specifically the relative proportion of light isotopes, at least prior to demonstrable widespread subduction has a function related to impact flux [5,31]. Specifically, greater kurtosis in the zircon record has, for at least certain periods of Earth history, been argued to reflect impacting directly or indirectly [5]. Direct influence could be via shallow impact-related melting [57] or transient impact-induced subduction [58,59], and indirect influence could be through larger volumes of crust produced by impacting being buoyant, thus having greater potential to interact with the hydrosphere over time or simply a raised geotherm on the early Earth due to greater bombardment supporting proportionally more shallow magmatism [26].

Zircon oxygen isotope kurtosis shows statistically significant positive correlation with HI density for the solar orbit through the Milky Way. Positive correlations at 3500–3650 Ma coincide with U/Pb ages of impact melt glass from lunar regolith samples. The 1700–2200 Ma period marked by various terrestrial craters (e.g., 2.23 Ga Yarrabubba, 2.02 Ga Vredefort, and 1.85 Ga Sudbury) aligns with broad temporal bands of lunar impact glasses. A positive correlation at 1400 Ma aligns with the U/Pb age of Chang’e-5 impact glass and the $^{39}Ar/^{40}Ar$ age of Apollo 14 impact glass [60,61]. Despite these correlations, the validity of using lunar glass to infer terrestrial impact flux rate clearly is predicated on these glasses resulting from inner rocky planet impact flux rather than some local process. Variability in glass compositions,

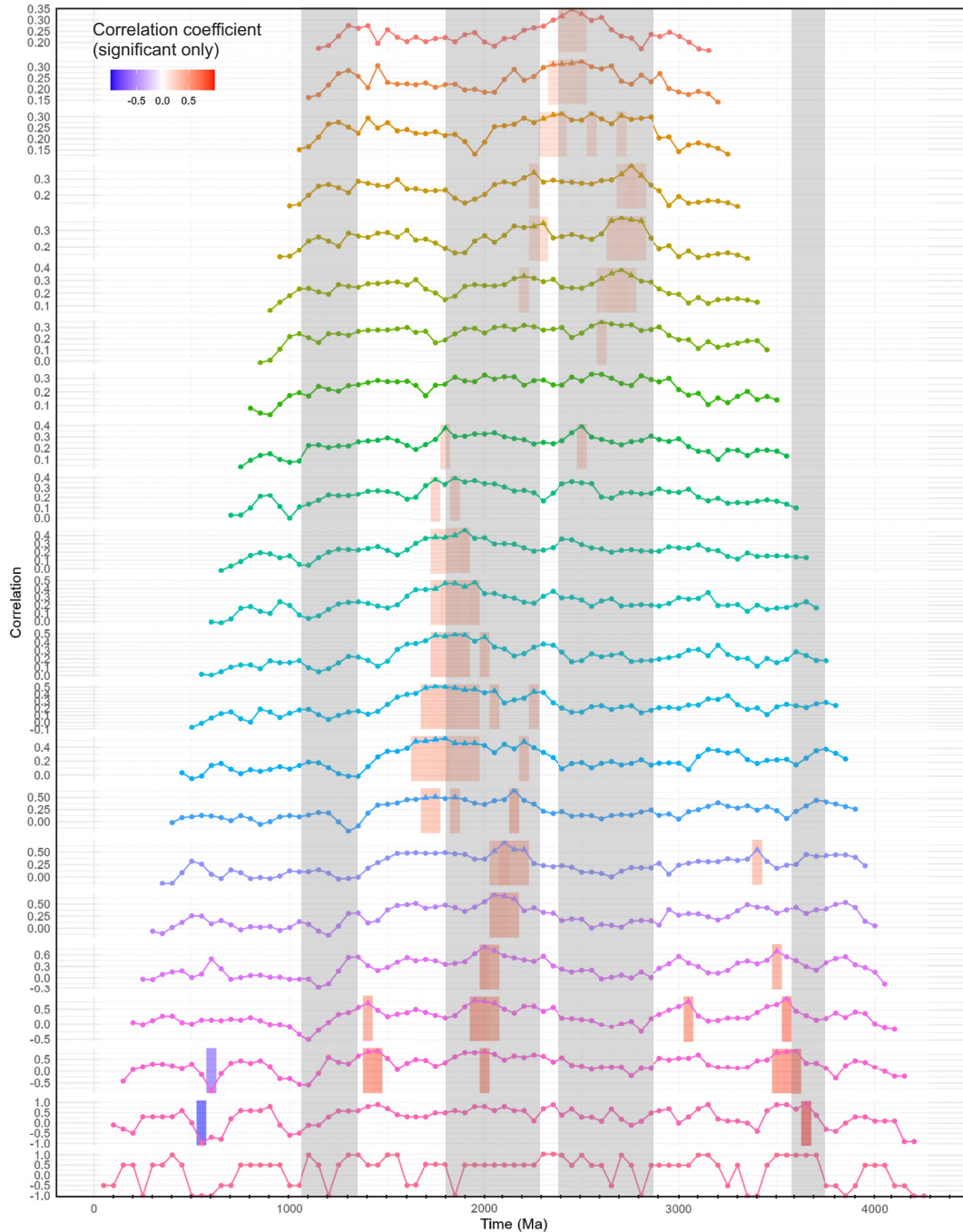


FIG. 3. Rolling correlation plot between zircon oxygen isotope kurtosis and Milky Way atomic hydrogen (HI). Rolling window size from 3 bins (150 Ma) to 47 bins (2350 Ma). Statistically significant correlations are denoted with a triangular symbol and are shaded according to the Spearman rank correlation coefficient. Background gray vertical bars denote >1 Ga “unmixed” glass ages from Apollo 14 lunar soil sample [61].

site-specific geological conditions, and incomplete understanding of impact processes undoubtedly complicate their use in reconstructing inner Solar System impact histories.

Due to our location within the galactic disk of the Milky Way, astronomical observations are inherently limited in their ability to map HI, CO, HII, and molecular hydrogen comprehensively. The dense accumulation of stars, dust, and gas within the Milky Way’s central bulge obstructs our view, particularly at galactic longitudes near 0° (rotational orbit of

ca. 180°), occluding observations toward the Galactic Center. Assuming the Sun is positioned approximately 8 kpc from the Galactic Center, about 17% of its orbit within the galactic disk remains unobservable from our current location. The averaged oxygen kurtosis across all orbits (Fig. 1) shows good agreement with the spiral arms, except for the Norma arm, which coincides with the occluded section of the Sun’s orbit. Assuming a correlation between zircon oxygen kurtosis, impacting, and HI, a reduction in oxygen kurtosis implies a

corresponding absence of HI in the occluded region. There is ongoing debate regarding the spiral structure of the Milky Way, with some studies supporting a two-arm configuration, while others suggest a four-arm configuration. However, recent findings show that the Milky Way, like other spiral galaxies, might be both a two-arm and a four-arm spiral, depending on the distance from the Galactic Center [62]. Specifically, the inner region of the Milky Way has been proposed to contain two primary arms within 6.5 kpc of the center, which bifurcates into four secondary arms further out.

Some studies suggest that the Norma arm may not be a major arm like the Scutum-Centaurus or Perseus arms but instead could be a spur. Spurs are smaller offshoots that extend from the main spiral arms. Hence, several astrophysical explanations may account for the apparent lack of zircon oxygen kurtosis in the expected location of the Norma arm, for a four-arm structure. First, the Solar System's position, approximately 8 kpc from the Galactic Center, is situated radially near the point where some propose the two primary spiral arms split into four secondary arms. Consequently, considering radial movement, the Solar System may not encounter one of the outer four spiral arms if it also coincides with the minimum radial distance. Second, spiral arms in galaxies are often incomplete, exhibiting varying degrees of discontinuity. While grand-design galaxies feature well-defined, continuous arms, flocculent galaxies display more fragmented and incomplete structures, with a spectrum of arm completeness between these two extremes. Colombo *et al.* [63] utilized the distribution and properties of molecular gas to argue for a flocculent Milky Way galaxy. In this scenario, the Solar System might pass through a region with a gap or discontinuity in the

spiral arms, rather than encountering a significant, well-defined armlike structure within the occluded region.

V. CONCLUSIONS

The general significant correlation between HI density and zircon oxygen kurtosis, for the Scutum-Centaurus and Perseus arms, implies the retention of a potentially important exogenic signal in average terrestrial crustal production process, explicable through periodic disruption of Oort cloud material during spiral arm transits. Hence, there is sufficient evidence to seriously consider the hypothesis that impacting on the frequency of galactic arm transits influenced rocky planet geology. Extending our understanding of Earth through deep time demands that we broaden our perspective to include astrophysical processes, as they provide a wider contextual framework, one that not only situates Earth within its galactic environment but also enables direct observation of earlier planetary states elsewhere, offering crucial analogues for deciphering Earth's own formative history.

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DATA AVAILABILITY

The data supporting this study's findings are available within the article [71].

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