

LETTER TO THE EDITOR

The Radcliffe Wave as the gas spine of the Orion Arm

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ABSTRACT

The Radcliffe Wave is a ~ 3 kpc long coherent gas structure containing most of the star-forming complexes near the Sun. In this Letter we aim to find a Galactic context for the Radcliffe Wave by looking into a possible relationship between the gas structure and the Orion (Local) Arm. We use catalogs of massive stars and young open clusters based on *Gaia* EDR3 astrometry, in conjunction with kiloparsec-scale 3D dust maps, to investigate the Galactic XY spatial distributions of gas and young stars. We find a quasi-parallel offset between the luminous blue stars and the Radcliffe Wave, in that massive stars and clusters are found essentially inside and downstream from the Radcliffe Wave. We examine this offset in the context of color gradients observed in the spiral arms of external galaxies, where the interplay between density wave theory, spiral shocks, and triggered star formation has been used to interpret this particular arrangement of gas/dust and OB stars, and outline other potential explanations as well. We hypothesize that the Radcliffe Wave constitutes the gas reservoir of the Orion (Local) Arm, and presents itself as a prime laboratory to study the interface between Galactic structure, the formation of molecular clouds in the Milky Way, and star formation.

Key words. Galaxy: structure – Galaxy: solar neighborhood – Galaxy: stellar content

1. Introduction

The spiral arms of disk galaxies play an intrinsic role in the dynamics of their stellar/interstellar material and are even theorized to trigger the onset of star formation (Roberts 1969). There are a multitude of astrophysical sources observed to trace spiral structure including masers, OB stars, HII regions, interstellar dust, and Cepheids. Detailed images of face-on spiral galaxies reveal elongated dust-lanes that often trace spiral patterns, but they are typically segmented and offset from the unobscured, blue-stellar component; an observation supported by the density wave theory of spiral arms (Lin & Shu 1964; Shu 2016a). The arrangement of our own Galaxy’s spiral arms is more ambiguous due to the Sun’s embedded location near the Galactic mid-plane. The first detection of the Sun’s nearest spiral arm (named the Orion Arm by van de Hulst et al. (1954)¹) was made by Morgan et al. (1953) using a limited sample of OB star parallaxes. Later studies of HII regions, 21-cm emission, parallax measurements of masers, and Cepheids have been interpreted in the context of a four-armed model of the Milky Way (Georgelin & Georgelin 1976; Taylor & Cordes 1993; Russeil 2003; Reid et al. 2014, 2019b; Minniti et al. 2021), with the Orion arm often absent or present only as a minor spur.

The precise astrometry measured for over one billion stars by the ESA *Gaia* mission (Gaia Collaboration et al. 2021) has transformed our understanding of the Milky Way’s structure and

the ability to accurately measure the distances and reddening for millions of stars near the Sun has unveiled the local ISM in three dimensions (Green et al. 2019; Lallement et al. 2019, 2022; Chen et al. 2019; Rezaei Kh et al. 2020; Leike 2020). Recently, Alves et al. (2020) discovered a ~ 3 kpc long, narrow (aspect ratio of 1:20), and undulating gas structure they name the Radcliffe Wave, connecting many nearby star-forming complexes (CMa, MonR2, Orion, Taurus, Perseus, Cepheus, North America nebula, and Cygnus), into a quasi-linear feature on the XY plane of the Galaxy. The discovery of this gas structure was made possible by the compendium of accurate cloud distances (Zucker et al. 2020), together with complementary distance measurements towards low column density clouds using the same method. When including ESA *Gaia* data, the Zucker et al. (2020) method reaches median distance errors to clouds of about 5%, or about a factor of 5-6 times better than previously possible, transforming our perception of the gas distribution in the Local Galaxy.

The Radcliffe Wave supersedes the long-held model of star-formation in the solar neighborhood, namely the Gould Belt (Gould 1874), a presumed ring of molecular gas and OB associations tilted at a 20° angle from the Galactic plane (e.g., Palouš & Ehlerová 2016). The compendium of molecular cloud distances from Zucker et al. (2020), complemented with measurements towards lower column density clouds in Alves et al. (2020), show that the "Gould Belt clouds" break down into two families of star-forming molecular clouds belonging to two much larger

¹ Also known as the Local arm

structures, the Radcliffe Wave and the Split, an apparent spur-like feature situated between the Orion (Local) and Sagittarius-Carina arms (Lallement et al. 2019).²

Two intriguing results emerge from the spatial structure of the Radcliffe Wave: One concerns its coherent undulation about the Galactic plane following a damped sinusoidal pattern, possibly originating from instabilities arising between the Milky Way’s disk and halo (Fleck 2020) or due to perturbations caused by the passage of a dwarf galaxy (Thulasidharan et al. 2021). The second result concerns the relation between the Radcliffe Wave and the Orion (or Local) Arm of the Galaxy. The Radcliffe Wave appears to cross the Orion Arm in the plane of the galaxy as traced by masers (Reid et al. 2016), as seen in the interactive Figure 2 from Alves et al. (2020), making it hard to assert if there is a relationship between the two structures. In this Letter, we focus on the latter of these two results. Specifically, we seek to understand if the Radcliffe Wave is part of the Milky Way’s spiral structure when considering tracers of the Orion Arm such as OBA-type stars, open clusters, and masers.

Section 2 of this Letter outlines the data used for studying Galactic spiral structure. Section 3 describes our analysis and results. Section 4 attempts to contextualize our results with respect to density wave theory and makes connections to spiral structure as seen in some nearby external disk galaxies.

2. Data

We use the Galactic XY positions of molecular clouds from Zucker et al. (2020) complemented with distances to clouds in the Radcliffe Wave from Alves et al. (2020). The line-of-sight (LOS) distances to these clouds were computed using a Bayesian method with optical photometry from PanSTARRS1 (Magnier et al. 2016; Chambers et al. 2016), the NOAO Source Catalog (Nidever et al. 2018), near-infrared photometry from the 2MASS survey (Skrutskie et al. 2007), and parallaxes from *Gaia* DR2 (Brown et al. 2018).

The availability of all-sky, multi-band photometric surveys and precise parallaxes from *Gaia* has led to the development of a multitude of three-dimensional maps tracing interstellar dust at varying resolutions and spatial extents (e.g., Green et al. 2019; Lallement et al. 2019; Chen et al. 2019; Rezaei Kh et al. 2020; Leike 2020). Dust mapping at kiloparsec scales has revealed traces of spiral structure, including the Orion (Local) Arm (Chen et al. 2019; Green et al. 2019; Lallement et al. 2019). In this work we use the map of Lallement et al. (2019), which was constructed using a Bayesian inversion technique applied to *Gaia* DR2 and 2MASS data. The resulting map has dimensions of $6 \times 6 \times 0.8$ kpc and achieves a 25 pc resolution for the portion of the map considered in this work.

Additionally, we investigate the Galactic XY distribution of OBA-type stars from Zari et al. (2021). This all-sky sample was constructed with color-color and color-magnitude cuts using photometry and astrometry from *Gaia* EDR3 and the Two Micron All Sky Survey (Skrutskie et al. 2007). The sample was selected to be more complete rather than pure; the authors indicate that some contamination might come from intermediate-mass and evolved high mass stars. They use the EDR3 astrometry combined with expected proper motions from Galactic rotation to derive “astro-kinematic” distances and remove spurious sources following this analysis. Additional spurious sources are accounted for using the classifier developed by Rybizki et al. (2021), leading to a final sample count of 435,273 stars. Poggio

et al. (2021) show that the Z21 data traces spiral structure, specifically the Sagittarius-Carina, Orion, and Perseus spiral arms, and hence makes the sample suitable for our study. Another tracer of young, bright, and massive stars are open clusters. We use 167 of the *Gaia* DR2 derived open clusters from Cantat-Gaudin et al. (2020) with inferred ages less than 30 Myr. Several works have recently shown that open clusters can trace nearby spiral structure (e.g., Xu et al. 2018; Poggio et al. 2021; Castro-Ginard et al. 2021b). Masers also play an important role in mapping spiral arms at kiloparsec scales due to their intense luminosities and their location within massive star forming regions. We also utilize the catalog of masers from Reid et al. (2019b) and we especially consider the log-spiral fit to the subset of masers that have been identified as the “Local Arm”.

3. Methods and Results

3.1. Dust-Star Offset

We replicate the method of Poggio et al. (2021) (hereafter P21) to plot the Z21 sample density in Galactic XY coordinates: Two bivariate Epanechnikov kernels are used, one with a bandwidth of 0.3 kpc to measure the local density and the other with a bandwidth of 2 kpc to measure the mean density. These density maps are input into Equation (1) of P21 which results in the clear spiral structure seen in Figure 1. P21 originally apply this method to their Upper Main Sequence (UMS) sample of stars, but additionally apply it to the Z21 sample (see their Figure B.1), finding that both samples, in a consistent way, recover traces of the Sagittarius-Carina, Perseus, and Orion arms (hereafter the P21 Orion arm).

Figure 1 also displays the Galactic XY positions of the star-forming clouds from Zucker et al. (2020), with the Radcliffe Wave apparent as a thin stretch of clouds from $(X, Y) \approx (-1, -1)$ kpc to $(X, Y) \approx (0.5, 2)$ kpc. There is a clear offset between the OBA-type stellar component of the Orion arm and the dust composing the Radcliffe Wave. To determine the size of this offset, we first rotate the OBA density counter-clockwise 32 degrees such that the P21 Orion arm is oriented vertically in a new coordinate frame XY' . We then smooth the collapsed, one-dimensional profiles along X' by 5σ in order to more easily trace the average shape of the P21 Orion arm rather than its individual over-density clumps. We locate the peaks of these smoothed profiles using the SciPy peak-finding algorithm³ and then fit them with a line, which we consider the ‘spine’ of the P21 Orion arm in the section we are considering (Figure 2). The resulting offset between the P21 Orion arm ‘spine’ and their nearest point along the Radcliffe Wave ranges between 250 to 730 pc with a median of 580 pc.

The Radcliffe Wave is also apparent as an elongated dust filament in the 3D map of Lallement et al. (2019) (Panel 3 of Fig. 1) and agrees with Zucker et al. (2020) distance estimates to molecular clouds, hence the dust-star offset is also seen in the diffuse dust. The authors in Z21 note a spatial mismatch between their hot-luminous star sample and the dust. However, since Z21 do not initially find clear spiral structure in their sample, this extended linear offset between the Radcliffe Wave and the P21 Orion arm was not obvious.

While both young open clusters and masers are shown to trace spiral structure in the Milky Way (Reid et al. 2019a; Castro-Ginard et al. 2021a), their spatial distributions in context to the aforementioned dust-star offset are more ambiguous (Figure 1).

² See interactive Figure 2 in Alves et al. (2020)

³ `scipy.signal.find_peaks`

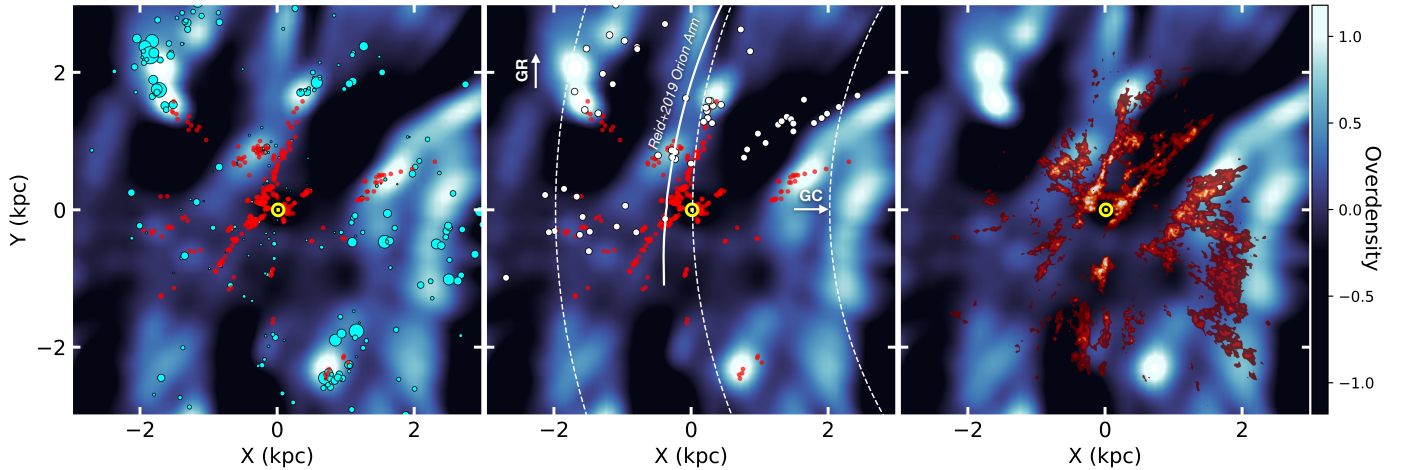


Fig. 1. A Galactic XY (bird's-eye) view of various stellar/dust distributions within ~ 4.25 kpc of the Sun (centered yellow dot). The over-density map of the OBA-type stars from Zari et al. (2021) (black-blue-white) is shown in the background of each panel. The emergent spiral features in this map, from decreasing to increasing values in X , are the Perseus, Orion, and Sagittarius-Carina arms. The star-forming clouds from Zucker et al. (2020) are displayed as red points in the first two panels, with the Radcliffe Wave appearing as a narrow alignment of clouds from $(X, Y) \approx (-1, -1)$ kpc to $(X, Y) \approx (0.5, 2)$ kpc. The cyan points in the first panel are the open clusters from Cantat-Gaudin et al. (2020) with ages less than 30 Myr, sized relative to their membership count. The second panel shows the masers (white points) and the fit to the Orion (Local) arm (solid white line) from (Reid et al. 2019b), three circles of constant, Galactocentric radius (white dashed lines), and two arrows pointing in the directions of the Galactic center/Galactic rotation. Overlaid in panel three is the dust map of Lallement et al. (2019) with a heat map color-scale showing increasing dust density.

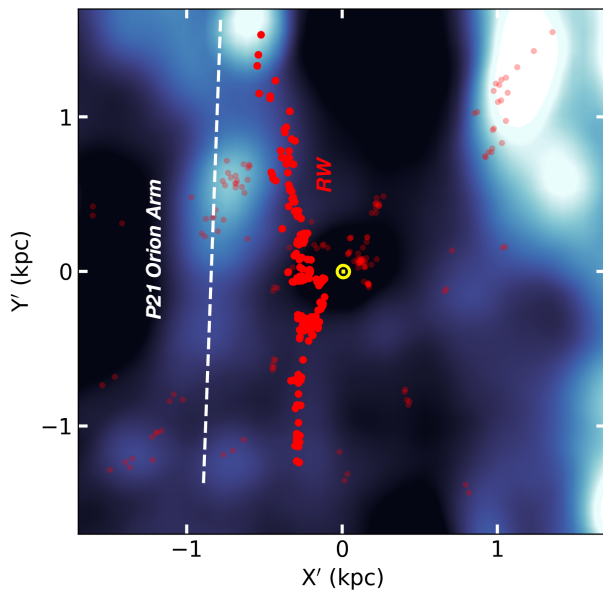


Fig. 2. A zoomed and rotated version of Figure 1 displaying the Z21 stellar over/under-density (black-blue-white) and star-forming region locations (Zucker et al. 2020) in red, with the bold-red points marking clouds belonging to the Radcliffe Wave. The dashed white line shows the fit to the over-density peaks along the P21 Orion Arm. The Sun is located at the center in yellow.

The spatial distribution of young open clusters (Fig. 1; panel 1) coincides with the locations of the P21 spiral arms, however the number of OCs is too sparse to alone unveil a general offset from the dust of the RW. A mismatch between the fit to the masers of the Orion arm from Reid et al. (2019b) and the Radcliffe Wave

was first mentioned by Alves et al. (2020). This mismatch is again shown in this work (Figure 1, panel 2) and is also apparent in comparison with the P21 Orion arm. The Radcliffe Wave has a local pitch angle of ~ 29 degrees and the P21 Orion arm has a similar pitch angle of ~ 31 degrees. This angle is in apparent disagreement with the results of Reid et al. (2019b) which reports a Local (Orion) Arm pitch angle of 11.4 degrees. This is principally a result of the masers that Reid et al. (2019b) identified as "Local Arm", since these source extend well beyond the area of the disk studied here.

An important issue is the role of the star formation region that we label as "Cepheus Far" (Figure A.1). This active star forming complex— which contains, among other members, the HII regions Sh2-140, Sh2-150, four masers, and the OB association Cep OB3— lies within the P21 Orion Arm. Reid et al. (2019b) identifies this as a Local (Orion) Arm star forming region. Recently, Pantaleoni González et al. (2021) has revived the possibility, first suggested by Morgan et al. (1953), that this star forming region is part of a "branch" of the Orion arm which they name the "Cepheus Spur". This spur is traced by the OB associations Cep OB4, Cam OB1, Aur OB1, and Gem OB1. Given the intersection of this structure with the P21 Orion arm, further investigation of this claim is warranted.

3.2. Stellar Mass Estimate

We compare the gas mass of the Radcliffe Wave to the young stellar mass for a portion of the P21 Orion Arm. To select the segment of stars along the arm that are parallel with the Radcliffe Wave, we draw a cylinder around the P21 Orion arm 'spine' (Figure 2) that selects 18575 stars within a 400 pc radius, which was chosen visually to match the width of the arm. The invoked lower mass limit of this stellar sub-sample is, in principle, that of an A0V-type star ($\sim 2M_{\odot}$), however this value is rather uncertain since it is shown by Z21 that there exists a contamination of lower mass F-type stars which may also be present as unresolved

binaries. Taking into account an *extreme* case where half of the Z21 sample has a spectral type later than an A0V-type star, we construct a Kroupa et al. (2001) initial mass function (IMF)⁴ and vary the initial mass until the number of stars above $2.0M_{\odot}$ is in the range of 0.5 to 1.0 times the number of stars in the selected sample. The total initial mass of the simulated stellar population is then $1.4 - 2.8 \times 10^5 M_{\odot}$ and the RW mass is calculated to be $\sim 3 \times 10^6 M_{\odot}$ based on column density measurements provided by the Planck dust map (Planck Collaboration et al. 2014; Alves et al. 2020). Assuming a star formation efficiency range of 1 – 3 % for the gas of the Radcliffe Wave, the initial stellar mass of the P21 Orion arm is 2 – 10 times the fraction of which the Radcliffe Wave could have produced, implying that the stars of P21 Orion arm formed from previous gas structures.

4. Discussion

The combined discoveries of spiral structure in the young-luminous stars (Poggio et al. 2021) and the unique linear arrangement of major star-forming regions composing the Radcliffe Wave (Alves et al. 2020) present a fascinating picture of the nearest spiral arm to the Sun. The offset found between the two young structures in this work confirms that spiral arms are density-waves (Lin & Shu 1964; Toomre 1969, 1977; Shu 2016b).

While it is established that spiral arms are density waves, significant debate remains about their lifetimes. Numerical experiments suggest that spiral arms are transient features, (Dobbs & Bonnell 2006; Foyle et al. 2011; Sellwood 2010; Wada et al. 2011; Roškar et al. 2012; Kawata et al. 2014; Pérez-Villegas et al. 2015; Sellwood et al. 2018), or fluctuating locally in density but being statistically long-lived (Fujii et al. 2011; D’Onghia et al. 2013). Note that multiple observational works have supported long-lived spiral arms via a variety of different tracers (Donner & Thomasson 1994; Zhang 1998; Martínez-García et al. 2009; Martínez-García & González-Lópezlira 2013; Scarano & Lépine 2013). Our resulting view of the Orion Arm complements previous observations suggesting that spiral arms can have at least sufficient longevity for the triggering of star formation.

Our mass estimate of the P21 component directly offset from the Radcliffe Wave (Section 3.2) reveals that the at-present molecular gas is not sufficiently massive to have produced the offset stellar mass. This result supports an evolutionary scenario for the Orion Arm in which previous gas segments have passed through an over-density, shocked, and collapsed to form the visible young and bright stars. The excess gas which failed to collapse and form stars eventually, has dissolved, with perhaps some residual gas remaining in the P21 Orion Arm (Figures 1, A.1). The Radcliffe Wave is then the present-day gas spine of star-forming regions and will also dissolve, similar to the gas spines that previously produced the young stars downstream from it. This scenario also requires the consideration of Galactic inflows as the source of sustained star-formation in the Orion Arm, as the gaseous disk would need to be replenished over time based on the mass ratio between the Radcliffe Wave and the P21 Orion arm. In this picture, the Radcliffe Wave would be the elongated filament of gas collected at the spiral structure over-density, indicating that all of the star-forming regions along the Wave have originated as a consequence of a Galactic spiral shock.

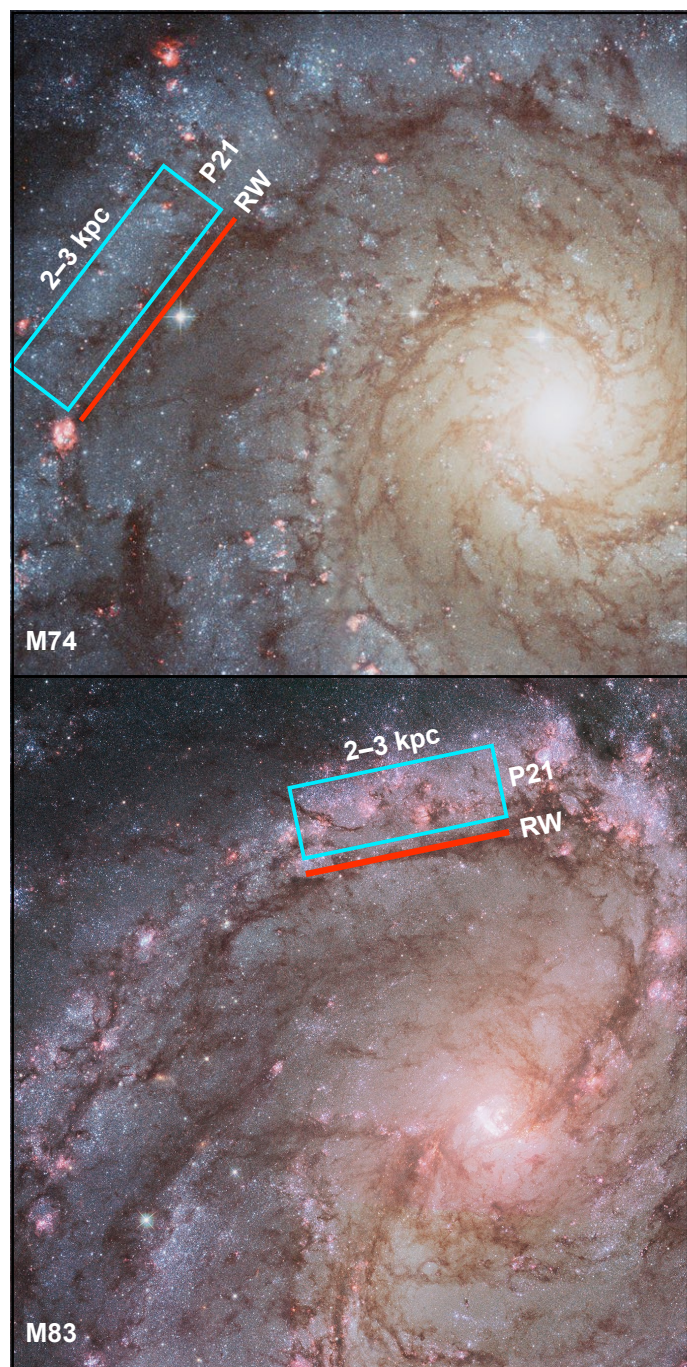


Fig. 3. Two Hubble Space Telescope images, with the top panel showing the grand-design spiral galaxy Messier 74 (M74) which demonstrates a prominent dust lane and a luminous, blue stellar region, offset from each other in one of its spiral arms. The bottom panel displays a more flocculent spiral galaxy, Messier 83 (M83), which tends towards a disordered configuration of dust, gas, and stars which may be more analogous to the Milky Way. The overlaid drawings are meant to represent the resemblance of the Orion arm’s dust/OBA offset shown in Figures 1 and 2 to those seen in these face-on spiral galaxies, with the red line and the blue rectangle depicting the Radcliffe Wave and the P21 Orion Arm, respectively. These representations of the Orion Arm are drawn approximately to-scale based on the distance measurements to M74 and M83.

Recent works based on *Gaia* hint at the location of a surface mass over-density responsible for the arrangement of Radcliffe Wave and the P21 Orion arm. The study of Eilers et al. (2020a) uses *Gaia* DR2 astrometry along with other all-sky surveys to

⁴ <https://github.com/keflavich/imf>

study the kinematics of luminous red giant branch (RGB) stars, assuming a steady-state model of a logarithmic spiral arm. They use the radial component (in the direction of the Galactic Center) of the stars' velocities and find two non-axisymmetric features which they can directly relate to stellar surface mass density via models (Figures 3, 4; Eilers et al. (2020a)). One of these features is near the Orion (Local) arm; a visual inspection reveals that the Radcliffe Wave partially overlaps with this over-density and lies, at most, 1 kpc downstream from it. In the steady-state density wave theory (Lin & Shu 1964), this feature is expected within the corotation radius, as the Radcliffe Wave and the emerging young stars rotate faster than the pattern speed of the density wave and eventually overtake it. However, outside corotation, the pattern speed of a spiral arm is faster than Galactic rotation, and hence the Radcliffe Wave would be expected to lie directly upstream from the over-density instead, and the P21 Orion arm would instead lie up-stream from the Wave. There are some caveats with this model that complicate the interpretation:

1. Spiral arms are not steady-state but constantly changing in density and are not always logarithmic.
2. The RW shows a vertical sinusoidal undulation (Alves 2020), which is not expected in the density wave theory (see Thulasidharan et al. 2022).
3. The steady-state model of logarithmic spiral applies better to grand-designed spiral galaxies. Note that this is not the case of the Milky Way, which seems to be multi-armed with more than one corotation radius.

Furthermore, the average age of the P21 Orion arm is unknown due to the uncertainty of its stellar composition (the fraction of O, B, and A-type stars present). In the Lin-Shu density wave theory, it is expected for age gradients traced by intrinsic stellar color gradients to be present across luminous stellar arms. From the Radcliffe Wave to the far edge of the P21 Orion arm there exists a gradient in the stars' colors (blue to red), however this is likely a product of dust reddening. There is no obvious color gradient across the P21 Orion arm alone, nor is there an obvious age gradient in the open clusters overlapping in this region, but this requires additional analysis incorporating multi-band photometry and spectroscopy. Additionally, if the P21 Orion arm has an average age of 100 Myr (assuming a sample of mostly A-type stars), with its spatial offset from the up-stream Eilers et al. (2020b) feature being 1-2 kpc, then the expected rotational velocity difference between the two structures would be in the range of 10-20 kms^{-1} . This may become observable with the upcoming expanded radial velocity catalog of *Gaia* DR3.

While a large fraction of local star-forming clouds lie along the Radcliffe Wave, there are also clouds of which make up the 'Split' (Figure 1; Lallement et al. 2019; Zucker et al. 2020) such as Sco-Cen, Aquila, and Serpens. It is not clear if the Split is related to the Orion arm, however its linearity and its direct overlap with the same feature from Eilers et al. (2020a) indicate that this structure and its star-forming regions might be part of the same global picture. Solidifying the formation history of the Radcliffe Wave and the Split will require future 3D kinematic analysis which will become increasingly viable with the future data releases from *Gaia* and other ground-based spectroscopic surveys measuring radial velocities.

In summary, the formation histories of the Radcliffe Wave and the offset P21 Orion arm remain unsolved; however, we find that their spatial arrangement poses a striking resemblance to the spiral arms of many external disk galaxies. Messier 51 (M51) is a remarkable example of a grand design spiral galaxy exhibiting

extended dust lanes lined along the edges of its luminous/blue spiral arms. Analysis of the density waves produced by older stars in M51 exhibits explicit offsets from the dust lanes in one of its arms, (Egusa et al. 2017). In top panel of Figure 3 we display a Hubble Space Telescope image of another grand design spiral galaxy, Messier 74 (M74), which exhibits extended dust lanes offset from its blue spirals, making a clear connection to the spatial arrangement of the Radcliffe Wave and the P21 Orion arm (Figures 1 and 2) with similar spatial scales based on the distance to M74. As previously mentioned, the Milky Way is likely not a grand design spiral galaxy (Castro-Ginard et al. 2021b) and even the existence of coherent structure in the prominent Perseus arm has been recently questioned (Peek et al. 2022). The bottom panel of 3 shows M83, an example spiral galaxy with more disordered spiral arms, yet still exhibiting extended dust lanes offset from unobscured, luminous stellar arms indicating that it is not quite a flocculent galaxy. The ability to detect distinct, parallel, and linear structures of the young stars and the dust suggests that the Milky Way is not a flocculent spiral, and instead, similar to M83, lies somewhere in between a galaxy with unambiguous spiral structure and one in which spiral arms are less traceable due to disordered dust and stars.

The spatial picture presented in this work further demonstrates that the star-forming regions composing the Radcliffe Wave (Figure A.1) have a connected history and indicates that the Wave is an important laboratory for star formation, not only on the scales of its individual complexes, but also on the scale of a Galactic spiral arm. Future work will employ a dynamical analysis incorporating the expanded radial velocity catalog of *Gaia* DR3 in order to pinpoint the physical processes which established this arrangement of dust and luminous stars.

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Appendix A: Labeled star-forming regions of the Radcliffe Wave

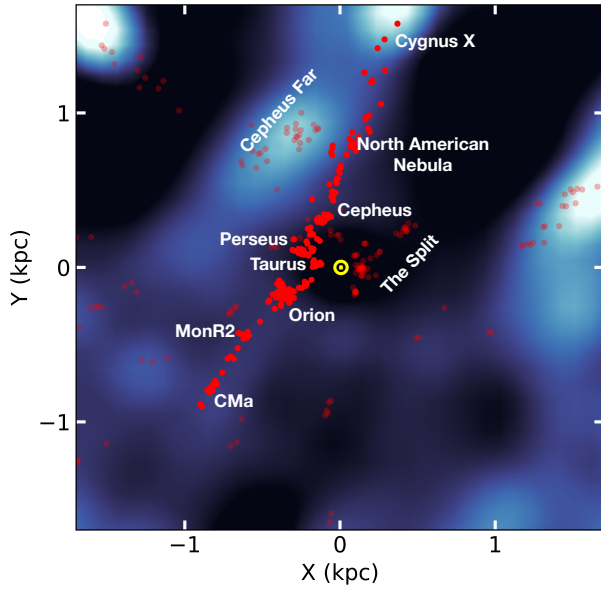


Fig. A.1. A zoomed version of Figure 1 displaying the Z21 stellar density (black-blue-white) and the Radcliffe Wave clouds (Zucker et al. 2020) in red, with labels placed next to its major star-forming regions. Both 'The Split' and 'Cepheus Far', which are not part of the Radcliffe Wave, are labeled as well. The Sun's location is marked in yellow.