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The Bones of the Milky Way

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ABSTRACT

The very long and thin infared dark cloud "Nessie" is even longer than had been previously claimed, and an analysis of its Galactic location suggests that it lies directly in the Milky Way's mid-plane, tracing out a highly elongated bone-like feature within the prominent Scutum-Centaurus spiral arm. Re-analysis of mid-infrared imagery from the Spitzer Space Telescope shows that this IRDC is at least 2, and possibly as many as 8 times longer than had originally been claimed by Nessie's discoverers, Jackson et al. (2010); its aspect ratio is therefore at least 150:1, and possibly as large as 800:1. A careful accounting for both the Sun's offset from the Galactic plane ($\sim$ 25 pc) and the Galactic center's offset from the $(l^{II}, b^{II}) = (0, 0)$ position defined by the IAU in 1959 shows that the latitude of the true Galactic mid-plane at the 3.1 kpc distance to the Scutum-Centaurus Arm is not $b = 0$, but instead closer to $b = -0.4$, which is the latitude of Nessie to within a few pc. Apparently, Nessie lies *in* the Galactic mid-plane. An analysis of the radial velocities of low-density (CO) and high-density (NH_3) gas associated with the Nessie dust feature suggests that Nessie runs along the Scutum-Centaurus Arm in position-position-velocity space, which means it likely forms a dense 'spine' of the arm in real space as well. No galaxy-scale simulation to date has the spatial resolution to predict a Nessie-like feature, but extant simulations do suggest that highly elongated over-dense filaments should be associated with a galaxy's spiral arms. Nessie is situated in the closest major spiral arm to the Sun toward the inner Galaxy, and appears almost perpendicular to our line of sight, making it the easiest feature of its kind to detect from our location (a shadow of an Arm's bone, illuminated by the Galaxy beyond). Although the Sun's ($\sim$ 25 pc) offset from the Galactic plane is not large in comparison with the half-thickness of the plane as traced by Population I objects such as

GMCs and HII regions ($\sim$ 200 pc; Rix & Bovy (2013)), it may be significant compared with an extremely thin layer that might be traced out by Nessie-like "bones" of the Milky Way. Future high-resolution extinction and molecular line data may therefore allow us to exploit the Sun's position above the plane to gain a (very foreshortened) view "from above" of dense gas in Milky Way's disk and its structure.

1. Introduction

Determining the structure of the Milky Way, from our vantage point within it, is a perpetual challenge for astronomers. We know the Galaxy has spiral arms, but it remains unclear exactly how many (cf. Vallée 2008). Recent observations of maser proper motions give unprecedented accuracy in determining the three-dimensional position of the Galaxy's center and rotation speed (Reid et al. 2009; Brunthaler et al. 2011). But, to date, we still do not have a definitive picture of the Milky Way's three dimensional structure.

The analysis offered in this paper suggests that some Infrared Dark Clouds[1]—in particular very long, very dark, clouds—appear to delineate major features of our Galaxy as would be seen from outside of it. In particular, we study a $> 3°$-long cloud associated with the IRDC called "Nessie" (Jackson et al. 2010), and we show that it appears to lie parallel to, and no more than just few pc from, the true Galactic Plane.

Our analysis uses diverse data sets, but it hinges on combining those data sets with a modern understanding of the meaning of Galactic coordinates. When, in 1959, the IAU established the current system of Galactic (l, b) coordinates (Blaauw et al. 1959), the

[1]The term "Infrared Dark Cloud" or "IRDC" typically refers to any cloud which is opaque in the mid-infrared.

positions of the Sun with respect to the "true" Galactic disk, and of the Galactic Center, were not as well determined as they are now. As a result, the Galactic Plane is typically **not** at $b = 0$, as projected onto the sky. The exact offset from $b = 0$ depends on distance, as we explain in §3.1. Taking these offsets into account, one can profitably re-examine data relevant to the Milky Way's 3D structure. The Sun's vantage point slightly "above" the plane of the Milky Way offers useful perspective.

"IRDCs" are loosely defined as clouds with column densities high enough to be obvious as patches of significant extinction against the diffuse galactic background mid–infrared wavelengths. Peretto & Fuller (2009) set the boundaries of IRDCs at an optical depth of 0.35 at 8 μm wavelength, equivalent to an H_2 column density $\approx 10^{22}$ cm^{-2}. In the Peretto & Fuller (2010) sample, clouds have average column densities of a few 10^{22} cm^{-2}. Some IRDCs actively form high–mass stars (e.g., Pillai et al. 2006 and Rathborne et al. 2007). Kauffmann & Pillai (2010) explain that while some "starless" IRDCs are potential sites of future high–mass star formation, and the few hundred densest and the most massive, IRDCs may very well contain a large fraction of the star–forming gas in the Milky Way, it is still true that most IRDCs are not massive and dense enough to form high–mass stars. Thus, a small number of very dense and massive IRDCs may be responsible for a large fraction of the galactic star formation rate, and an extragalactic observer of the Milky Way might "see" IRDCs not unlike Nessie hosting young massive stars as the predominant mode of star formation here.

The traditional ISM-based probes of the Milky Way's structure have been HI and CO. Emission in these tracers gives line intensity as a function of velocity, so the position-position-velocity data resulting from HI and CO observations can give three dimensional views of the Galaxy, if a rotation curve is used to translate line-of-sight velocity into a distance. Unfortunately, though, the Galaxy is filled with HI and CO, so it is very hard to disentangle features when they overlap in velocity along the line of sight. Nonetheless, much of the basic understanding of the Milky Way's spiral structure we have now comes from HI and CO observations of the Galaxy, much of it from the compilation of CO data presented by Dame et al. (2001).

Recently, several groups have targeted high-mass star-forming regions in the plane of the Milky Way for high-resolution observation. In their BeSSeL Survey, Reid et al. are using hundreds of hours of VLBA time to observe hundreds of regions for maser emission, which can give both distance and kinematic information for very high-density ($n > 10^8$ cm^{-3}) gas (Reid et al. 2009; Brunthaler et al. 2011). In the HOPS Survey, hundreds of positions associated with the dense peaks of infrared dark clouds have now been surveyed for NH_3 emission (Purcell et al. 2012), yielding high-spectral resolution velocity measurements towards gas whose density typically exceeds 10^4 cm^{-3}. In follow-up spectral-line surveys to the ATLASGAL (Beuther et al. 2012) dust-based survey of the Galactic Plane, Wienen et al. (2012) have measured NH_3 emission in nearly 1000 locations. The ThrUMMs Survey aims to map the entire fourth quadrant of the Milky Way in CO and higher-density tracers (Barnes et al. 2010), and it should yield additional high-resolution velocity measurements.

Targets in high-resolution (e.g. BeSSeL) studies are usually identified based on continuum surveys, which show the locations of the highest column-density regions, either as extinction features ("dark clouds" in the optical, "IRDCs" in the infrared), as dust emission features (in surveys of the thermal infrared), or as gas emission features (e.g. HII regions).

Great power lies in the careful combination of continuum and spectral-line data when one wants to understand the structure of the ISM in three-dimensions. Thus, there have already been several efforts to combine dust maps with spectral-line data, whose goal is often the assignment of more accurate distances to particular clouds or regions e.g. (Foster et al. 2012). These improved distances allow for more reliable conversion of measured quantities (e.g. fluxes) to physical ones (e.g. mass).

In this study, our aim is to combine morphological information from large-scale mid-infrared continuum "dust" maps of the Galactic Plane with spectral-line data, so as to understand the nature of very long infrared dark clouds that appear parallel to the Galactic Plane. We focus in particular on the IRDC named "Nessie" in the study presented by Jackson et al. (2010). In that 2010 paper, Nessie is shown to be a highly elongated filamentary cloud (see Figure 1) exhibiting the after-effects of a sausage instability that led to several massive-star-forming peaks spaced at regular intervals. We extend the work of Jackson et al. by first by literally "extending" the cloud, to a length of at least 3 degrees (§2). In §3, we show that a careful accounting for the modern measures of the Sun's height off of the Galactic mid-plane and of the true position of the Galactic Center imply that Nessie lies not just parallel to the Galactic Plane, but *in* the Galactic Plane. We consider what velocity-resolved measures of the material associated with Nessie tells us about its three-dimensional position in the Galaxy, and we conclude, in §4.1 that Nessie likely marks the "spine" of the Scutum-Centaurus arm of the Milky Way in which it lies. In §4.2, we consider, in the light of coming computational and observational capabilities, the likelihood of finding more "Nessie-like" structures in the future, and of using them, in conjunction with the Sun's vantage point just above the mid-plane of the Milky Way, to map out the skeleton of our Galaxy.

2. Nessie is Longer than We Thought

Nessie was discovered and named using Spitzer Space Telescope images that show the cloud as a very clear absorption feature at mid-infrared wavelengths Jackson et al. (2010).

Using observations of the dense-gas tracer HNC, Jackson et al. (2010) further show that the section of the cloud from l = 337.85 to 339.1 (labelled "Nessie Classic" in Figure 1) exhibits very similar line-of-sight velocities, ranging over $-40 < v_{LSR} < -36$ km s^{-1}. The similarities of these line-of-sight velocities is taken to mean that the cloud is a coherent, long structure, and not a chance plane-of-the-sky projection of disconnected features. Thus, "Nessie Classic" is shown to be a dense, long ($\sim 1°$), narrow ($\sim 0.01°$), filament, and Jackson et al. (2010) ultimately conclude that it is undergoing a sausage instability leading to density peaks hosting active sites of massive star formation.

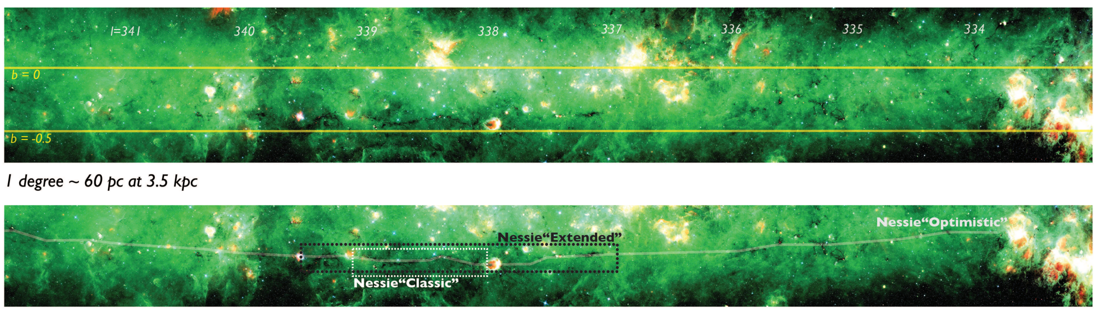

Fig. 1.— . Nessie "Classic," "Extended," and "Optimistic." It is recommended that this high resolution figure be viewed electronically, as zooming and panning are necessary to reveal the structures discussed. Background imagery is a three-color image constructed from Spitzer where red shows MIPS 24 μm, green IRAC 8.0 μm, and blue IRAC 5.8 μm. Image (brightness/contrast) adjustment used emphasizes Nessie and also makes the image look a bit greener than is "natural." Yellow horizontal lines show $b = 0°$ and $b = -0.5°$. Small white numbers show galactic longitude (l) in degrees. Full size version of this figure is available at this link (submit to Journal). A non-annotated high-dynamic-range view of this Spitzer image is available as a supplement to this paper at http://hdl.handle.net/1902.1/22050. (Note that related figures below show less exaggerated contrast, and zoom in on the central portions of Nessie.)

Our purpose in looking at Nessie again here is not to further analyze the star-forming nature of this cloud. Instead, our focus is on how long the full Nessie feature might be, and what its length and its three-dimensional position might imply about its role in the Galaxy. Casual inspection of Spitzer imagery given in Figure 1 suggests that Nessie is at least two or three times longer than "Nessie Classic," measuring at least 3° long ("Nessie-Extended"). Very careful inspection (pan and zoom Figure 1) of the Spitzer images suggests that Nessie *could be* even longer. If one optimistically connects what appear to be all the relevant pieces then "Nessie Optimistic" could be as much as 8° long (light white chalk line in Figure 1). The optimism involved in seeing the longest extent for Nessie could be warranted if bright star-forming regions have broken up the continuous extinction feature, and/or if the background emission fluctuates enough to make the extinction hard to detect.

Determining the physical, three-dimensional, nature of extensions to the Nessie cloud requires a detailed analysis of the velocity of the gas associated with the dust responsible for mid-IR extinction. We offer such an analysis below (§3), but here we note that if Nessie (as is nearly certain given its velocity range) lies in or near the Scutum-Centaurus Arm of the Milky Way, then its distance is roughly 3.1 kpc (cf. Jackson et al. 2010). At that distance, Nessie Classic is roughly 80 pc long, Nessie Extended is 160 pc long, and Nessie Optimistic is 430 pc long. For any of these lengths, the dark filament's width is of order 0.01 degrees (0.5 pc), according to Jackson et al.'s (2010) analysis of the Spitzer imagery. Thus, clouds's axial ratio is about 150 for Nessie Classic, 300 for Nessie Extended, and nearly three times more, 800, for Nessie Optimisitc. (These calculations are based on Table 1 a publicly-available interactive spreadsheet, at this link, a snapshot of which is shown as Figure 2.)

Table 1: Estimates of Nessie's Density and Mass

Assumptions:	*Baryonic mass of Milky Way (Msuns)*				*1.25E+11*						
	Distance to Nessie (pc)				*3,100*						
Nickname	**Length** *deg*	**Radius** *deg*	**Length** *pc*	**Radius** *pc*	**Average density** *cm^-3*	**H2 column density** *cm^-2*	**Equiv. Av** *mag*	**Mass** *Msuns*	**Mass per unit length** *Msuns/pc*	**# to equal mass of Milky Way**	**aspect ratio**
	for innermost Spitzer IRDC ...										
"Nessie Classic"	1.5	0.005	81	0.3	1E+5	8E+22	81	1E+5	1,208	1E+6	150
"Nessie Extended"	3	0.005	162	0.3	1E+5	8E+22	81	2E+5	1,208	6E+5	300
"Nessie Optimistic"	8	0.005	431	0.3	1E+5	8E+22	81	5E+5	1,208	2E+5	800
	for envelope (width as observed in HNC, Jackson et al. 2010)...										
"Nessie Classic"	1.5	0.05	81	2.7	5E+2	4E+21	4	5E+4	604	3E+6	15
"Nessie Extended"	3	0.05	162	2.7	5E+2	4E+21	4	1E+5	604	1E+6	30
"Nessie Optimistic"	8	0.05	431	2.7	5E+2	4E+21	4	3E+5	604	5E+5	80

Fig. 2.— Estimates for the density and mass of Nessie, under various assumptions about its length. The **top set** of values shows estimates for a cylinder with radius, length, and average density appropriate to the Spitzer "shadow" shown in Figure 1. The average density is set to 10^5 cm^{-3} so as to achieve a visual extinction of ~ 100 magnitudes, consistent with the typical extinction on tenths of pc scales in an IRDC. The **lower set** of values is different only in that a density of 500 cm^{-3} is used, as an estimate of the typical density of the region seen to emit in HNC by Jackson et al. 2010.

3. The Three-Dimensional Position of Nessie within the Milky Way

3.1. Looking "Down" on the Galaxy

Astronomers would love to travel far beyond the Milky Way, so that we could observe its spiral pattern face-on, as we do for other galaxies. But our Sun is so entrenched in the Milky Way's plane that an "overhead view" of the Milky Way's structure is impossible. Or is it? What if the Sun were just far enough above the Galactic Plane that we could use its height to give ourselves a tiny bit of perspective on the Galactic Plane that would spatially separate features–if they are very narrow–at different distances to be at different projected latitudes? Turns out we *are* lucky in this way–the Sun *is* apparently located a bit above the Plane (see below), and we can use that vantage point to out advantage.

To understand why most astronomers do not yet consider the possibility or value of an overhead view, we need to consider the origin of our current Galactic coordinate system, and our current understanding of the Sun's and the Galactic Center's 3D positions. Writing in 1959 on behalf of the International Astronomical Union's (IAU's) sub-commission 33b, Blaauw et al. wrote:

> The equatorial plane of the new co-ordinate system must of necessity pass through the sun. It is a fortunate circumstance that, within the observational uncertainty, both the sun and Sagittarius A lie in the mean plane of the Galaxy as determined from hydrogen observations. If the sun had not been so placed, points in the mean plane would not lie on the galactic equator.

In a further explanation of the IAU system in 1960, Blaauw et al. explain that stellar observations did, at that time, indicate the Sun to be at $z_{\rm Sun} = 22 \pm 2$ (22 pc above the plane), but the authors then discount those observations as too dangerously affected by hard-to-correct-for extinction in and near the Galactic Plane (Blaauw et al. 1960). Instead, the 1959 IAU system relies on the 1950's measurements of HI, which showed the Sun to be at $z_{\rm Sun} = 4 \pm 12$ pc off the Plane, consistent with the Sun being directly in the Plane ($z_{\rm Sun} = 0$). Interestingly, since the 1950's, the Milky Way's HI layer has been shown to have corrugations on the scale of 10's of pc (Malhotra 1995), and there may be similar fluctuations in the mid-plane of the H_2 (Malhotra 1994), so it is still tricky to use gas measurements to determine the Sun's height off the plane.

Astronomers today are still using the (l^{II}, b^{II}) Galactic coordinate system defined by Blaauw et al. (1959), but it is *not* still the case, within observational uncertainty, that the Sun is in the mean plane of the Galaxy, and the true position of the Galactic Center is no longer at $(l^{II} = 0, b^{II} = 0)$. Instead, a variety of lines of evidence (Chen et al. 2001; Maíz-Apellániz 2001; Jurić et al. 2008) show that the Sun is approximately 25 pc above the stellar Galactic mid-plane, and VLBA proper motion observations of masers show that the Galactic Center is about 7 pc below where the (l^{II}, b^{II}) system would put it, at $b = -0.046^\circ$ (Reid & Brunthaler 2004). These offsets, as predicted by Blaauw et al., imply that "points in the mean plane [do] not lie on the galactic equator."

Figure 3 shows a schematic (not-to-scale) diagram of the effect of the Sun's and the Galactic Center's offsets from the mid-plane defined by the IAU in 1959 (and still in use as (l^{II}, b^{II}) today). The tilt of the the true, physical, Galactic mid-plane to the presently IAU-defined plane means that, within about 12 kpc of Sun[2] any feature that is truly "in" the Galactic mid-plane will appear on the Sky at negative b^{II}. Figure 5 shows an example of this effect, where the rainbow-colored dashed line indicates the sky position of the physical

[2]12 kpc is the approximate distance where the physical and IAU planes cross, on a line toward the Galactic Center. Along other directions toward the Inner Galaxy, as shown in the lower panel of Figure 4, it will be further to the crossing point, and toward the Outer Galaxy, for a "flat" disk, the mid-plane will always appear at negative latitudes.

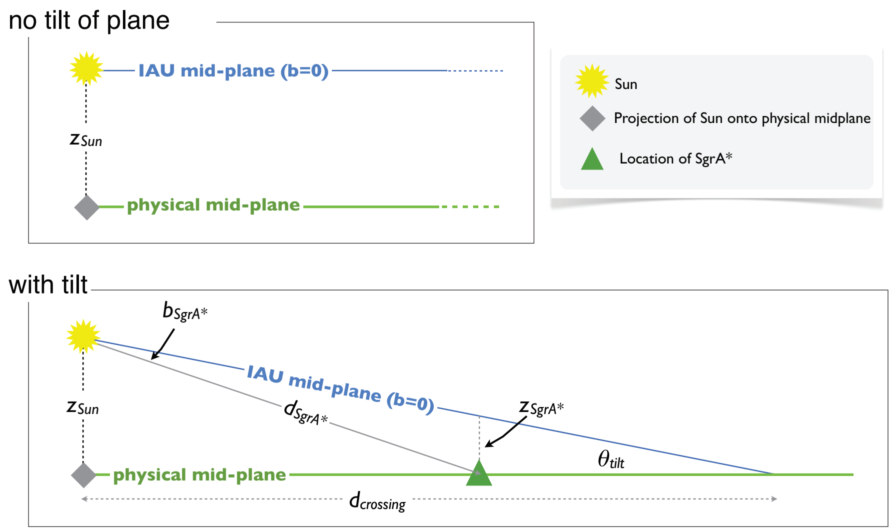

Fig. 3.— . Schematic side-views of the of the physical mid-plane of the Galaxy with respect to the IAU-defined mid-plane. The drawings are **not to scale**. In both panels, $z_{\rm Sun}$ represents the height of the Sun above the Galactic mid-plane. In the **upper panel**, and in figures labeled "no tilt of plane" below, we consider *only* the Sun's offset from the plane in calculating the observed coordinates of the true "physical" mid-plane. In the **lower panel**, and in figures labeled "with tilt" below, we also take the offset, $z_{\rm SgrA*}$, of the Galactic Center (Sgr A*) into account. For reference, if the distance to SgrA*, $d_{\rm SgrA*}$, is 8.5 kpc and $z_{\rm Sun}$=25 pc and $z_{\rm SgrA*} = 7$ pc (based on $b = -0.046°$ for SgrA*) then the angle by which the IAU mid-plane is tilted with respect to the physical plane is $\theta_{\rm tilt} = 0.12°$ and the distance from the Sun to where the two planes cross is $d_{\rm crossing} = 12$ kpc.

Galactic mid-plane at a Nessie-like distance of 3.1 kpc (assuming the the Sun is 25 pc off the plane, a distance to SrgA* of 8.5 kpc, a rotation speed for the Milky Way of 220 km s^{-1}, and (U,V,W) motion for the Sun of 11.1, 12.4, and 7.2 km s^{-1}, respectively).

3.2. Using Rotation Curves and Velocity Measurements to Place Nessie in 3D

Ever since velocity-resolved observations of stars and gas have been possible, astronomers have been modeling the rotation pattern of the Milky Way. Using a measured rotation curve for the Milky Way's gas, (e.g. McClureGriffiths & Dickey 2007,), one can translate observed LSR velocities to a unique distance in the Outer Galaxy, and to one of two possible ("Near" or "Far") distances toward the Inner Galaxy. Figure 4 shows iso-v_{LSR} contours toward the Inner Galaxy, around the longitude range of Nessie, superimposed on the data-driven cartoon of our current understanding of the Milky Way's structure. Notice that velocities associated with the near-side of the Scutum-Centaurus Arm in Nessie's longitude range should be near 40 km s^{-1}.

Combining a modern estimate for the Sun's height above the plane ($z_{\rm Sun} \sim 25$ pc), with the IAU Galactic coordinate definitions, we can determine where the physical mid-Plane of the Galaxy *should* appear in the (l^{II}, b^{II}) system at any particular distance from the Sun. Figure 5 shows where the Scutum-Centaurus Arm would appear on the Sky (for a distance to SrgA* of 8.5 kpc, a rotation speed for the Milky Way of 220 km s^{-1}, and (U,V,W) motion for the Sun of 11.1, 12.4, and 7.2 km s^{-1}, respectively). As its caption explains in detail, Figure 5's colored lines are associated with the near part of the Scutum-Centaurus Arm. Two versions of this plane-of-the-Sky view are shown, one *only* accounting for the offset of the Sun, and the other also accounting for the tilt of the coordinate system caused by the Galactic Center also not lying in the IAU plane (see Figure 3).

The dashed colored lines in Figure 5, indicating the predicted position of the Galactic Plane on the Sky at the distance to the near side of the Scutum-Centaurus Arm, pass almost directly through Nessie, regardless of whether or not one considers the "tilt" of the coordinate system caused by SgrA*'s offset. Solid colored lines show 20 pc above and below the Plane at the distance to the Scutum-Centaurus Arm, so Figure 5 makes it is very clear that Nessie lies within just a few pc of the Plane, along its entire length. This is either an extremely fortuitous coincidence, or an indication that Nessie is tracing a significant feature that effectively marks the mean location of the Galactic Plane. Given the waviness of the plane on 10 pc scales (see above, (Malhotra 1994)), the location at even less than 10 pc from the mean plane is likely fortuitous–but the location so close to the mean is not.

3.2.1. CO Velocities

CO observations trace gas with mean density around 100 cm^{-3}. CO emission associated with the Scutum-Centaurus Arm of the Milky Way (Dame & Thaddeus 2011)(Dame et al. 2001) is shown in Figure 6, which presents a plane-of-the-sky map integrated over $-50 < v_{LSR} < -30$ km s^{-1}. The velocity range is centered on -40 km s^{-1}, the average velocity of the Scutum-Centaurus Arm in Nessie's longitude range (see Figures 4 and 5). The white chalk line superimposed on Figure 6 is the same tracing of "Nessie Optimistic" shown in Figure 1. The black feature labeled "Nessie" refers to "Nessie Classic."

Judging by-eye vertical (latitude) centroid of the CO emission in Figure 6 appears to follow Nessie remarkably well, even out to the full 8° (430 pc) extent of Nessie Optimistic. We have also calculated a curve representing the locus of latitude centroids for CO in this velocity range, and even at this coarse resolution, a curve following Nessie's shape is clearly a better fit than a straight line passing through the CO centroids.

Table 1 estimates that the Nessie IRDC has a typical H_2 column density of $\sim 10^{23}$ cm^{-2} and a typical volume density of $\sim 10^5$ cm^{-3}. Thus, the plane-of-the-sky coincidence of the line-of-sight-velocity-selected "Scutum-Centaurus" CO emission and the mid-IR extinction suggests that the Nessie IRDC may be a kind of dense "spine" or "bone" of this section of the Scutum-Centaurus Arm, as traced by much-less-dense ($\sim$ 100 cm^{-3}) CO-traced gas.

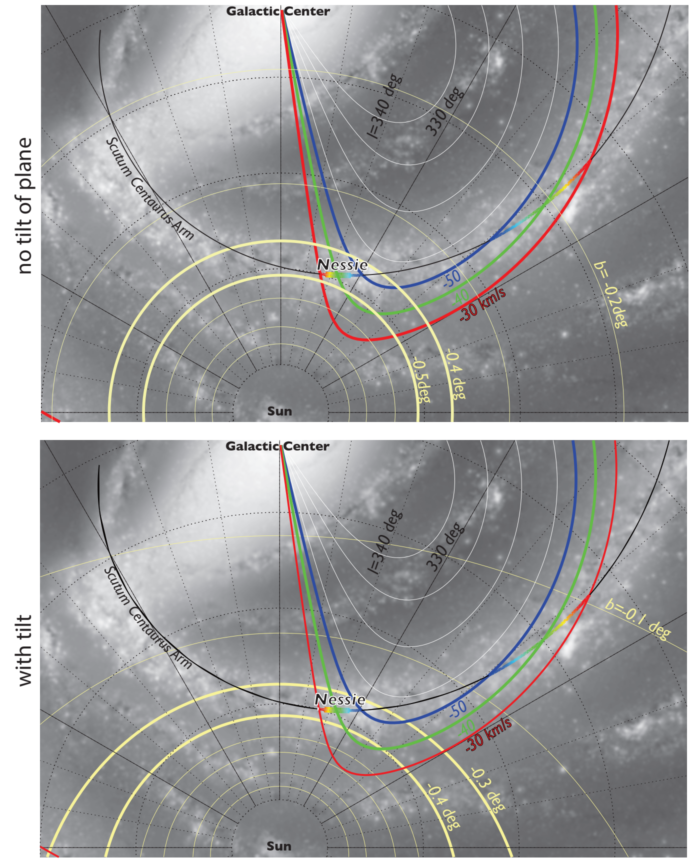

Fig. 4.— For the fourth quadrant of the Milky Way, contours of constant LSR velocity of -30,-40,and-50 km s^{-1} (using a rotation curve from McClureGriffiths & Dickey 2007,) are superimposed on a cartoon model of the Milky Way. CO and dense gas observations (see below) give LSR velocities associated with Nessie (shown here as rainbow curve) near -40 km^{-1}, placing Nessie in the Scutum-Centaurus arm (highlighted in black), about 3.1 kpc from the Sun. Yellow-highlighted curves show positions in the Galaxy that would have the labeled value of Galactic Latitude (b) when viewed from the Sun. In the **top panel**, *only* the height of the Sun off the plane (taken to be 25 pc in this example) is considered in drawing the iso-b curves, and in the **bottom panel**, a 7 pc offset of the Galactic Center (see text), which causes an overall tilt of 0.12° is *also* taken into account.

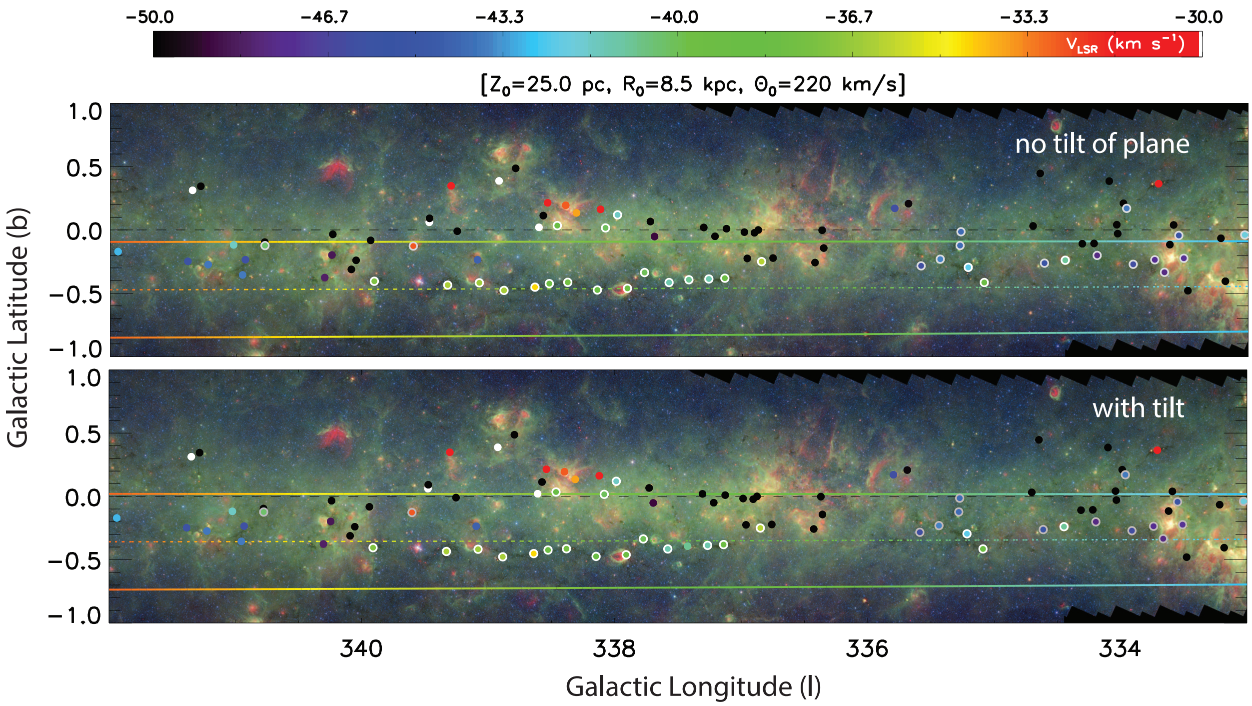

Fig. 5.— . Predicted Sky Position and Radial Velocities for the Scutum-Centaurus Arm of the Milky Way. In both panels, the colored lines are color-coded by velocity, given in the color bar at the top. The colored dashed line shows the predicted position for the Galactic Plane for the near side of the Scutum-Centaurus Arm (roughly 3.1 kpc from the Sun). The solid colored lines show ±20 pc from the mid-Plane at the same (~ 3.1 kpc) distance. These lines and colors are calculated using a model of a (flat) Milky Way described by the parameters shown below the color bar. Background imagery is from Spitzer, as in Figure 1. A black dashed line emphasizes the position of $b = 0$. As in Figure 4: in the **top panel**, only a 25 pc offset of the Sun above is taken into account; and in the **bottom panel**, a 7 pc offset for the Galactic Center is also used in the calculation.

But, the spatial resolution of the CO map is too low ($8'$), and the 20 km s^{-1} velocity range associated with the Arm in CO is too broad to decide based on this evidence alone whether Nessie is a well-centered "spine" or just a long skinny feature associated with, but potentially significantly inclined to, the Scutum-Centaurus Arm.

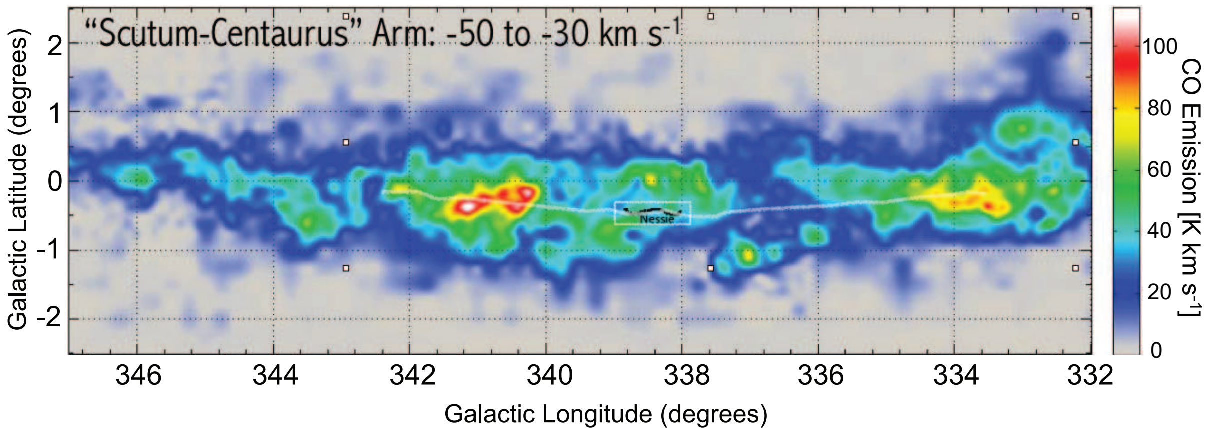

Fig. 6.— . CO emission, integrated between -50 and -30 km s^{-1}, as projected on the sky, based on data from (Dame et al. 2001), with trace of Nessie Optimistic (light white line) from Figure 1 superimposed. The dark black squiggle labeled "Nessie" (surrounded by a light white box) marks the position of Nessie Classic.

3.2.2. NH_3 Velocities

To estimate the 3D orientation of Nessie more precisely, we need to employ a gas tracer whose emission is sparser than CO's in position-position-velocity space. Many recent studies have shown that IRDCs typically host over-dense blobs of gas (often called "clumps" or "cores") that provide the gaseous reservoirs for the formation for massive stars. Thus, several studies have been undertaken to survey IRDCs and their ilk for emission in molecular lines that trace high-density ($\gg 10^3$ cm^{-3}), potentially star-forming, gas.

The H_2O Southern Galactic Plane (HOPS) Survey (Purcell et al. 2012) has surveyed hundreds of sites of massive star formation visible from the Southern Hemisphere for NH_3 emission, which traces gas at densities $n \gtrsim 10^4$ cm^{-3}. The HOPS targets were selected based on H_2O maser emission, thermal molecular emission, and radio recombination lines, so as to include nearly all known regions of massive star formation within the surveyed area. These "massive-star-forming region" selection criteria mean that the HOPS database includes NH_3 spectra for dozens of positions within the longitude range covered by Nessie.

Figure 7 shows an overlay of HOPS sources' NH_3-determined LSR velocities on the Spitzer image of Nessie used in Figure 5. The (color-coded) velocities of the HOPS sources, for both Nessie Classic, and Nessie Extended (see Figure 1), agree remarkably well with what is predicted for the Scutum-Centaurus Arm (color-coded lines). Note that agreement of the NH_3 and predicted velocity to within 5 km s^{-1} is indicated by light-colored circles around the HOPS symbol (see caption for details). White circles correspond to the Nessie Extended sources also shown in Figure 8, below, and grey circles mark other points, in Nessie Optimistic, also likely (based on their velocity) to be associated with the Scutum-Centaurus arm. The velocities of sources at latitudes much different from Nessie's within this longitude range largely do *not* agree, and those sources are unlikely to associated with the near-side of the Scutum-Centaurus Arm.

For Nessie Classic, Jackson et al. (2010) had already noted a very narrow velocity range for dense gas associated with the IRDC, based on HNC observations. What is new here is the three-dimensional (latitude, longitude, *and* velocity) association of a *longer* Nessie's dense gas with predictions for where the centroid of the Milky Way's Scutum-Centaurus Arm's "middle" would lie.

Figure 8, which offers a position-velocity diagram of CO (color) and NH_3 emission (black dots) together, shows the association of the Nessie-HOPS sources with the Scutum Centaurus Arm most clearly. What is most remarkable about Figure 8 is that the black line sloping through the figure is *not* a fit to the black dots representing the HOPS sources. Instead, that line indicates the position-velocity trace of the Scutum-Centaurus Arm based on (Dame & Thaddeus 2011) data for the full Galaxy, not just this small longitude range. Figure 8 implies that Nessie goes right down the "spine" of the Scutum-Centaurus Arm, as best we can measure its position in CO position-velocity space.

4. What is the Significance of Nessie-like structures within a Spiral Galaxy?

4.1. A Bone of the Galaxy

All the evidence presented in this paper, taken together, strongly suggests that Nessie forms a spine-like feature that runs down the center of the Scutum-Centaurus Arm of the Milky Way. How did it get there? Is it the crest of a classic spiral density wave (Lin & Shu 1964), or does it have some other cause? Any feature this long and skinny that is not controlled by Galactic-scale forces will be subject to a variety of instabilities, and cannot last long. It would be great if we could look to numerical simulations for answers, but today's simulations can, alas, only give hints. Nessie is *so* skinny, and *so* much denser than its surroundings that no extant numerical simulation has the combination of spatial

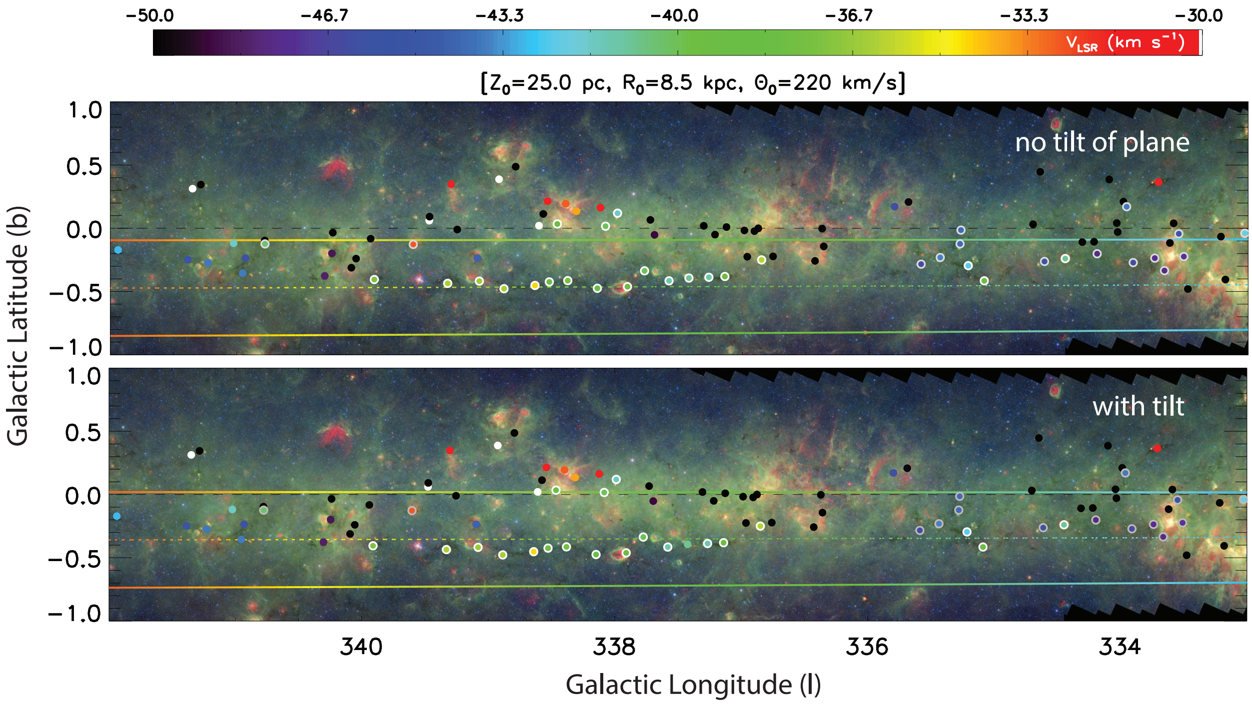

Fig. 7.— . Superposition of HOPS Sources, color-colored by NH_3-determined LSR velocity. Colored lines have the same meaning (predicted LSR velocity) as in Figure 5, so the colorful dashed lines at $b \sim -0.5°$, in both panels, represent the physical Galactic mid-plane, and the solid colorful lines indicate 20 pc above and below the plane. Agreement of the NH_3 and predicted LSR velocity (color) to within 2.5 km s^{-1} is indicated by a *white circle* around the HOPS symbol, and *grey* circles indicate agreement to within 5 km s^{-1}. As in Figures 4 and 5: in the **top panel**, only a 25 pc offset of the Sun above is taken into account; and in the **bottom panel**, a 7 pc offset for the Galactic Center is also used in the calculations.

resolution and dynamic range in density needed to produce a feature like it.

Figure 9 offers a snapshot of a numerical simulation Dobbs & Pringle (2013) that represents the state of the art at present (available as a movie at this link). One can see density features that are highly elongated, both within the spiral arms, and also between the arms. Many of the features between the arms in Figure 9 are similar to the

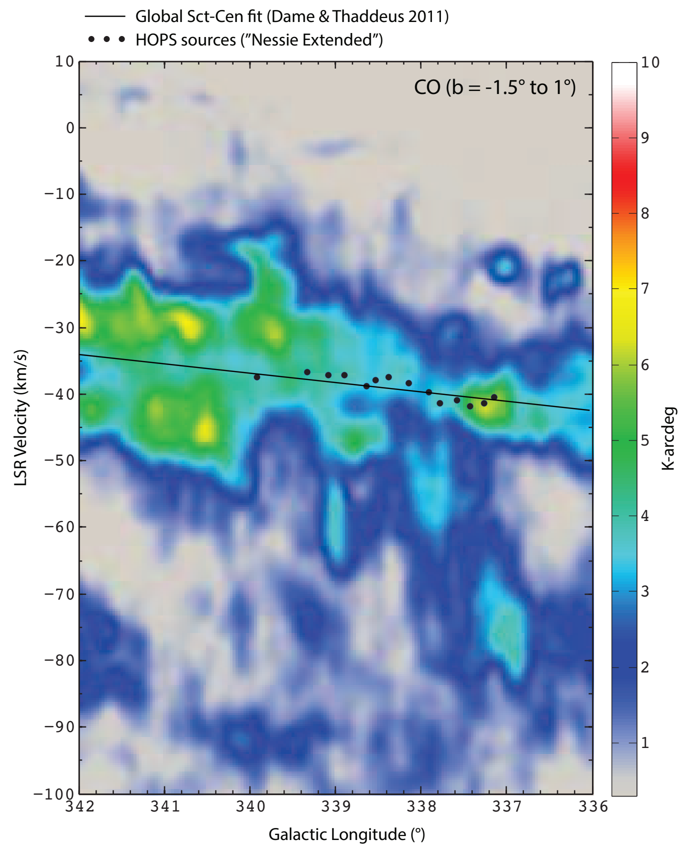

Fig. 8.— . Position-velocity diagram of CO and NH_3. Colored background shows CO emission integrated over $-1.5 < b < 1°$. Black dots show HOPS sources coincident with Nessie Extended, also shown in Figure 7 as white-circle-highlighted colored points. The dots are plotted at the longitudes given in Figure 7, and the LSR velocities given by the centroid of the NH_3 emission for each HOPS source. The black line shown is *not* a fit to the HOPS or the CO data shown: it is a segment of a *global* log-spiral fit to CO data for the entire Scutum-Centaurus Arm, extending almost 360° around the Galaxy (taken from Fig. 4 of Dame & Thaddeus (2011).

'spurs' and 'feathers' that have been simulated and observed by E. Ostriker and colleagues (Shetty & Ostriker 2006; La Vigne et al. 2008; Corder et al. 2008). Figure 10 (discussed below) shows a recent WISE image of the galaxy IC342 (Jarrett et al. 2013), and it is clear from that image that some 'spiral' galaxies also exhibit inter-arm filaments that are even more pronounced than the simulated spurs and feathers.

In the case of Nessie, the velocity information analyzed in §3.2.1 and 3.2.2 seems to very strongly favor Nessie's being oriented exactly along (within, as the backbone of) an arm (Scutum-Centaurus) over the idea that Nessie is a spur or interam filament.

Estimates for the mass of Nessie under various assumptions are given in Table 1. Jackson et al. 2010 model Nessie as a(n unmagnetized) self-gravitating fluid cylinder supported against collapse by a "turbulent" analog of thermal pressure, undergoing the sausage instability discussed in Chandrasekhar & Fermi (1953). For the observed line width of HNC, the theoretical critical mass per unit length, m_l, is 525 $M_\odot$/pc for Nessie. But, if, as Jackson et al. explain, one estimates m_l using HNC emission itself and (uncertain) abundance values for HNC, then $110 < m_l < 5 \times 10^4 M_\odot pc^{-1}$. Given that the low end of this range ($110 M_\odot pc^{-1}$, favored by Jackson et al.) gives a very low value for extinction toward Nessie ($A_V \sim 4$ mag), we favor higher values m_l, needed to be consistent with the observed IR extinction. Recent LABOCA observations of dust continuum emission from pieces of Nessie (Kauffmann, private communication), suggest that $m_l \gtrsim 10^3$ in the mid-IR-opaque portions of Nessie. So, at present, it would appear that there is at least an order-of-magnitude uncertainty in m_l. Some of this uncertainty is caused by the definition of Nessie's shape, which makes it unclear which "mass" to measure in calculating m_l, but more is due to the vagaries of converting molecular line emission and/or dust continuum to true masses.

It is not the goal of this paper to produce a more definitive estimate of Nessie's m_l or total mass, or to model Nessie's internal density structure. Instead, here, we only seek to estimate the total mass of Nessie in order to consider its mass as a fraction of that in the Galaxy or in a spiral arm. So, Table 1 offers rough estimates of the mass of cylinders, whose (constant) average density is set so that the typical extinctions associated with Nessie's IR-dark ($A_v \sim 100$) and HCN bright ($A_V \gtrsim$ a few mag) radii are sensible. Assuming a mean density for the mid-IR opaque material of 10^5 cm^{-3}, then Nessie Classic is 1×10^5 M$_\odot$, Nessie Extended is 2×10^5 M$_\odot$ and Nessie Optimistic is 5×10^5 M$_\odot$. If one assumes that the envelope traced by the HNC observations of Jackson et al. (2010) for Nessie Classic continues along Nessie's length, then the mass of a $n \sim 500$ cm^{-3} cylindrical tube (see Table 1) associated with Nessie would be 5×10^4 M$_\odot$ for Classic and 3×10^5 M$_\odot$ for Optimistic. For the Optimistic case, this mass amounts to 2 millionths of the total baryonic mass (assuming $\sim 10^{11}$ M$_\odot$ total) of the Milky Way. To use this fraction in order to estimate the total number of "Nessies" discoverable in the Milky Way's ISM, we need to remember that the HCN mass is likely a lower limit (meaning the mass fraction is an upper limit), and that most of the gas mass in the ISM is at low density, following a log-normal-like density distribution. Given those caveats, we estimate that of order thousands of additional Nessie-like features should be discoverable, if they are characteristic of spiral arms.

4.2. Can We Map the Full Skeleton of the Milky Way?

In an ideal Universe, we would be able to travel far enough outside of the Milky Way to observe it from "outside," the way that we see, for example, Andromeda. The story for years has gone that generating an observationally-based plan (overhead) view of the Milky Way is impossible, because we are "in" the Plane. It is as if Earth-bound astronomers have been living in the 2D world Edwin A. Abbott famously called 'Flatland (Abbott 2008) when it comes to thinking about how to image the Milky Way's spiral structure. But, we can

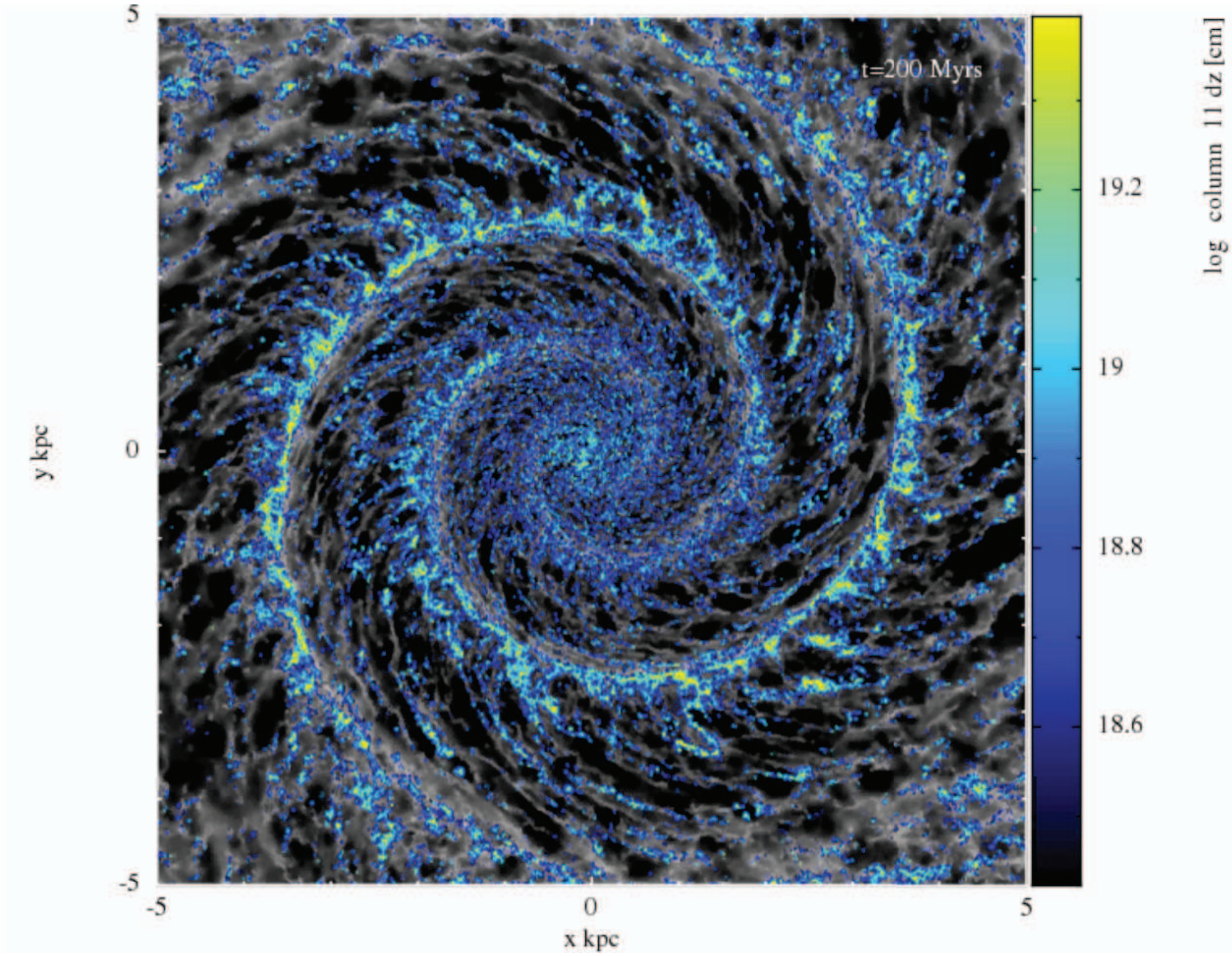

Fig. 9.— . Snapshot of a simulation of a 2 armed spiral galaxy, with heating and cooling, self gravity of the gas, and stellar feedback (Figure 1 of Dobbs & Pringle 2013). The gas is gathered together into GMCs in the spiral arms, and later becomes sheared into long, thin 'spurs', or 'feathers'. The snapshot is taken at a time of 250 Myr, shows the galaxy out to a radius of 7 kpc, and is from a simulation with 8 million particles.

escape Flatland by realizing that the tiny offset of the Sun above the Milky Way's midplane can give us a tiny, but useful, bit of perspective on the 3D structure of the Milky Way, and it can offer a (highly-foreshortened!) overhead view. This perspective is only useful when looking at very sharp, very narrow, features like Nessie, because puffier, more standard, arm-defining features will overlap too much to be separated in a very foreshortened view.

Carry out the following thought experiment. Draw a rough plan of a spiral galaxy on a very flat piece of paper. Position a vantage point a tiny distance (a few hundredths of an inch) above that piece of paper, about two-thirds of the way out from the center of the galaxy. Now give the observer at that vantage point super-sharp eyesight and ask if the observer can separate the spiral arm features you drew, as they observe them. They can–if and only if the spiral you drew has very narrow features defining its arms. If the observer were exactly *in* the piece of paper (living in Flatland), separating the arms would be impossible, regardless of their width. We are, like your observer, are at a tiny, tiny, elevation off of a spiral galaxy, and our vision is good enough to separate very skinny arm-like features.

So, how might we use out vantage point above the Plane to map out more of the Milky Way's skeleton? It turns out that Nessie is located in a place where seeing a very long IRDC projected parallel to the Galactic Plane should be easiest. Look again at Figure 4, and consider Nessie's placement there. According to the current (data-based cartoon) view of the Milky Way shown in Figure 4, Nessie is in the closest major spiral arm (Scutum-Centaurus) to us, along a direction toward, but not exactly toward, the (confusing) Galactic Center. Nessie's placement there means that it will have a bright background illumination as seen from further out in the Galaxy (e.g. from the Sun), and that it will have a long extent on the Sky as compared with more distant or less perpendicular-to-our-line-of-sight objects. It is always good when one finds what should be the easiest-to-see example of a new phenomenon first, so we are reassured that Nessie was the first "Bone" of the Milky Way found.

To find more 'Nessies,' if such narrow "bone-like" features are in fact typical in spiral arms, we need to be clever about where and how we look. Our current understanding of the Milky Way's spatial and velocity structure will allow us to draw more velocity-encoded lines like the ones shown in Figure 5 on the Sky, mapping out the whole Galaxy as seen from the Sun's vantage point. With such predictions in hand, we should design algorithms to look for dust clouds elongated (roughly) along those lines, and then we should examine the velocity structure of the elongated features, as we do in §3, above. Of course, we need to be flexible in which features we accept as possible other "bones," remembering that the model we will use to draw the expected features on the Sky is the same one we seek to refine! It is likely that a Bayesian approach, using the extant Milky Way model as a prior, will succeeed in this way.

As extinction and dust emission maps cover more and more of the sky at ever-improving resolution and sensitivity, we should be able to map more and more of the Milky Way's skeleton. New wide-field extinction-based efforts based at first on Pan-Starrs, and ultimately on Gaia, will be tremendously helpful in these efforts in the coming decade.

Recent (e.g. Spitzer, Herschel) mid- and far-infrared imagery already suggests that: 1) not all galaxies once thought to be dominated by a spiral pattern really are; and 2) not all IRDCs are likely to be part of the Milky Way's skeleton. As mentioned above, images like Figure 10 clearly show that spiral galaxies can be very web-like, with long, straight filaments interconnecting spiral arms. Thus, some of the features seen as long, skinny, IRDCs in the Milky Way could very well *not* be part of spiral arms, even if they are part of a Galaxy-wide structural pattern. This possibility will clearly complicate the modeling discussed above, but that just makes it more interesting! New data from ever-deeper and ever-sharper extragalactic observations will likely reveal even more complex galaxy strucutres. Combining ALMA thermal dust emission and molecular line observations of slightly-inclined galaxies will allow us to combine structural image with velocity information facilitating ever-improving model comparison.

Over the past 15 years, since their discovery, there have been many efforts to catalog and characterize IRDCs, and it is clear that not all IRDCs are, or should be, part of Nessie-like bones.

The catalog compiled by Peretto & Fuller (2009) lists 11,000 IRDCs, but none of the features cataloged will be Nessie-like on its own. The structure-finding algorithm used in the Peretto & Fuller work is biased toward finding core-like roundish peaks, so a cloud like Nessie forms a connect-the-dots pattern in the Peretto & Fuller catalog. In fact, Nessie is comprised of $\sim$ 100 Peretto & Fuller sources. So, while the Peretto & Fuller catalog is tremendously useful to the study of the properties of massive star forming cores, it will only become useful for finding "bones" when someone applies a clever dot-connecting algorithm to it, and its ilk.

Some very large, and/or very extended, IRDCs, such as the so-called "Massive Molecular Filament" studied by Battersby & Bally (2012), are not located along the plane-of-the-sky projected spiral arms. These clouds, which are probably just massive star-forming regions near but not exactly in the Galactic plane, do not appear as straight or highly-elongated as Nessie (cf.the"wisp" discussed by Li et al. (2013)), and they may offer a hint at what threshold to set in looking for elongated features as we search for more bones. Futher, once numerical galaxy-simulation modeling resolution catches up to observational resolution, models should be able to say whether they other, non-bone-like, massive IRDCs had their origins long ago in bones, or form in some other way.

Fig. 10.— . IC342 as seen by WISE, reproduced from Jarrett et al. 2013. The colors correspond to WISE bands: 3.4 μm (blue), 4.6 μm (cyan/green), 12.0 μm (orange), 22 μm (red).

5. Contributions and Facilities

5.1. Contributions

This paper was a truly a group effort, and the author list includes only some of the many people who have contributed to it. The entire project was inspired by a question: "Is Nessie parallel to the Galactic Plane?," asked by Andi Burkert at the 2012 Early Phases of Star Formation (EPoS) meeting at the Max Planck Society's Ringberg Castle in Bavaria. Three EPoS attendees beyond the author list contributed significant ideas and data to this work, most notably Steven Longmore, Eli Bressert, and Henrik Beuther. We are grateful to Cormac Purcell for giving us advance online access to the HOPS data, and to Mark Reid for generously sharing his expertise on Galactic structure. The text here was largely written by Alyssa Goodman; the theoretical ideas come primarily from Andi Burkert; and much of the geometrical analysis was carried out by Christopher Beaumont, Bob Benjamin, and Tom Robitaille. Tom Dame and Bob Benjamin provided expertise on Galactic structure, and they created several of the figures shown here. Jens Kauffmann provided expertise on IRDCs, and also was first to point out the potential relevance of the Sun's non-zero height above the Galactic Plane. Joao Alves provided expertise on the potential for using extinction maps to find more Nessie-like features, and Michelle Borkin was instrumental in early visualization work that led to our present proposals for using the Sun's "high" vantage point to map out the Milky Way. Jim Jackson contributed critical expertise on the Nessie IRDC, based both on the 2010 study he led and on unpublished work since.

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5.2. Facilities

Data in this paper were taken with the following telescopes. The CO Survey of the Milky Way data Dame et al. (2001) are from the 1.2-Meter Millimeter-Wave Telescope in Cambridge, Massachusetts, USA. NH_3 observations of cores Purcell et al. (2012) in and near Nessie are from the Mopra 22-meter telescope near Coonabarabran, Australia. The mid-infrared images of the Galactic Plane used to define Nessie are from NASA's Spitzer Space Telescope, and they were made as part of the Galactic Legacy Infrared Mid-Plane Survey Extraordinaire (GLIMPSEBenjamin et al. (2003),Churchwell et al. (2009)) and MIPSGAL (where MIPS=Multiband Infrared Photometer for Spitzer (MIPS))Carey et al. (2009) Surveys of the Galactic Plane.

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