Massive Star Formation: Observations Confront Theory
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The Spiral Structure of the Galaxy: Something Old, Something New...

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Abstract. I review some of the old difficulties in determining the spiral structure of the Galaxy using kinematic distances, and present some of the new results on the stellar spiral structure of the Galaxy which do not suffer from the same systematic difficulties. I conclude the discussion with something borrowed (spiral structure studies in other galaxies) and discuss how it relates to something blue (massive star formation).

1. Something Old: Kinematic Methods for Mapping the Galaxy

From the very beginning, one of the chief goals of 21-cm mapping of neutral hydrogen was a global map of the spiral structure of the Galaxy. To get a sense of this history, I recommend starting with a meeting summary by Simonson (1970). Participants arrived filled with enthusiasm for converting HI surveys into maps, but left somewhat deflated due to lack of convergence in maps produced with the same data. Liszt (1985) describes the same state of affairs over a decade later. His Figure 7 collects several distinctly different maps, leading him to worry that ongoing CO surveys of the Galaxy would yield a similar impasse. The review of CO results by Combes (1991) shows that these concerns were not unfounded. Similarly, attempts to map the HII region distribution, most famously by Georgelin & Georgelin (1976), continue to suffer from significant ambiguities, e.g., Sewilo et al. (2004).

Part of the problem is demonstrated in Fig. 1, which shows how, by assuming circular rotation and adopting a rotation curve, one can assign a radial velocity to every parcel of gas in the Galaxy. The Galaxy can be mapped, in principal, by converting the velocity back to position. The fundamental difficulties with this method are well known: **(1)** assuming circular rotation, the velocity-to-distance relation is double valued in the first ($0 < l < 90^\circ$) and fourth ($270 < l < 360^\circ$) quadrants. Additional information is needed to resolve the near-far distance ambiguity; **(2)** the distance accuracy depends upon the model $dv_{\rm rad}/dr$, which varies with longitude. Near $l = 0^\circ$ or $l = 180^\circ$, one loses all distance resolution; **(3)** gas has "random" velocity (whose origin is poorly, or perhaps multiply, understood) of order 7-10 km s^{-1}, producing distance uncertainties that are longitude dependent; and **(4)** significant non-circular motion is expected near spiral arms and near any non-axisymmetric structures in the inner galaxy, i.e., bars. In this case, the velocity-to-distance relation can be multiply valued, e.g., Gómez (2006). A thorough review of all of these issues is provided in Burton et al. (1992).

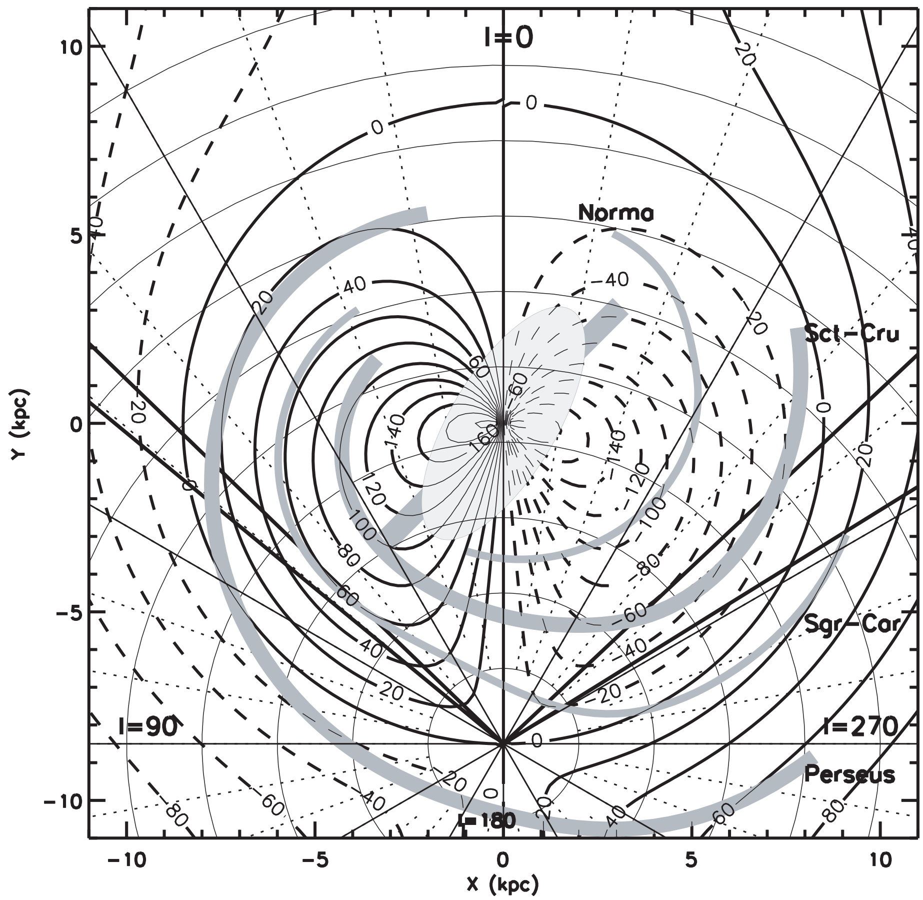

Figure 1. Schematic face-on map of the inner Galaxy. The Sun is located at (X,Y)=(0,-8.5 kpc) at the center of circles drawn every 2 kpc. Galactic longitude is indicated with dotted diagonal lines spaced every 10°, with thin solid diagonal lines every 30°. The labeled contours, spaced every 20 km s^{-1}, show the radial velocity as a function of position in the Galaxy, using the rotation curve of Clemens (1985). The putative location of four spiral arms (Norma, Scutum-Crux, Sagittarius-Carina, and Perseus) are taken from the Taylor & Cordes (1993) compilation, and are based principally on HII regions distances from Georgelin & Georgelin (1976). The Perseus and Scutum-Crux arm are emphasized for reasons given in the text. The tangency directions for these two arms have been claimed in the area between two diagonal bold lines at $l = 46 - 50.5^o$ and $l = 302 - 313^o$. The length and orientation of the two stellar bars shown are explained in the text.

Kinematic mapping of spiral structure suffers from a "catch-22". Distances to spiral arms rely on a model of the velocity field, but the velocity field depends on the positions of the spiral arms. It has been suggested by many that perhaps we are being too ambitious in demanding a face-on map, and should stick to defining "spiral arms" as coherent features in a velocity-longitude diagram, using different mapping functions to convert this into spatial information. Simonson (1970) reports that Harold Weaver suggested that *l-v* plots should be published on a rubber-sheet! However, even for this approach, spurious features can result for directions where a large range of distance maps to a small range of velocity (Burton et al. 1992). Finally, it is worth pointing out that the association of arm segments in the first/fourth and second/third quadrant is somewhat dicey. Because radial velocities go to zero at $l = 0, 180°$, associations are hard to prove.

2. Something New: Non-Kinematic Methods for Mapping the Galaxy

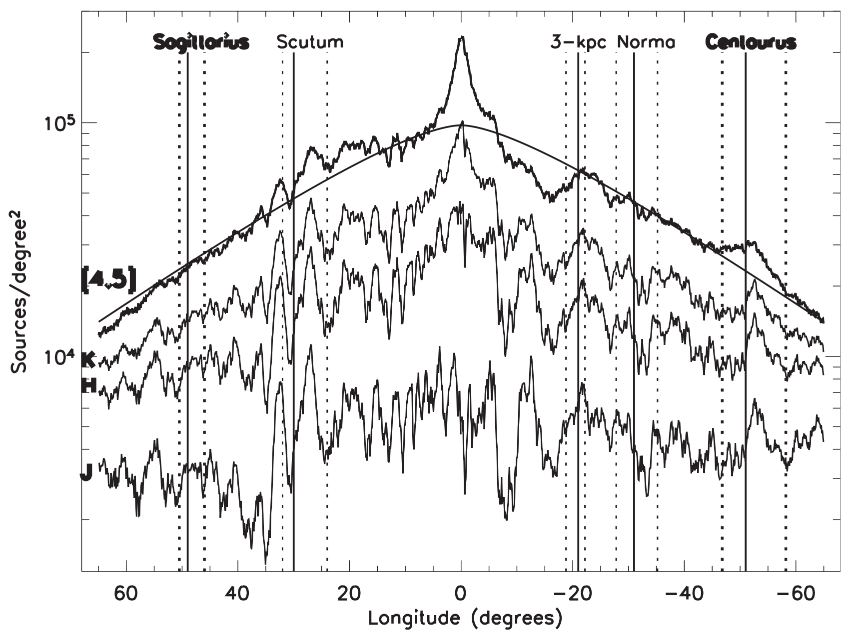

Figure 2. Density of sources in the Galactic plane ($|b| < 1°$) for near and mid-infrared bands (J, H, K, and *Spitzer/IRAC* [4.5], as labeled) in the magnitude range m =6.5 to 12.5 averaged over $2° \times 0.1°$ strips. Note in particular the presence of an enhancement in star counts in the $l = 302 - 313^o$ Centaurus arm tangency directions, but the *lack* of an enhancement for the expected $l = 46 - 50.5^o$ Sagittarius arm tangency. The smooth line is the best-fit model (Benjamin et al. 2005).

Mapping the stellar structure of the Galactic disk has the potential to improve the situation. Optical color-magnitude diagrams and spectroscopic work continue to refine distances to nearby stellar clusters, e.g., Russeil et al. (2007). Improving angular resolution and sensitivity in the near- and mid-infrared have made it possible to look at the distribution of stars in the inner Galaxy. COBE/DIRBE maps and several near-infrared surveys show evidence for non-axisymmetric stellar structures in the inner Galaxy, reviewed by Gerhard (2002) and Merrifield (2004). Although integrated infrared light (or total star counts) do not allow for direct *mapping* of the stellar component, models for the bar of the Galaxy were matched to the COBE data, finding a bar of half-length $R_{bar} = 3.1 - 3.5$ kpc oriented at $\phi = 20 - 25°$ (see Fig. 1) with bar axis ratios of 10:4:3 (length:width:height). Calculating the potential of this stellar distribution allowed for models of non-axisymmetric gas flow. Englmaier & Gerhard (1999) showed that some of the oddities of the HI/CO position-velocity diagrams, like the feature referred to as the "expanding 3-kpc" arm, could be plausibly produced by non-axisymmetric gas flow caused by the bar. Since then, several groups (Hammersley et al. 2000; Nishiyama et al. 2005; Benjamin et al. 2005) have used "red clump stars" to trace out a longer, vertically thinner bar, with $\phi = 44 \pm 10^\circ$ out to $R_{\rm long} = 4.4 \pm 0.5$ kpc.[1] This extension takes the bar out to the estimated position of the Scutum spiral arm. It is not clear if the discrepancy in angle between the thicker, shorter bar and thinner, longer bar is real – models should be revised to fit both structures simultaneously.

"Red clump" stars, the helium-burning phase of moderate mass ($0.5-2\,M_\odot$) stars, have a fixed luminosity with uncertainty $\Delta m = 0.03$ (Cabrera-Lavers et al. 2007), which gives a distance uncertainty of $\Delta d/d = 1.3\%$. They are extremely useful for mapping the old stellar disk, and have also been used to map the stellar warp (Momany et al. 2006). The chief difficulty in using these sources is the difficulty of near-infrared color selection in the presence of large extinction. Recently, the Spitzer/GLIMPSE mid-infrared survey of the Galactic plane (Benjamin et al. 2003) has allowed for the nearly-extinction free characterization of the stellar sources in the inner Galaxy. In particular, Fig. 2 shows that the mid-infrared stars counts as a function of Galactic longitude is quite symmetric, especially when compared to the near-infrared star counts. Most importantly, this simple star count plot shows the Centaurus tangency[2] is present in stars; the Sagittarius tangency, supposedly at a similar distance from the Sun, has no detectable stellar counterpart! This supports a previous claim (Drimmel 2000; Drimmel & Spergel 2001) that the Milky Way is a two armed spiral in the old (Population II) stellar disk. What is new is detailed information on the arm structure, which could not be resolved with COBE data, as well as greatly reduced extinction.

Before moving on, it is worth noting that the infrared investigations have also enabled the non-kinematic mapping of dust clouds, e.g., (Drimmel et al. 2003; Marshall et al. 2006), and radio parallax measurements of sufficiently bright masers in star formation region have begun to yield stunningly accurate distances with precisions in the range of 1-5% (Xu et al. 2006). The future looks bright for high-precision Galactic cartography.

3. Something Borrowed: The Extragalactic View of Spiral Structure

The fact that the Galaxy is a strongly barred galaxy was something that was only hinted at when HI and CO astronomers were first working to map out spiral

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[1] All distances in this contribution assume the distance from the Sun to Galactic Center is the IAU standard $R_o = 8.5$ kpc. Recent characterization of orbit of the S2 star around Sgr A* indicate $R_o = 7.62 \pm 0.32$ (stat)± 0.16 kpc (Eisenhauer et al. 2005). Using red clump stars, Nishiyama et al. (2006) find $R_o = 7.52 \pm 0.10$(stat)± 0.35 (sys) kpc.

[2] The Centaurus tangency at $l = 302 - 313^\circ$ is the fourth quadrant tangency of the what is frequently referred to as the Scutum-Crux arm. This tangency is quite clearly in the constellation Centaurus, however, not Crux.

structure. But with the knowledge that the Galaxy has such a pronounced bar, it is instructive to look at other barred galaxies to look at the range of spiral structure encountered. First, barred galaxies (types SB and SAB) are *usually* grand design: 71%±7% of isolated spirals, 72%±4% of group spirals, and 93%±5% of binary-galaxies (Elmegreen & Elmegreen 1982). Moreover, in the infrared, a larger fraction of galaxies are barred: 30% of galaxies in the Ohio State Bright Galaxy Survey are classified as barred in the optical B band, while 60% are barred in the infrared H band (Eskridge et al. 2002).

I speculate that the Galaxy has two *principal* arms which attach to the long bar: the Scutum-Centaurus arm, which wraps off the near end of the long bar shown in Fig. 1, and the Perseus arm which is consistent with wrapping off the far end of the bar with the same pitch angle as the Scutum-Centaurus arm. But then how does one explain the Sagittarius-Carina arm? Observations of other galaxies show that it is not unusual for galaxies to have optically visible arms, without underlying enhancements in the old stellar disk (Block & Wainscoat 1991). Models, both old and new (Shu et al. 1973; Martos et al. 2004), show how it is possible to form arms of compressed gas without increasing the stellar surface density. So perhaps the Sagittarius-Carina arm is a qualitatively different type of structure than the Perseus and Scutum-Centaurus arms.

4. Something Blue: Massive Star Formation in the Galaxy

If this speculation is correct, a comparison of the star formation in the $l = 302 - 313^o$ (stellar/gas arm) and the $l = 46 - 50.5^o$ (gas arm) teaches us about the global formation of massive, blue stars. Reviews of star formation (McKee & Ostriker 2007) discuss the possibility that the surface density of the stellar disk plays a role in determining the molecular fraction, and therefore the star formation, e.g., (Blitz & Rosolowsky 2004). These two directions with tangencies at similar galactocentric radii but with differing stellar surface densities, provide a *nearby* environment for testing models of global star formation.

In addition, if the model of a principally two-armed spiral for the Galaxy is correct, the Centaurus tangency provides an ideal testing ground for models of spiral density wave theory, as discussed by Roberts & Burton (1977). Certainly, the $l = 302 - 313^o$ direction is known for several distinct anomalies, including large deviations in the HI velocity field (McClure-Griffiths & Dickey 2007), and a clear magnetic field reversal (Brown et al. 2007). In addition, the CS detection rate of MSX-selected dark clouds drops from about 80% to 20% in this direction (Jackson et al. 2008), suggesting that the densest molecular gas in the inner Galaxy lies principally in this Scutum-Centaurus arm which is, we argue, the region of the deepest gravitational potential.

It is important to remember that all of the massive star formation that we see occurring in the Galaxy has a context, a context that is very important for shaping our understanding of the global nature of galaxies as star-formation engines. Much of the star formation that we so clearly see now is probably occurring in spiral arms and spurs. The challenge continues to be to unite the microscopic view of the Galactic astronomer with the macroscopic view of the extragalatic astronomer.

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