The Galaxy Disk in Cosmological Context
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Spiral Arm Tangencies in the Milky Way

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Abstract. The historical directions of spiral arm tangencies in the Milky Way are presented and compared to results of mid-infrared star counts using the Spitzer Space Telescope. While the Scutum and Centaurus tangency directions show a 20-30% excess of star counts, all other expected tangency directions show no similar increases. These two tangencies are probably associated with a density wave arm that comes off the near side of the bar of the Galaxy while the other arms whose tangencies are not detected may be compression in the gas, but not in the old stellar disk.

Keywords. Galaxy: structure – Galaxy: disk – Galaxy: fundamental parameters – Galaxy: kinematics and dynamics – Galaxy: evolution

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1. Galactic Spiral Structure in a Cosmological Context

Whatever happened to the study of Galactic spiral structure? IAU Symposium No. 1: *Coordination of Galactic Research*, which gathered 27 participants near Groningen in June 1953, marked the beginning of an era focused on Galactic structure in general and spiral structure in particular. Thirty years later, IAU Symposium No 106: *The Milky Way Galaxy*, which reassembled 150 participants in Groningen in June 1983, marked the end of spiral structure. The review of the subject in this second volume (Liszt 1985) collects over a half dozen maps, all strikingly different, many based on the same HI data, concludes that "there is really no adequate method available for solving this problem", and further warns that "the newly-begun process of deriving galactic structure in CO seems to be recapitulating the history laid down by HI observers." And at this IAU Symposium No. 254, twenty five years later almost to the day, the Milky Way has become a *disk* galaxy, as opposed to a *spiral* galaxy, and we debate its cosmological context. We seem to have dodged the question posed so innocently back in 1953.

All of which leads one to wonder, does Galactic spiral structure even *matter* in a cosmological context?

It might be that obtaining a complete understanding of the details of the spiral pattern is not necessary to construct adequate models for the global evolution and star formation history of disk galaxies. A study of spiral galaxies by Elmegreen & Elmegreen (1986), for example, showed little difference between the star formation rate of grand design and flocculent spiral galaxies, leading them to argue that well-organized spiral arms contribute less than 50% to the overall star formation rate of a disk galaxy. And in this volume, Bruce Elmegreen shows that for younger galaxies in the process of assembly, the bulk of star formation might have been much more irregular and episodic. Recent work shows evolution in the fraction of disk galaxies that show bars (Sheth *et al.* 1986), but not much is known about the cosmological evolution of spiral structure. Perhaps spiral arms only show up after disks have quieted down: an interesting, but irrelevant, regularity in the structure of disk galaxies.

But if we truly understand galactic disks, particularly the interrelation between the gaseous, stellar, and star formation components, I would think that we would also have a secure model of spiral structure: Spiral arms provide a test that any robust disk model must be able to pass. Unfortunately, although the Milky Way is the one galaxy in the Universe where we can separate out all the different stellar populations, measure kinematics, and study the ISM on a cloud-by-cloud basis, it is also the one spiral galaxy for which we do not have a satisfactory map of spiral structure.

2. Spiral Arm Tangencies for the Milky Way

Hunt through *Galactic Astronomy* (Binney & Merrifield 1998), and you will find three not-very-compelling maps of kinematic distances to molecular clouds, selected HII regions, and the distribution of Cepheids. From the latter two, the authors describe "a picture of the distribution of young stars that is woefully out of focus so that a measure of imagination will be required to make out features that may in reality be well-defined." The pitfalls of mapping spiral structure using kinematic distances to HI and CO emission are well known (Burton *et al.* 1992), the chief difficulty being that arms will be marked by deviations from circular rotation, while gas is mapped by *assuming* circular rotation. Another complicating factor is the fact that maps of spiral structure could depend on the tracer one uses. Binney & Merrifield (1998) make a distinction between gas arms, mass arms, and star formation arms. These features may not have similar amplitudes, or even be spatially coincident.

However, one aspect of Galactic spiral structure *ought* to be robustly established: the directions of spiral arm tangencies. In an ideal grand-design spiral galaxy, mapping spiral structure would be as simple as (1) identifying tangencies in direction and distance in the first quadrant ($l = 0 - 90°$), (2) identifying the corresponding tangencies in the fourth quadrant ($l = 270 - 360°$), and (3) connecting these points with a logarithmic spiral. A check of the method would be that the fourth quadrant tangencies should be a larger angle from the Galactic center than the corresponding first quadrant tangencies, since we expect the Milky Way to be a trailing spiral.

Figure 1 shows two different methods for locating the spiral arm tracers. The pairs of tangencies come from integrating the CO intensity of Dame *et al.* (2001) over a ± 15 km s^{-1} range around the tangent point velocity to identify the directions with the greatest tangent point emission (Dame, priv. comm). The historical range of tangencies, taken from a selective compilation of the literature by Englmaier & Gerhard (1999), is shown as well. A reassessment of the direction of spiral arm tangencies, using modern high angular resolutions surveys in CO and HI, would be extremely desirable. For arms interior to the Sun, a rational naming system would identify the arms by their first and fourth quadrant tangency locations. As this figure shows, the system is far from rational. The *Sagittarius-Carina* arm, for example, should really be the *Sagitta-Vela* arm, and the *Scutum-Crux* arm should probably be called the *Aquila-Centaurus* arm!

All of the previous work of spiral structure has focused on the distribution of gas and star formation, but GLIMPSE results (Benjamin *et al.* 2005) have shown that the high resolution, low extinction mid-infrared view of the stellar disk can yield surprises. GLIMPSE (Galactic Legacy Infrared MidPlane Survey Extraordinaire) and GLIMPSE 2 are *Spitzer Space Telescope Legacy Programs* to survey the inner Galaxy ($|l| \leqslant 65°$ and $|b| \lesssim 1°$) at 3.6, 4.5, 5.8, and 8.0 μm using the Infrared Array Camera (Benjamin *et al.* 2003). Fitting the average number of sources per square degree in the outer Galaxy with the model expectations for an exponential disk yielded an exponential stellar disk scale length, $H_* = 3.9 \pm 0.6$ kpc. This disk has been divided out in Figure 1. We found an extended Galactic bar, characterized by an enhancement of red clump giants at ~12th magnitude with a brightness decreasing with decreasing longitude, yielding a bar angle, $\phi = 44° \pm 10°$ and half-length, $R_{bar} = 4.4 \pm 0.5$ kpc. This is different from the $20 - 25°$ seen for the shorter COBE/DIRBE bar (Gerhard 2002), which appears to be a distinct structure. This maximum longitude of the Long Bar is also the expected direction for the Scutum spiral arm tangency, suggesting that the spiral arm joins onto the bar at this point. We also detected a 25% excess of sources corresponding to the Centaurus spiral arm tangency, confirming the claim of Drimmel & Spergel (2001) based on the K-band light distribution as studied with COBE/DIRBE.

3. The "Missing" Spiral Arms

The clear detection of the Centaurus stellar disk tangency in Figure 1, and the excess of stars associated with the Bar/Scutum tangency seems to indicate that this feature of the Galaxy is characterized by an overdensity in stars as well as gas and star formation. But then, what is one to make of the fact that all the other expected tangencies are not evident in the GLIMPSE data? The "missing" Sagittarius arm tangency at $l \approx 50°$ was also noted by Drimmel (2000) and Drimmel & Spergel (2001). We agree with these

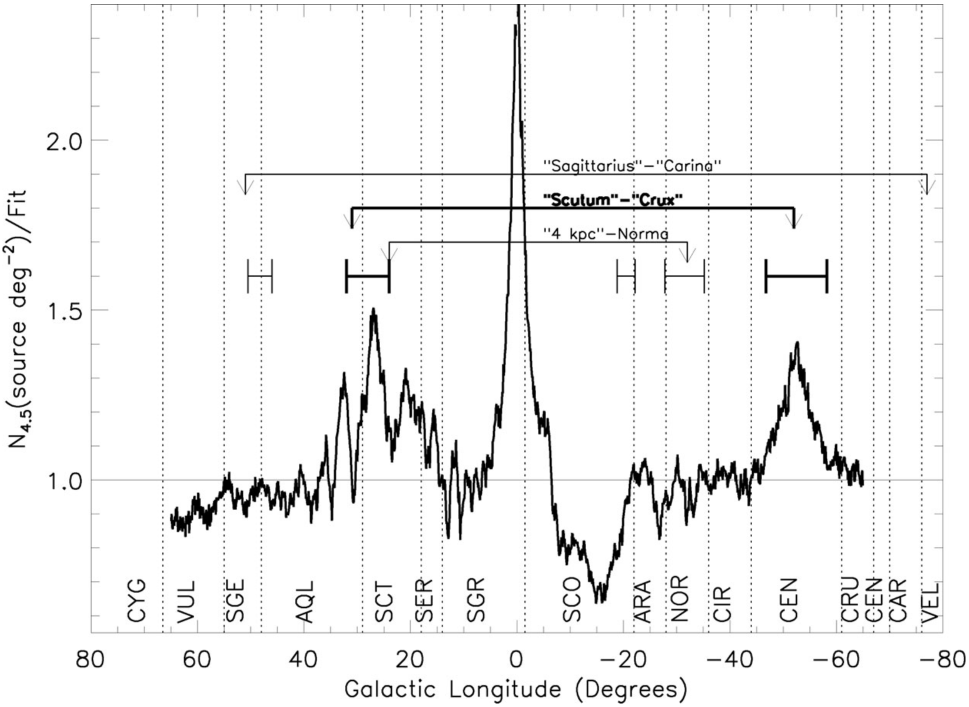

Figure 1. GLIMPSE 4.5 μm star counts between 6.5 and 12.5 magnitude normalized to a Bessel function fit to the data to take out the contribution of the exponential disk (Benjamin *et al.* 2005). Much of the jaggedness of the curve is attributable to extinction. The *Long Bar* ($l = 30°$ to $l \approx -15°$) can be seen clearly. Tangencies locations and spiral arm names based on CO studies (Dame, 2008, priv comm) are given with the horizontal bars with arrows. Note that in most cases, the name of the arm does not match with the constellation labels shown at the bottom of the graph. The "historical" tangency directions compiled by Englmaier & Gerhardt (1999) are shown for the *Sagittarius*, *Scutum*, *3 kpc Norma* and *Centaurus* tangency. Note that for all these tangency directions, the only two which seem to show an excess in star counts over an exponential stellar disk are the Scutum and Centaurus directions.

authors that the most likely explanation is that there is a qualitative difference between the different spiral arms of the galaxy: 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 (Shu, Milione, & Roberts 1973) and new (Martos *et al.* 2004), show how that it is possible to form arms of compressed gas without increasing the stellar surface density.

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. 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, we argue, is the region of the deepest gravitational potential.

The field of Galactic spiral structure has been moribund for more than a decade, but thanks to new surveys and tracers, I believe that a resurgence is at hand.

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