A Bar Guide to the Milky Way Galaxy (via GLIMPSE)

Artist’s conception of MW (Robert Hurt, SSC/IPAC/JPL)
http://ipac.jpl.nasa.gov/media_images/ssc2008-10b1.jpg
The mid-infrared (3-5 µm) is the ideal wavelength window for star counts. This is because

1. lower extinction as \( \lambda \) increases,
2. lower diffuse emission as \( \lambda \) decreases,
3. stellar fluxes for giants (which dominate number counts for an extinction-free galaxy) peak in the near IR.
GLIMPSE Survey Area

Optical panorama courtesy of Axel Mellinger
“Historical” directions for spiral arm tangencies (Englmaier & Gerhard 1999) shown.
Bar I: The Galactic Bar—Other works

Analysis of COBE data
Many authors...
- $\phi = 20^\circ$ (10-45$^\circ$)
- $R \sim 3.5$ kpc
- Axis ratios $10:3-5:3$

COBE/DIRBE
3.5 $\mu$m
(0.7$^\circ$ beam)
Freudenreich
(1998)

Other techniques
- Off-plane red clump stars
- Microlensing
- 2MASS star counts

Reviews by
- Gerhard (2002)
- Vanhollebeke et al (2009)
Bar 1: The Galactic Bar—Principal confusions

1. Nomenclature
   Galactic Bulge=Triaxial Bulge=Boxy/Peanut Bulge=COBE/DIRBE Bar

2. Variation in fit parameters for angle ($\phi_B$), dimensions ($a_B:b_B:c_B$) and mass ($M_B$)

\[
\begin{align*}
\phi_B & \quad 25^\circ & \quad 10^\circ \text{ to } 40^\circ \\
(a_B:b_B:c_B) & \quad 10:4:3 & \quad 10:7:4 \text{ to } 10:3:3 \\
M_B & \quad 1 \times 10^{10} M_\odot & \quad 0.5 \times 10^{10} M_\odot \text{ to } 2 \times 10^{10} M_\odot
\end{align*}
\]

Variations due to
(a) difference in the density fitting function used (c.f., Dwek et al 1995),
(b) difference in luminosity function used
(c) which other parameters (like disk component) are held fixed or float
(d) incomplete sampling of the sky.
Simultaneously evolving gas and **stellar bar**. [Animations from Fux 1999, but see also Englmaier & Gerhard (1993)… Bissantz, Englmaier, & Gerhard (2003)]
The Far 3kpc Arm appears to be the virtual twin of the near arm (Dame & Thaddeus 2008)!

Placement on a “map” requires non-axisymmetric model of gas flow.

Methanol masers indicate high mass star formation in these arms (Green et al 2009).
Bar 2: The Long Bar—GLIMPSE results

Log₁₀ (Counts mag⁻¹ deg⁻²) vs. [4.5] Magnitude

- Red left of G.C. (l=10-65)
- Blue right of G.C. (l=350-295)

Sun

G.C.

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Bar 2: The Long Bar—GLIMPSE results

(|| > 10° in Benjamin et al 2005)

Confusion limit

More sources:
Faint and small,l

Fewer sources:
Bright and large,l

W33/M17
W41/W42

54°
34°

G.C.

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“Red Clump” Giants: A Standard Candle for Galactic Structure

- Red clump stars come from ~solar metallicity stars between 0.5 - 2.0 $M_\odot$ stars
- Numerous and relatively long lived evolutionary stage of core helium burning with a fixed luminosity (determined by the mass of the helium core upon ignition).
- Their use as standard candles has been very well established: (see Cabrera-Lavers 2007 for refs).

Isochrones of 1-5 $M_\odot$ solar metallicity stars.
Note the red clump box starts to fill up at $\tau \sim 1$ Gyr.

$\Delta m = 0.03 \quad \rightarrow \quad \Delta d/d = 1.3\%$
Red clump: $M_{[3.6]}$ and $M_{[4.5]}$

197 cluster red clump giants selected

$M_{[3.6]}-M_{[4.5]} = -0.05 \pm 0.04$

$M_{K}-M_{[3.6]} = 0.07 \pm 0.04$

No trend in metallicity seen; colors agree with Kurucz and PHOENIX model atmospheres of red clump giants.

Any shift in red clump peak due to extinction, not color correction.
Bar 2: The Long Bar—Comparison with other results

The GLIMPSE results were a confirmation of several previous group who detected the same structure in the midplane using near IR color-selected red clump giants (Hammersley et al 2000…see López-Corredoira et al 2007).

Two recent claims:
Cabrera-Lavers et al (2008) use UKIDDS selected red clump stars to show that at \( b=0, l<10^\circ \), the red clump stars indicate an angle of \( \phi=24^\circ \), not \( \phi=44^\circ \).

Nishiyama et al (2005) use...
Bar 2: The Long Bar—Principal questions

Discrepant angles for Galactic Bar ($\phi_B = 24^\circ$), Long Bar ($\phi_{LB} = 42^\circ$)?

1. Could a 20° “twist” in similar length bars (3.5 vs. 4.5 kpc) be observed in other galaxies?  
   (Not claimed, but not searched for.)

2. Can the same models that explain how the central parts of thin bars thicken over time explain the observed twisting?

Debattista et al (2005)

See also Athanassoula (2005, 2007)
Bar 2: The Long Bar—Principal questions

Mass and mass distribution of the Long Bar?

López-Corredoira (2007) estimates
\[ a_{\text{LB}} : b_{\text{LB}} : c_{\text{LB}} = 10 : 1.5 : 0.2 \]
\[ M_{\text{LB}} = 0.6 \times 10^{10} M_\odot \]

Is this a discrete structure or is it a continuous extension of the Galactic Bar that is not easily parameterize as a triaxial spheroid?

Effects of Long Bar on stellar/gas kinematics?

Relation of Long Bar to spiral structure / star formation?

The Long Bar extends to the longitude of the Scutum spiral arm tangency and “Molecular Ring”. This longitude/velocity range is known to have at least three major superbubbles (extending up to 25 degrees above the plane), the greatest concentrations of IR dark clouds and the three of the largest galactic clusters of red supergiants.

Alexander et al 2009/Clark et al 2009
\[ M_{\text{cl}} = 20,000 M_\odot \]
\[ d = 6 \pm 1 \text{ kpc} \]
Bar 3: The Nuclear Bar – Before GLIMPSE

Alard (2001) – Using a magnitude cutoff of $m_K=9$, extinction correct 2MASS sources assuming intrinsic colors of M giants.

Fit vertical cuts with exponentials, and subtract off these fits to yield nuclear bar.


1. Reanalyzed 2MASS data in a similar way, but fit star counts with disk/triaxial bulge/nuclear bar

2. Developed model of gas flow in double barred system (with locked pattern speed) to match observed CO kinematics.

Star counts: $\phi_{NB}=60-120^\circ$ for all $\phi_B$

$\phi_{NB}=90-105^\circ$ for $\phi_B=10^\circ$

Kinematics: $\phi_{NB}=60-75^\circ$

$M_{NB}=0.2 \times 10^{10} M_\odot$

Bar 3: The Nuclear Bar – Preliminary Results

Longitude asymmetry confirmed…

…but enhanced counts in a nuclear disk/bar unclear.

K band star count map (m=6-12 mag)
No extinction correction

GLIMPSE star counts (m=6-12 mag)
(Also no extinction correction)
A New Stellar View of the Milky Way

• The combination of transparency, sensitivity, and resolution makes GLIMPSE (Benjamin et al 2003) a vital tool in laying bare the structure of the Milky Way. Analysis confirms one (soon two?) bars that were not commonly accepted.

1. The prevalence of red clump giants in the Galactic bar allow us to use mid-IR longitude-magnitude diagrams to map the locus of the (Long) Bar (Benjamin et al 2005), with recent work focusing on the vertical and inner structure. Our results are in agreement with other groups. The Long Bar is thinner and longer than the COBE bar, and probably at a different angle. We will have to learn to live with both of them.

2. We find no clear evidence for an excess of sources in the inner few degrees of the Galaxy beyond the exponential vertical extrapolation of bulge counts. The observed longitude asymmetry is complicated by uncertain extinction corrections. Given the evidence of non-axisymmetric gas kinematics, this should be pursued further using bulge functions with different “cuspiness” and careful treatment of extinction.

Public access to GLIMPSE images—http://www.alienearths.org/glimpse
Barred galaxies are usually grand design (Elmegreen & Elmegreen 1982):
- 71±7% of isolated spirals
- 72±4% of group spirals
- 93±5% of binary galaxies.

Barred galaxies are divided into
- SB(s): spiral begins at the ends of the bar
- SB(r): spiral comes off a central ring

In SB(s) galaxies, an almost-straight dust lane parallels the ridge line of the bar but is displaced slightly forward in the direction of galactic rotation; these connect up with prominent dust lanes seen on the trailing side of the arms in global pattern spirals. These dust lanes are almost never present in SB(r) galaxies (Kormendy & Kennicutt 2004).
Spiral galaxies are more likely to be barred in the infrared (Eskridge et al 2002):
• 30% barred in B band
• 60% barred in H band

Many barred galaxies have very active star formation in their centers (K&K 2004)

Star formation is concentrated in "tiny" rings with mean radii 500 pc. (K&K 2004)

Bars are frequently assumed to be responsible for/related to boxy isophotes in edge-on galaxies. (K&K 2004)

K&K Figure 7; Models from Athanasoula (1993)
There can be bars within bars, but they are oriented randomly with respect to the main bar. As many as three are seen in some galaxies. (K&K 2004; Erwin 2004)

Bars end in or near co-rotation: $R_{CR}/R_{\text{bar}} = 1$ to 1.2 (Elmegreen 1996; Binney & Tremaine 2008)

Bars are typically one disk scalelength long: $R_{\text{bar}}/R_{\text{disk}} \sim 1$ (Kormendy 1979)

The scalelength of the pseudobulge* is 0.1 (range: 0.08 to 1.3) times the scalelength of the disk. (K&K 2004)

*pseudobulges are bulges that have been built up by secular evolution due to star formation in the gas channelled to the center of the galaxy.

K&K Figure 14; Data from R. Buta
Galactic Cartography with GLIMPSE: Spiral Structure

1. Detection of enhanced mid IR star counts in the direction of the Centaurus (and possibly Scutum) spiral arm tangencies...

   and non-detection of enhancements for “Sagittarius”, Norma, and Carina tangencies.

2. Comparison of different tracers of spiral arm tangencies. [Handout]

3. Use of red clump stars as a standard candle for the Long Bar.

4. Attempting to use red clumps stars as a tracer of spiral structure.

5. Arguments that the Scutum-Centaurus Arm is a “dominant” arm
Is it really a Molecular Ring?

“The Molecular Ring is an important Galactic structure. It contains about 70% of all of the molecular gas within the solar circle. Most of the Galactic giant HII regions, far IR luminosity, diffuse ionized gas, and SNR are associated with the ring (Burton 1976; Robinson et al 1984).”


Authors expressing doubts about “ringiness”

Dame (1993)
Binney & Merrifield (1998)
Stark & Lee (2006)
Jackson et al. (2008)
(and more…)
Star Formation where Long Bar meets Scutum Arm

• Vigorous star formation appears to occur at the end of the Long Bar at l~28.5-31.5°. This also appears to be the among the densest concentration of MSX infrared dark clouds (Jackson et al 2008).

Davies et al 2007
26 RSGs!
d=5.83(+1.9/-0.8)

Alexander et al 2009/Clark et al 2009
Mcl=20,000 M☉
d=6±1 kpc
 Galactic distribution of CO from \( l=+90^\circ \) to \(-90^\circ \) (Dame et al 2001)

Next overlay: 3/4 keV emission from \( \sim 3 \times 10^6 \) K gas (Snowden et al 1994)

HI supershells reaching into halo, one with confirmed X-ray emission!

Pidopryhora et al (2007): \( l=25-35^\circ \) \( b=0 \) to \(+25^\circ \) \( v=+60 \) to \(+80 \) km/s

Maciejewski et al (1996): \( l=31-37^\circ \) \( b=0 \) to \(+10^\circ \) \( v=+56 \) km/s

Callaway et al (2000): \( l=14-20^\circ \) \( b=0 \) to \(-12^\circ \) \( v=+40 \) km/s
- Fit by $N = N_0 (l/l_0) K_1 (l/l_0)$ where $l_0 = 24 \pm 4^\circ$ [4.5 band] (17-30$^\circ$)

- $R_{\text{disk}} = 3.9 \pm 0.6$ kpc

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Results of Star Counts toward Carina Tangency
Vela-Carina survey (PI: S. Majewski)

All sources between 6.5 and 12.5 mag:
1.5 deg (lat) x 0.1 deg (lon)

No (wide) Carina enhancement!
But an unexplained discontinuity at GLIMPSE/VelaCar boundary…
Slope of \( m \text{ vs } \log N \) 
\[-1.0 < b < 1.0\]
GLIMPSE star counts:
Dividing out the disk