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An Upper Limit to The Age of the Galactic Bar

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ABSTRACT

Using data from the Two Micron All-Sky Survey (2MASS), we identify a population of infrared carbon (IR C) stars with J$-$K$_S$ ≥ 2 in the Milky Way. These stars are shown to trace the stellar bar previously identified in IR and optical surveys. The properties of C stars strongly suggest that they are of intermediate age. We conclude that the bar is likely to have formed more recently than 3 Gyr ago, and must be younger than 6 Gyr. Implications and further tests of this conclusion are briefly discussed.

Subject headings: Galaxy: structure — stars: carbon — Galaxy: disk

1. Introduction

It is by now well-established that there is a strong stellar bar in the inner disk of the Milky Way. A central bar was first hypothesized by de Vaucouleurs (1964), although the observational evidence has only become overwhelming during the past decade (e.g., Kuijken 1996). Near and far-infrared source count maps have led numerous authors to identify a triaxial bar roughly 3–5 kpc long, with its near side in the first quadrant of the Galaxy (e.g., Blitz & Spergel 1991; Nakada et al. 1991; Weinberg 1992; Weiland et al. 1994). The OGLE survey extended these maps of the inner Galaxy to optical wavelengths and also found the bar morphology (Stanek et al. 1994, 1997). Recent work based on 2MASS data (Skrutskie et al. 2001) shows the full bar quite clearly.

Dynamical arguments suggest that bars in galaxies may be triggered by satellites and companions, intrinsic halo asymmetry, or as a result of disk instability. Once formed, bars may be important for driving the evolution of galaxies through global angular momentum redistribution and increased rates of gas transport to galaxy centers. As a result, barredness may affect a galaxy's star-formation history and nuclear activity. The dynamics of bars together with knowledge of bar ages may be crucial to understanding disk-halo interactions and merger histories. Despite the wealth of data on bar morphologies, little is known of their ages, except for the statistical result that bar frequency appears to decline with redshift for $z \gtrsim 0.5$ (Abraham et al. 1999). If the stellar populations of the Milky Way bar can be age-dated, then the approximate time of the triggering event can be established. This is a first step towards reconstructing the dynamical history of disk asymmetries in the Galaxy.

We know that infrared carbon (IR C) stars reliably map out the Milky Way bar (Skrutskie et al. 2001, this paper). In §2, we briefly recapitulate the selection criteria for IR C stars that allow us to identify this population and to invert its magnitude distribution into a distance distribution. §3 describes the arguments for an intermediate age for the IR C stars. We argue that they are certainly younger than 6 Gyr, and probably younger than 3 Gyr, and therefore the bar must have formed more recently than these limits. In §4, we discuss the implications of this result for studies of bar formation and suggest further work to refine our conclusion. In short, if the Milky Way is typical, bars might be temporary features that can be successively re-excited during a galaxy's lifetime.

2. Tracing the Bar with 2MASS

Carbon stars come in several flavors, differing in their colors and luminosities, evolutionary states, kinematics, and surface enrichment patterns. The brightest ($-4 > \mathrm{M_{bol}} > -6$), and reddest ($\mathrm{J{-}K_S} \gtrsim 1.2$) C stars are the classical N-type AGB stars; they are typified by IRC +10216 (CW Leo). Throughout this paper, the term "C star" will be used to refer to these cool, luminous AGB stars only; the term "IR C star" will be used to refer to the subset of C stars redder than $(\mathrm{J{-}K_S})_0 = 2$.

The IR C stars may be identified, with care, in the 2MASS ($\mathrm{J{-}K_S}$, $\mathrm{K_S}$) CMD (Skrutskie et al. 2001). To illustrate, Figure 1a shows the Hess diagram of a 4 deg^2 region of the Large Magellanic Cloud (LMC). A detailed exploration of the 2MASS view of the LMC has been made by Nikolaev & Weinberg (2000), so we will only touch on the most prominent features here. The main ridgeline of stars extending up to $\mathrm{K_S} \approx 11$ is the red giant and asymptotic giant (AGB) sequence of the intermediate-age and old stellar population. The brighter plume reaching $\mathrm{K_S} \approx 8$ consists of red supergiants. The C stars occupy a bilinear sequence redward of $\mathrm{J{-}K_S} \approx 1.4$, with a slope change at $\mathrm{J{-}K_S} \approx 2$. The redder sources are intrinsically similar to the warmer stars, but are enveloped in a thick shroud of dust. Thus the extended C star sequence lies nearly parallel to the reddening vector.

The IR C star branch of the 2MASS CMD of the Milky Way is shown in Figure 1b. The figure includes roughly 3 $\times 10^4$ sources drawn from the entire sky excluding the Magellanic Clouds. The color-magnitude distribution is wider than that in Figure 1a because of the large distance spread within the Galaxy and the high number of deeply embedded sources in the larger Galactic sample. An additional dispersion due to contamination by OH/IR stars must be present; these have similar luminosities and near-IR colors to the IR C stars (Lepine, Ortiz, & Epchtein 1995).

Spectra of stars in this region of the CMD have been obtained in the LMC (e.g., Hughes, Wood, & Reid 1991), the outer Galaxy (e.g., Liebert et al. 2000), and the inner Galaxy (M. Skrutskie, private communication). A high fraction of the measured stars have C-type spectra, with significant contamination by highly reddened (E(B−V) > 2) M supergiants and OH/IR stars. We thus expect that a high fraction of the total number of color-selected sources are carbon-rich too.

Hipparcos parallaxes have shown $\langle \mathrm{M_K} \rangle = -7.6 \pm 1$ for carbon-rich Mira and SRa variables (Wallerstein & Knapp 1998). The LMC population has $\langle \mathrm{K_S} \rangle = 10.8$ and $\sigma_K = \pm 0.6$, which yields $\langle \mathrm{M_K} \rangle = -7.7$ for an assumed distance modulus of 18.5 mag. We are therefore confident that the Galactic sample is similar to the LMC IR C stars. Figure 1 shows that the $\mathrm{K_S}$ magnitude of the IR C stars, with an appropriate color correction, is stable enough to allow rough calculations of Galactic structure. A least-squares fit to the IR C star branch of the LMC yields a linear relation, $\Delta \mathrm{K_S} = -0.48\ (\mathrm{J}-\mathrm{K_S} - 2)$. Application of this shift to the individual $\mathrm{K_S}$ magnitudes reduces all IR C stars to a common basis from which their approximate line of sight distances can be derived. The result is shown in Figure 2, which shows the symmetric disk plus central bar morphology of the Galaxy.

Our simple inversion distorts the image, although the bar signature is unambiguous. The width of the $\mathrm{M_K}$ distribution, due to pulsational variations and age/metallicity differences, stretches and twists the bar in Figure 2. We systematically account for these biases by using a Bayesian parameter estimation for an exponential disk with a quadrupole bar. Restricting the sample to $|b| > 2^\circ$ to minimize confusion error, and correcting for extinction (Schlegel, Finkbeiner, & Davis 1998), we find the most likely disk parameters to be: a scale length $a = 3.5 \pm 0.15$ kpc, a bar radius of 2.6 ± 0.15 kpc, a position angle $\phi = 31 \pm 8^\circ$, and a relative bar strength of 0.32 ± 0.15. The method and results will be further described in a later paper. The position angle and shape of the inferred bar are hatched in Figure 2. Density cuts through the data along lines parallel and perpendicular to the Sun-Galactic center line are shown for comparison to the exponential scale length in Figure 3.

The low sensitivity of IR colors to reddening ensures that the IR C star sequence is relatively free from contamination for colors redder than $\mathrm{J}-\mathrm{K_S} \approx 2.5$. Even if large differential reddening is present, its effect should be small because the IR C star sequence runs virtually parallel to the reddening vector. The striking symmetry of our inferred Galactic disk shows that selection effects are not driving our result.

3. The Ages of Carbon Stars

Whether a thermally pulsing AGB star becomes a C star depends on its initial mass and metallicity. Theoretical calibration of the minimum mass (and hence maximum age) necessary for C star formation is uncertain due to the poorly understood physics of the dredge-up process (Marigo et al. 1999). Empirical determination of the age range for C star formation has been hampered by the lack of massive ($\gg 10^3$ $M_\odot$) intermediate-age star clusters in the galaxy, and the age gap in Large Magellanic Cloud clusters between 3 and 9 Gyr (Marigo et al. 1996). Synthetic models put the lower mass limit for C star production at 1.13 $M_\odot$ for $Z = 0.004$, and 1.32 $M_\odot$ for $Z = 0.008$; these masses correspond to ages of 5.2 and 3.9 Gyr, respectively (Marigo et al. 1999). Empirical evidence confirms the theoretical prediction for a diminishing probability of C star formation with increasing metallicity (Cook, Aaronson & Norris 1986).

Claussen et al. (1987) determined the scale height of field C stars to be similar to that of main-sequence F stars, which have ages of roughly 1–3 Gyr. Star cluster ages are more easily measured; Figure 4 shows a sample of clusters in the Milky Way and the Magellanic Clouds whose C star content is known. The clusters are sorted by age and M_V. Solid and open symbols differentiate between clusters with and without IR C stars. For clusters with C stars, the approximate number is given in parentheses, with the total C star population before the slash and the IR C star population, where present, after. C star content is taken from Frogel, Mould & Blanco (1990), Nishida et al. (2000), and Scalo & Miller (1979) for the open and Magellanic clusters. Globular clusters do not contain C stars (McClure 1985; Wallerstein & Knapp 1998). While many clusters aged younger than 2 Gyr containing IR C stars have been omitted from Figure 4, we are unaware of *any* clusters older than 3.2 Gyr containing– or suspected of containing– them.

The oldest cluster in the Galaxy thought to contain an IR C star is Trumpler 5 (Kalinowski, Burkhead, & Honeycutt 1974). Trumpler 5 is aged 2.8 Gyr, and membership of the IR C star, V493 Mon, is not confirmed due to the lack of proper motion studies of the cluster. NGC 2121, an LMC cluster aged 3.2 Gyr, is the oldest cluster known to harbor an IR C star. Metal-poor SMC clusters as old as 5–7 Gyr contain luminous C stars, but none as red as $J-K_S = 2$. The efficiency of C star production dramatically drops with age among bright clusters: compare the C star content of NGC 419 (1.6 Gyr, 9 C stars) with NGC 416 (6.9 Gyr, 1 C star), and the globular cluster NGC 362 (12 Gyr, no C stars).

Perhaps IR C stars are born, but with reduced efficiency, at ages larger than 3 Gyr; the lack of bright clusters aged 3–5 Gyr makes it difficult to tell. A stricter limit may be imposed by the lack of IR C stars in M32. M32 is known to harbor a significant intermediate-age stellar population (O'Connell 1980); del Burgo et al. (2001) derive 3–5 Gyr and $Z \approx Z_\odot$. However, Corbin, O'Neil & Rieke (2001) find that its JHK colors are dominated by early K giants, and Davidge (2000) reports that M32's AGB terminates blueward of $J-K = 1.5$. Because of the high luminosity of M32 ($M_V = -16.7$) compared to a star cluster, its blue AGB may be the strongest observational evidence for a cutoff in C star production at approximately 3 Gyr for populations of roughly Solar metallicity.

In summary, all empirical age estimates for IR C stars indicate ages less than about 3 Gyr. This agrees with theoretical expectations for a shutdown of the C star formation mechanism between 4–5 Gyr for stars of Magellanic Cloud metallicity, and possibly younger ages for higher metallicities. The oldest known C stars are roughly 6 Gyr old, but the metallicity dependence of C star formation and the lack of very red AGB stars in M32 makes ages of 1–3 Gyr much more probable.

4. Discussion and Conclusions

We have used 2MASS data to trace the structure of the Galactic disk and bar using the Skrutskie et al. (2001) sample of IR C stars with $(J-K_S) > 2$. The epoch of strong star formation along galactic bars is expected to be brief ($\lesssim$1 Gyr— Martin & Roy 1995; Martin & Friedli 1997), and to occur during their formation. Little or no star formation is expected to occur within the bar once it has become well-established, and stars that subsequently form in the disk cannot themselves join the bar. Some support for this view comes from the observation that H II regions are common in the bars only of late-type, active, or morphologically disturbed galaxies (e.g., Martin & Friedli 1997, and references therein). Therefore, the progenitors of the IR C stars were born prior to or during the formation of the bar, and hence their lifetimes give an upper limit to the bar age.

The oldest attested C stars (in SMC clusters with $[Fe/H] \approx -1.3$) are 5–7 Gyr old. If all the C stars in the Galactic bar were similar to the metal-poor SMC stars, reddened into our color window, the bar could thus be as old as roughly 6 Gyr. Among the oldest star clusters with IR C stars are NGC 2121 (LMC, 3.2 Gyr), and *possibly* Tr 5 (Milky Way, 2.8 Gyr). M32 appears not to contain IR C stars (Davidge 2000), and contains a large stellar population aged 3–5 Gyr (del Burgo et al. 2001). We thus find it highly probable that the Milky Way bar is younger than 3 Gyr. This time frame is intriguing, given the reports of a declining bar frequency among galaxies with redshifts $z \gtrsim 0.5$ (Abraham et al. 1999), corresponding to lookback times of 5–6 Gyr.

Few age estimates have been made for the Milky Way bar. Ng et al. (1996) ascribed an 8–9 Gyr stellar population in Baade's Window to the bar, but the population's spatial distribution is not known, making the bar identification tentative. Sevenster (1999) inferred an age of 7.5 Gyr from OH/IR stars with $M \approx 1.3\ M_{\odot}$; updated theoretical models (Girardi et al. 2000) give 4.7 Gyr for this mass[1]. The main-sequence turnoff of a 3 Gyr-old population should be readily traceable along the Galactic bar from $V \approx 17$ at the near end to $V \approx 19$ at the far end (modulo reddening differences).

Could the IR C stars be a trace population that wandered into the bar by chance? The LMC has $M_{\rm disk} \approx 10^{10}\ M_{\odot}$, and contains 2100 IR C stars. Stanek et al. (1997) give $M_{\rm bar} \approx 2 \times 10^{10}\ M_{\odot}$, and we find 5300 sources with $J{-}K_S > 2$ inside the bar radius. For reasonable rates of contamination by OH/IR stars, the bar seems to have an IR C star specific frequency comparable to the LMC's, arguing against the idea that 2MASS is seeing a trace young population within a much older bar. 2MASS observations of the LMC show that our color cut excludes roughly 75% of the N-type C stars (Nikolaev & Weinberg 2000). If more of the C stars could be traced, an accurate estimate of the fraction of intermediate-age stars in the bar could be made (Aaronson & Mould 1985).

Could the IR C stars be older than roughly 3 Gyr? Membership studies for Tr 5 and other potential C star-bearing open clusters would help to empirically set the upper age limit for C star formation. Further study of M32's AGB, to definitively measure its red extent, could push the likely age of the bar upwards, if its $J{-}K_S$ reaches ≈ 2.5 (Freedman 1992).

Bar dust lanes can have high molecular gas content, yet low star-formation rates (e.g., Downes et al. 1996). Even in galaxies undergoing transient bursts (e.g., NGC 7479), the intensity of star formation along the bars is generally suppressed relative to that of the disk (Laine et al. 1999). This suggests that a bar contains a snapshot of the disk stellar population at the time of its formation. However, barred galaxies typically have enhanced star formation at the ends of their bars and in their nuclei. Could these young stars join the bar as they form? A star can only be trapped in the bar by losing angular momentum as its orbit passes through a resonance. This can only happen efficiently if the bar is actively evolving. The existence of a well-described molecular ring in the Galaxy, presumably near corotation, suggests that our bar has a stable pattern speed, and therefore is not rapidly swallowing its own ends.

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[1] Because the OH/IR stars yield a similar age to the IR C stars, even a catastrophic misjudgment of the C star fraction in Figure 1b does not invalidate our bar age limit.

Bars are ubiquitous in numerical simulations; detailed studies by many authors show that the quasistatic gas response agrees well with observed morphology (e.g., Athanassoula 1992). This morphological coincidence suggests that the bars are at least several rotation times ($\sim$1 Gyr) old, and that their pattern speeds are not rapidly evolving. On the other hand, a concentrated dark matter halo can cause a bar to lose angular momentum through dynamical friction. Debattista & Sellwood (2000) have argued that bars such as the Milky Way's are strongly braked by this effect, which would imply rapid bar evolution. However, Weinberg & Katz (2002) have hypothesized that a primordial bar that forms during the epoch of disk assembly will torque up the inner halo as it is braked, producing a core in the halo density distribution. This initial, transient bar paves the way for a long-lived, stellar bar, since the altered halo mass profile does not slow bars as efficiently. The genesis of the current Milky Way bar remains to be explained. Tidal triggering by the LMC, the Sagittarius dwarf, or a now-merged satellite is a plausible origin (Murali & Tremaine 1998; Weinberg 1998; Vesperini & Weinberg 2000).

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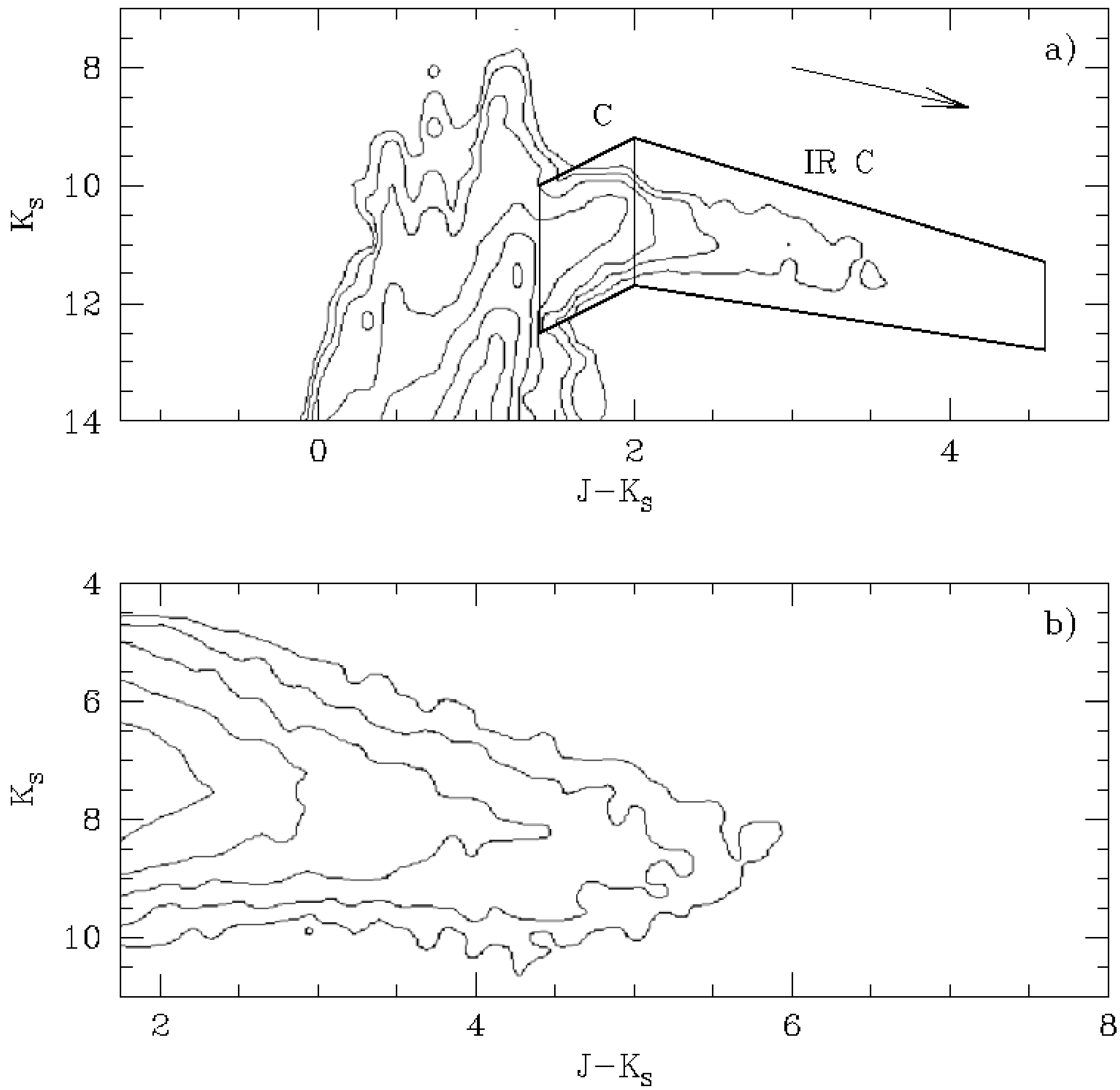

Fig. 1.— 2MASS Hess diagrams for: *a)* The LMC, showing the major stellar sequences and emphasizing the bilinear C star sequence. The arrow shows the reddening vector for E(B−V) = 2 mag, and *b)* The IR C star sequence of the Milky Way, which shares a color-magnitude relation with that of the LMC and extends more than 2 magnitudes redder. In the top (bottom) panel, each contour shows 4× (2×) the density of the previous one.

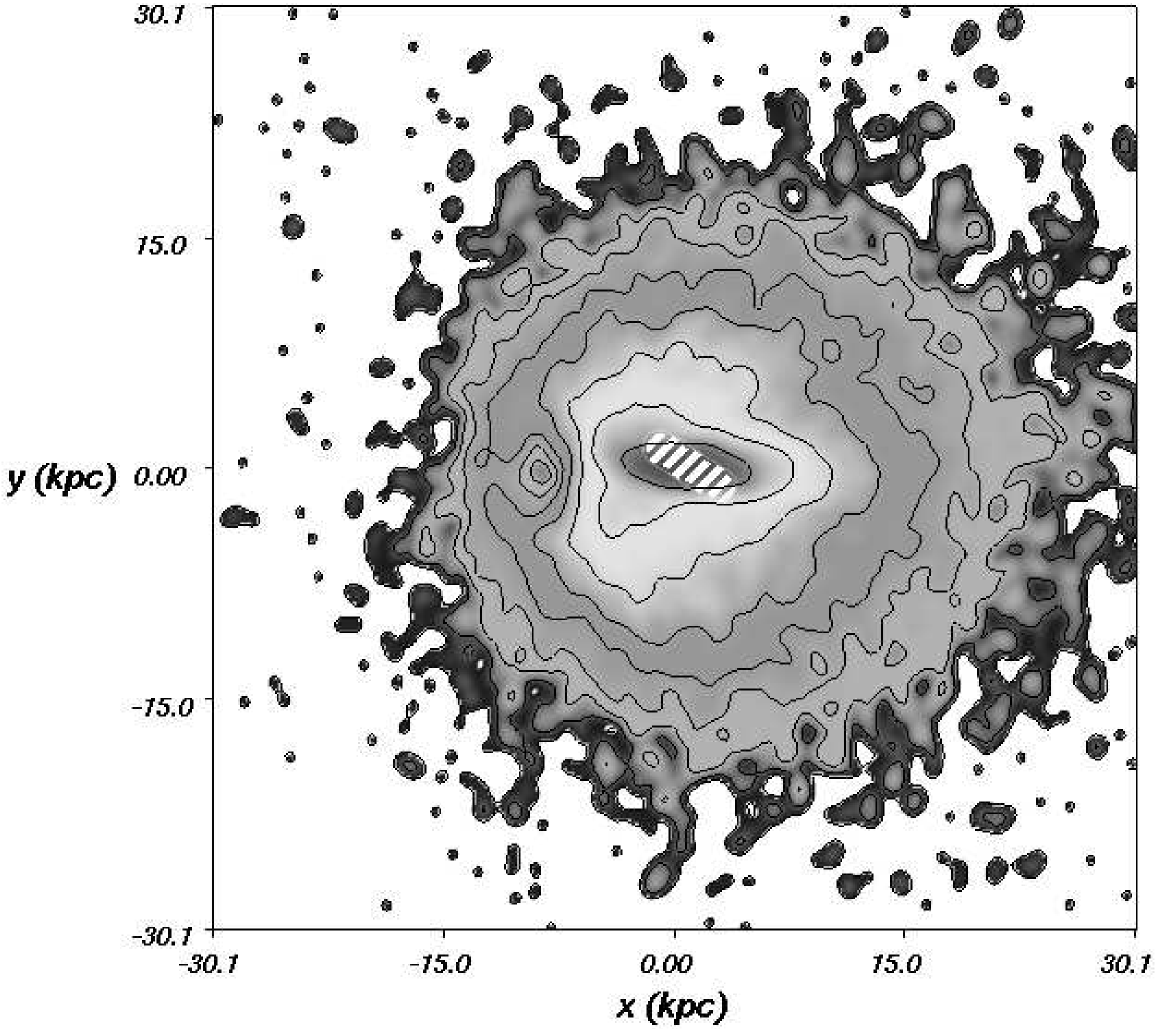

Fig. 2.— Spatial distribution of IR C stars within the Galaxy, with logarithmic contours. The apparent hole around the Sun ($x = -8$, $y = 0$) owes to the saturation of nearby stars. The symmetric disk structure and strong central bar are obvious; the position angle of the bar is distorted by the variance in M_K among the IR C stars. The hatched bar is our best estimate of the position angle and length, accounting for this bias.

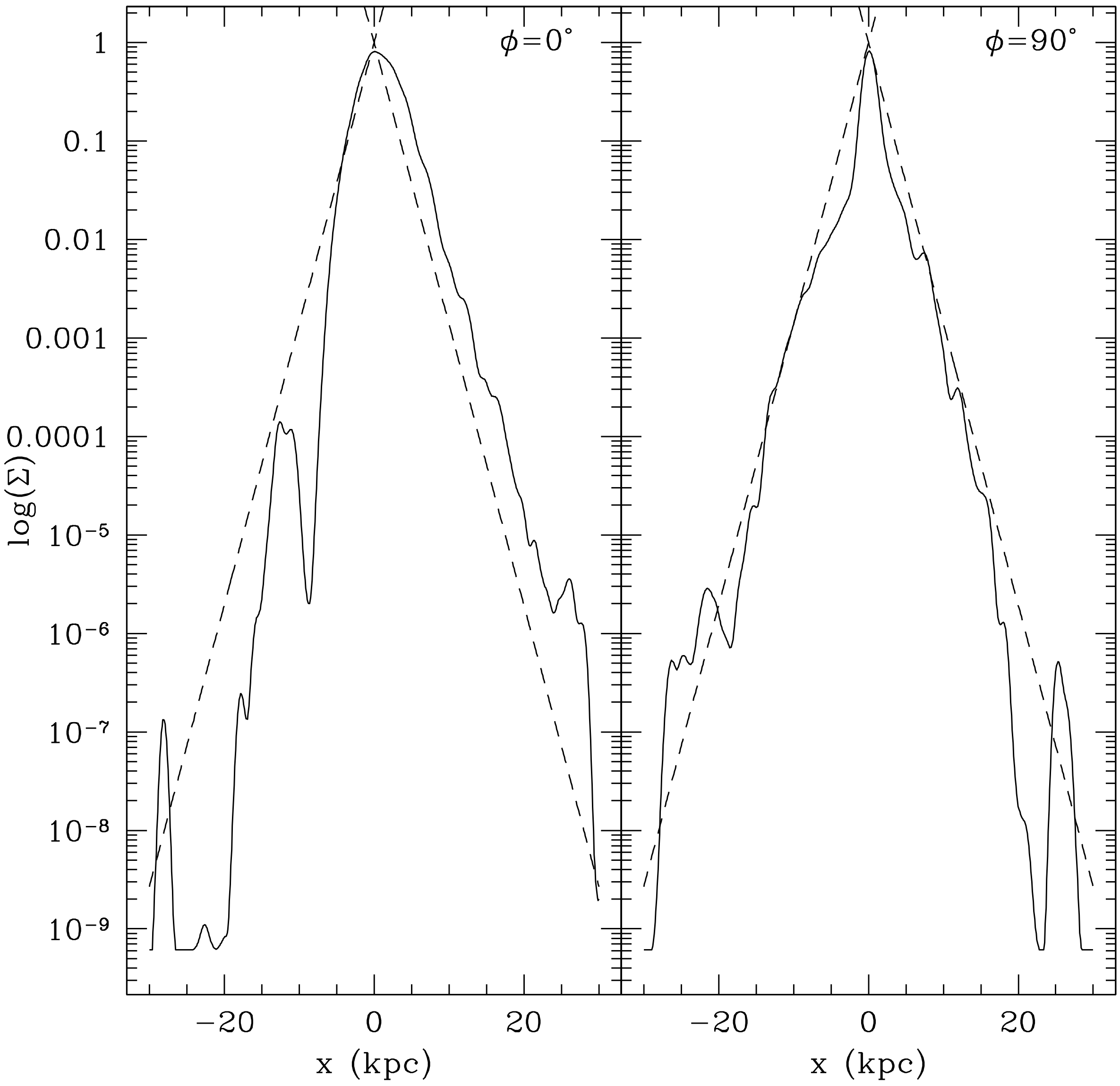

Fig. 3.— Surface density profiles through the Galactic center parallel to the Sun-Galactic center line ($\phi = 0°$, left) and perpendicular to it ($\phi = 90°$, right). The variance in luminosity for a given color (see Fig. 1) stretches the distribution for $\phi = 0°$. The distortion is much smaller in the direction perpendicular to the line of sight ($\phi = 90°$) and closely follows the inferred exponential profile of $a = 3.5$ kpc out to the edge of the disk. The dip at the Solar position, $x = -8$ kpc, is due to undersampling.

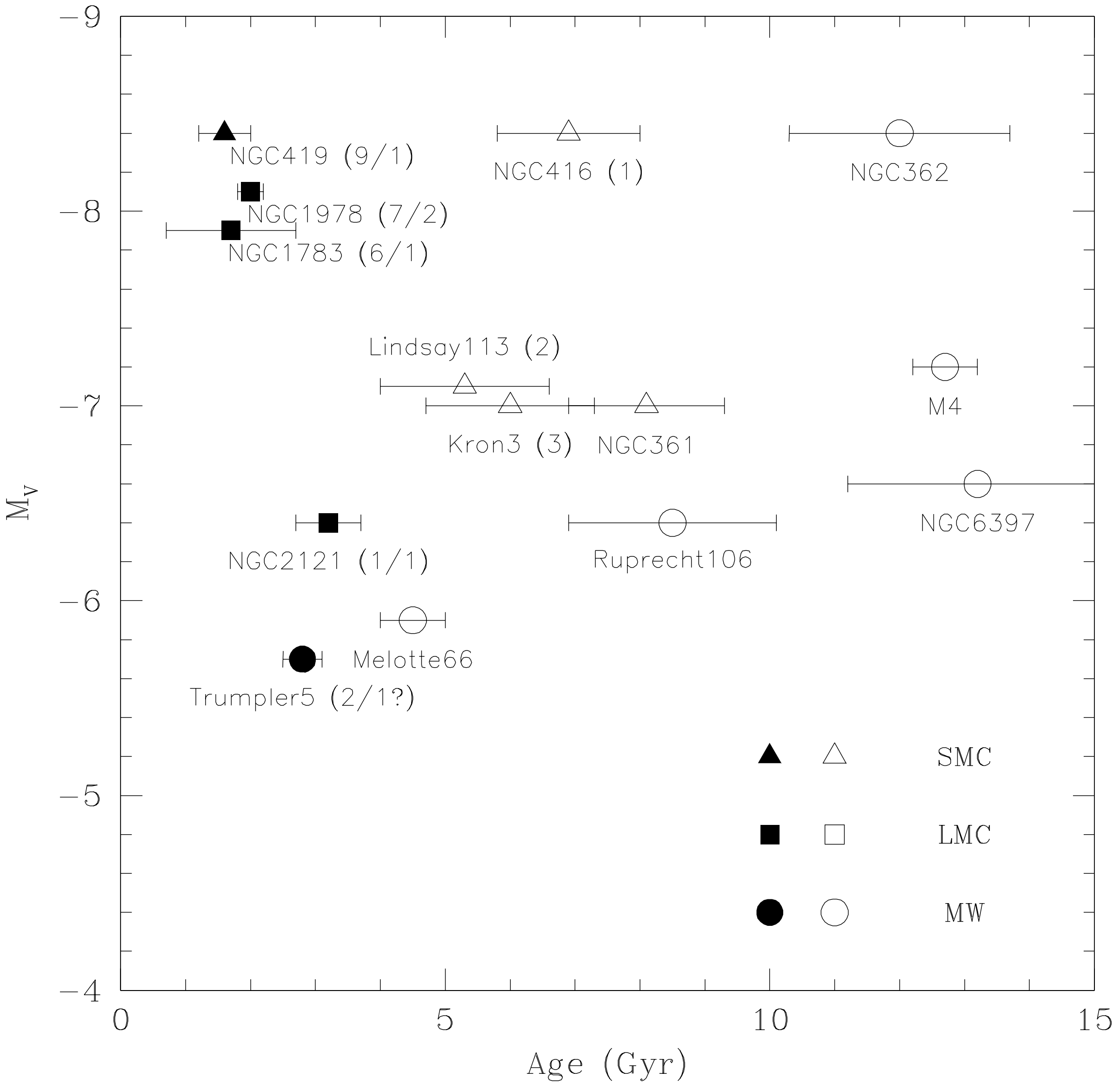

Fig. 4.— Star clusters with and without C stars. Clusters with known or suspected IR C star members are marked as solid symbols, those without as open ones. Globular cluster magnitudes are taken from Harris (1996), with ages from Buonanno et al. (1998); MC and open cluster magnitudes are derived from SIMBAD data; their ages are from the recent literature, relying primarily on Piatti et al. (2002), Nishida et al. (2000), and Sarajedini (1999).