

# THE 2MASS COLOR-MAGNITUDE DIAGRAM OF THE CENTER OF THE SAGITTARIUS DWARF GALAXY: PHOTOMETRIC MEASUREMENTS OF A SURPRISINGLY HIGH MEAN METALLICITY

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## ABSTRACT

We present the Two Micron All Sky Survey (2MASS) ( $J-K$ ,  $K$ ) color-magnitude diagram for the region within  $1^\circ$  of the center of the Sagittarius dwarf spheroidal galaxy. Using the slope of the red giant branch (RGB), we determine a mean metallicity for the main stellar population of  $[\text{Fe}/\text{H}] = -0.5 \pm 0.2$ . The Sagittarius RGB possesses a blue tail that overlaps with the foreground Milky Way giant branch and suggests that approximately one-third of the RGB is more metal-poor than  $[\text{Fe}/\text{H}] \sim -1$ . Direct comparison with the Large Magellanic Cloud confirms the metal-rich nature of the bulk of the Sagittarius population. Our result is marginally consistent with the even higher metallicities determined from high-resolution spectroscopy.

*Subject headings:* galaxies: abundances — galaxies: individual (Sagittarius dSph) — galaxies: stellar content

## 1. INTRODUCTION

The Sagittarius dwarf spheroidal galaxy was discovered by Ibata, Gilmore, & Irwin (1994). It is the closest known satellite galaxy of the Milky Way and is in the process of strong tidal disruption, on the way to an eventual merger. Its structure, stellar populations, and distance have been studied extensively by a number of authors (e.g., Ibata, Gilmore, & Irwin 1995; Mateo et al. 1995; Sarajedini & Layden 1995; Whitelock, Irwin, & Catchpole 1996; Fahlman et al. 1996; Layden & Sarajedini 1997, 2000; Marconi et al. 1998; Bellazzini, Ferraro, & Buonanno 1999a, 1999b). The basic parameters adopted from Mateo (1998) are the center position  $(l, b) = (5^\circ 61', -14^\circ 1')$ , distance modulus  $(m-M)_0 = 16.9 \pm 0.1$ , and reddening  $E(B-V) = 0.15 \pm 0.03$ .

It has become apparent that the Sgr dwarf has experienced a complex star formation history (SFH), spanning most of the age of the universe (e.g., Layden & Sarajedini 2000, hereafter LS2k). To determine its SFH accurately requires reliable knowledge of the age-metallicity relation. For Sagittarius, this remains elusive, as shown by the more than factor of 5 difference between mean metallicity estimates in the literature.

Optical and near-infrared (NIR) color-magnitude diagram (CMD) analyses have usually yielded low values for the mean metallicity (cf. Sarajedini & Layden 1995; LS2k). Table 1 shows a selection of CMD-based metallicities from the literature. The literature average derived by Mateo (1998) is  $[\text{Fe}/\text{H}] = -1.1 \pm 0.2$ , with a spread of  $\pm 0.5$  dex intrinsic to the galaxy.

Direct measurements of the abundance based on high-dispersion, high signal-to-noise ratio spectroscopy of a few red giants have determined a mean metallicity of  $[\text{Fe}/\text{H}] \approx -0.25$  (Bonifacio et al. 2000; T. A. Smecker-Hane & A. McWilliam 2001, in preparation). This number is surprisingly high: for comparison, the mean metallicity of the red giant branch (RGB) in the Large Magellanic Cloud (LMC) is  $[\text{Fe}/\text{H}] \approx -0.55$  (Cole, Smecker-Hane, & Gallagher 2000). If the true mean metallicity of the Sgr dwarf is  $[\text{Fe}/\text{H}] \approx -0.25$ , the galaxy would be enriched by nearly an order of magnitude above the mean  $[\text{Fe}/\text{H}]-M_V$  relation for dwarf galaxies. Like the LMC, the Sgr dwarf does not appear to be strongly enhanced in the  $\alpha$ -elements relative to the solar-scaled abundance (see Bonifacio et al. 2000, Pagel & Tautvaišienė 1998, and references therein).

The continuing discrepancy between photometric and spectroscopic metallicity estimates motivates us to study the NIR ( $J-K$ ,  $K$ ) CMD of the Sgr dwarf. There have been fewer studies of Sagittarius in the NIR than in the optical, so a new look at the NIR CMD is needed. The NIR is less susceptible to systematic errors from interstellar reddening. New methods for metallicity estimation via the NIR colors of red giants have recently been published (Kuchinski & Frogel 1995; Ivanov et al. 2000). And finally, the superb photometric uniformity and precision of the Two Micron All Sky Survey (2MASS) allows us to compare directly a Sagittarius field with other objects, e.g., the LMC. The central region of the Sgr dwarf is contained within the 2MASS second incremental data release and is available electronically.<sup>1</sup> We present the 2MASS CMD of the region within  $1^\circ$  of the center of the Sgr dwarf in § 2, make a new photometric determination of the metallicity in § 3, and place our results in the context of earlier work in § 4.

## 2. THE 2MASS CMD OF THE CENTER OF SAGITTARIUS

The 2MASS was carried out at Mount Hopkins and Cerro Tololo using dedicated 1.3 m telescopes. Data were obtained in the  $J$ ,  $H$ , and  $K_s$  (“ $K$  short”) passbands and were processed, photometered, and calibrated at IPAC. Further details are contained in the Explanatory Supplement to the 2MASS Second Incremental Data Release by R. M. Cutri et al. (2000).<sup>2</sup> We selected stars from the 2MASS point source catalog within  $1^\circ$  of the center of the Sgr dwarf galaxy, excluding stars within the tidal radius of the globular cluster M54. We selected sources with good point-spread function fit magnitudes in all three survey bands, excluding objects associated with extended sources or minor planets. The mean photometric error of the selected objects, for  $K_s \leq 14$ , is  $\sigma J = 0.03$ ,  $\sigma K_s = 0.04$ .

The resulting CMD is shown in Figure 1. The RGB of the Sgr dwarf is the feature extending brightward and redward of the local M dwarf plume from  $(J-K_s, K_s) \approx (1, 14)$  to  $(1.25, 10.6)$ . The RGB is surmounted by asymptotic giant branch (AGB) stars, extending nearly a magnitude brighter, and a red plume of carbon stars (as already noted by Ibata et al. 1995). The three other “fingers” of the CMD are the disk main sequence,

<sup>1</sup> See <http://irsa.ipac.caltech.edu>.

<sup>2</sup> See <http://www.ipac.caltech.edu/2mass/releases/second/doc/expsup.html>.

TABLE 1  
CMD-BASED METALLICITY ESTIMATES FOR THE SGR DWARF

CMD Feature	Colors	Mean [M/H]	Reference
RGB color .....	$B, V$	$\approx -1.25$	1
	$V, I$	$-0.52 \pm 0.09$	2
	$J, K$	$\leq -0.8 \pm 0.2$	3
	$V, I$	$-1.1 \pm 0.3$	4
	$V, I$	$\approx -1.1$	5
RGB, MSTO shape .....	$V, I$	$-1.1 \pm 0.3$	6
RGB slope .....	$J, K$	$-0.58 \pm 0.25$	3
10 Gyr isochrones .....	$V, I$	$-1.0 \pm 0.2$	7
9–12 Gyr isochrones .....	$V, I$	$-1.3 \pm 0.2$	8
4–6 Gyr isochrones .....	$V, I$	$-0.7 \pm 0.2$	8
0.5–3 Gyr isochrones .....	$V, I$	$-0.4 \pm 0.3$	8
Literature average .....		$-1.0 \pm 0.2$	9

REFERENCES.—(1) Ibata et al. 1995 found a minority population with  $[\text{Fe}/\text{H}] = -1.3$ ; (2) Sarajedini & Layden 1995 found a metallicity spread from  $-1.58$  to  $-0.71$ ; (3) Whitelock et al. 1996 found a metallicity spread of 0.8 dex; (4) Marconi et al. 1998; (5) Bellazzini et al. 1999a; (6) This solution was rejected by Mateo et al. 1995 (MSTO = main-sequence turnoff); (7) Fahlman et al. 1996 quotes a dispersion of  $\pm 0.5 \pm 0.1$  dex; (8) LS2k; (9) Mateo 1998.

the disk/bulge red clump, and the disk/bulge red giants. The reddening maps of Schlegel, Finkbeiner, & Davis (1998) show very small differential reddening across this field:  $\sigma_{E(B-V)} = 0.015$ .

More than 1400 stars are contained in the distinct Sgr dwarf RGB. Because the color of the RGB is metallicity-dependent, the eye tends to emphasize the most metal-rich stars. It is apparent from the comparable color extent of the foreground RGB and the main Sgr RGB that the Sgr dwarf is quite metal-rich. While stars appear to fill in the entire metallicity range between the foreground plume and the metal-rich population, most of the stars are concentrated toward the metal-rich end.

### 3. THE METALLICITY OF THE SAGITTARIUS RGB

The equations relating RGB color and slope to  $[\text{Fe}/\text{H}]$  from Kuchinski & Frogel (1995) and Ivanov et al. (2000) refer to the Caltech/Cerro Tololo Inter-American Observatory system (Elias et al. 1982). We use the color transformations computed by Carpenter (2001) to transform the 2MASS natural magnitudes to this system. We adopt the distance and reddening quoted above, deriving  $A_K = 0.048$ , and  $E(J-K) = 0.084$  from the relations in Bessell & Brett (1988). We show the derived CMD in Figure 2. The left panel of Figure 2 is overlain by empirical, linear fits to globular cluster RGBs derived from Ivanov et al. (2000), for  $[\text{Fe}/\text{H}] = -1.5$ ,  $-1.0$ , and  $-0.5$ . The right panel is overlain by isochrones from Girardi et al. (2000) for age-metallicity pairs (10 Gyr,  $Z = 0.001$ ; 5 Gyr,  $Z = 0.004$ ; 2.5 Gyr,  $Z = 0.008$ ) chosen following LS2k. The effect of age-metallicity degeneracy is apparent from the similarity of the 2.5 and 5 Gyr tracks. Figure 2 plainly shows that the bulk of the stellar population in the center of the Sgr dwarf is of intermediate age and only moderately metal-poor.

Quantitative estimates of the mean metallicity can be derived from the RGB color and slope (e.g., Ivanov et al. 2000). The RGB slope method has the advantage that it is independent of distance and reddening. For 1410 stars brighter than  $M_K = -4$ , we derive a slope  $d(J-K)/dK = -0.106 \pm 0.002$ , with an rms deviation of 0.039, comparable to the photometric error and indicating a high quality of fit. According to the calibration of Ivanov et al. (2000), this implies a mean metallicity of  $[\text{Fe}/\text{H}] = -0.46 \pm 0.06$ . The precision in the relation is estimated to be 0.2 dex. If instead we adopt the calibration of Ku-

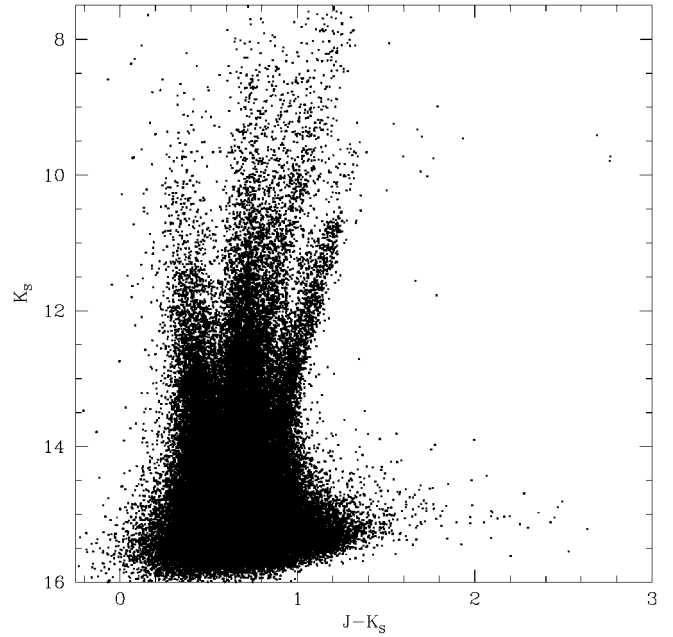


FIG. 1.—Stars within  $1^\circ$  of the center of the Sgr dwarf. The four most prominent CMD features are the main-sequence turnoff stars in the foreground disk, red clump stars in the foreground disk, red clump and RGB stars in the bulge, and the Sagittarius RGB and AGB.

chinski & Frogel (1995), we find that  $[\text{Fe}/\text{H}] = -0.45 \pm 0.05$ , with an estimated precision of 0.25 dex. Another recent calibration is given by Ferraro et al. (2000); it gives  $[\text{Fe}/\text{H}] = -0.49 \pm 0.05$  on the Carretta & Gratton (1997) scale or  $-0.38 \pm 0.05$  on the Zinn & West (1984) scale. Ivanov et al. (2000) also provide a relation between the RGB color at  $M_K = -5.5$  and metallicity, which is dependent on distance and reddening. Applying their calibration to 79 stars in the range

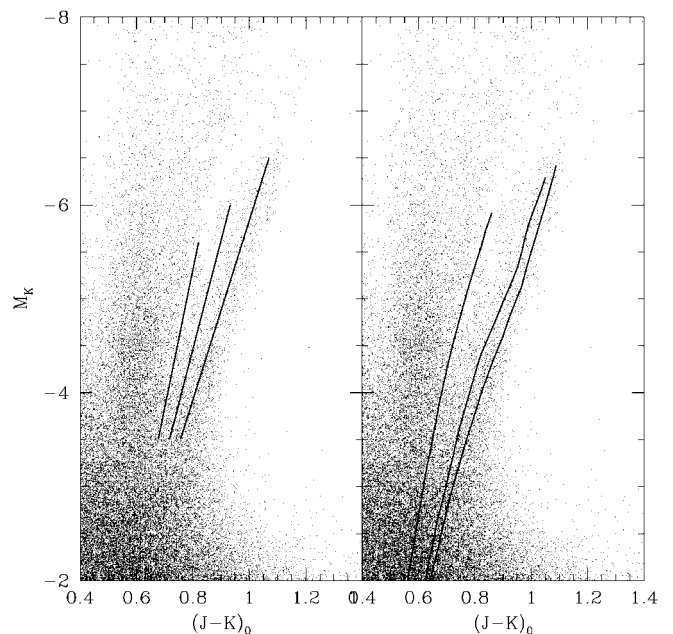


FIG. 2.—Sagittarius RGB, with empirical RGB sequences for  $[\text{Fe}/\text{H}] = -1.5$ ,  $-1.0$ , and  $-0.5$  overlain (left) and with isochrones for  $(\log t, Z) = (10.0, 0.001)$ ,  $(9.6, 0.004)$ , and  $(9.4, 0.008)$  overlain (right).

$-5.6 \leq M_K \leq -5.4$ , we find that  $\langle (J-K)_0 \rangle = 0.967 \pm 0.040$ , yielding  $[\text{Fe}/\text{H}] = -0.49 \pm 0.27$ .

While these values are high compared with the literature average of photometrically determined abundances, they may in fact be too low. First, the relations are calibrated according to globular clusters; age effects may bias the results low by 0.1–0.2 dex (Tiede, Martini, & Frogel 1997). And second, the calibrating globulars are enhanced in their abundance of  $\alpha$ -elements relative to a scaled solar abundance, so that their effective metallicities  $[M/\text{H}]$  are higher than their true metallicities  $[\text{Fe}/\text{H}]$  (e.g., Carney 1996). The Sgr dwarf is not  $\alpha$ -enhanced (Bonifacio et al. 2000), further contributing to a photometric abundance underestimate. These effects may be partially countered by the relative difficulty of separating metal-poor stars from the foreground.

We can estimate the metallicity spread by looking at the color distribution of the RGB. Figure 3 shows the  $(J-K_s)$  color histogram for all stars in the range  $11 \leq K_s \leq 12.5$ . The bright limit was chosen to avoid large bias against the metal-poor stars, and the faint limit was chosen to minimize confusion with differentially reddened foreground stars. The colors were shifted by  $0.106(K_s - 12.5)$  to account for the RGB slope. The peak corresponding to the Sagittarius RGB is distinct and narrow at  $J-K_s \approx 1$ . The dashed line shows the results of a Gaussian fit, with the  $\sigma$  constrained to be equal to the mean photometric error  $\langle \sigma(J-K_s) \rangle = 0.05$ . It is seen that the RGB width is barely wider than the photometric error on the red side but that a significant tail exists on the blue side. As expected, there is little evidence for differential reddening. The exact proportion of stars in the blue tail is hard to determine precisely because of contamination by the much larger number of foreground giants. A very rough estimate can be made by assuming that all of the stars in Figure 3 with  $J-K_s \geq 0.85$  are true Sgr members. Dividing the area under the Gaussian fit by the total number of stars redward of this limit suggests that approximately two-thirds of the Sgr RGB belongs to the population with  $[\text{Fe}/\text{H}] \geq -1$ . According to LS2k, this dominant population would be 0.5–7 Gyr old. Due to the probable inclusion of some foreground as well as the likely exclusion of some of the most metal-poor Sgr giants, we estimate the uncertainty in this fraction to be at least  $\pm 20\%$ . Comparison with a control field did not prove useful in determining the relative numbers more precisely because the detailed morphology of the foreground is highly dependent on small-scale reddening variations as well as on larger scale spiral structure, yielding a very uncertain subtraction.

#### 4. DISCUSSION AND SUMMARY

By analyzing the slope of the RGB in the  $(J-K, K)$  CMD, we have determined a mean metallicity of  $[\text{Fe}/\text{H}] = -0.5 \pm 0.2$  for the Sgr dwarf. Theoretical considerations regarding the age and  $[\alpha/\text{Fe}]$  of Sagittarius relative to Galactic globular clusters imply that this may be underestimated by  $\sim 0.2$  dex. Thus, the photometric abundance of the main Sagittarius RGB is in reasonable agreement with the recently determined results from high-resolution spectroscopy (Bonifacio et al. 2000; T. A. Smecker-Hane & A. McWilliam 2001, in preparation). The true abundance distribution in our CMD is masked by age-metallicity degeneracy because of the temporally extended SFH of the Sgr dwarf (LS2k).

We agree with previous CMD analyses that have found a large spread in metallicity, but we find a larger fraction of high-metallicity stars than low-metallicity ones. The color histogram

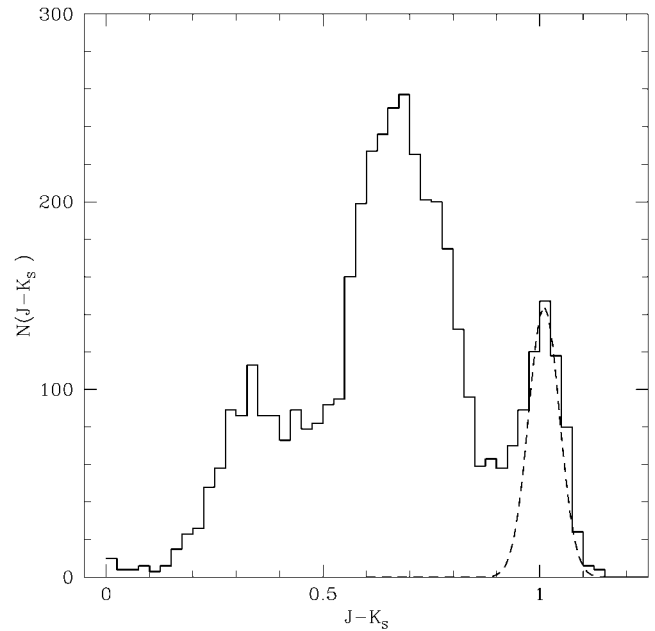


FIG. 3.—Color histogram of all stars with  $11 \leq K_s \leq 12.5$ . The Sgr dwarf RGB, with  $J-K_s \approx 1$ , is barely wider than the spread because of the photometric error (dashed line) at the peak and to the red. However, there is a tail toward the blue that consists of metal-poor stars in Sagittarius, contaminated with some foreground stars.

of the RGB sample shows that there is a significant tail of low-metallicity stars in Sgr dwarf that has not been represented in the spectroscopic sample. Very roughly, one-third of the Sagittarius RGB is too blue in  $J-K_s$  to be accounted for by the high-metallicity population. This is contrary to the scenario proposed by Bellazzini et al. (1999b), in which the  $\approx 10$  Gyr epoch contributed the majority of stars to the Sagittarius field, and implies a longer period of significant star formation. It is important to remember that our field is located at the center of the Sgr dwarf. Bellazzini et al. (1999a) find that the intermediate-age population is strongly concentrated in this region, and Dohm-Palmer et al. (2001) have shown evidence for a lower average metallicity in radially distant fields. This issue will be explored using 2MASS data in a future paper.

The colors of theoretical isochrones in the  $[(J-K)_0, M_k]$ -plane are consistent with the age-metallicity relation proposed by Layden & Sarajedini (2000). A large fraction of intermediate-age stars is consistent with the significant population of AGB stars above the tip of the RGB and carbon stars with colors as red as  $J-K_s \approx 2.5$ . It is difficult to determine precisely the ratio of metal-poor to metal-rich stars because of the contaminating foreground.

The previously published NIR CMD of Sagittarius, by Whitelock et al. (1996), reported a low metallicity for the galaxy, in contrast to what we find here. However, this result was based on a small number of stars and relied on a comparison with the globular cluster 47 Tuc. This comparison is not necessarily a good one because of the large age difference and because the  $\alpha$ -enhancement of 47 Tuc by  $\approx 0.2$  dex changes its RGB morphology (e.g., Vazdekis et al. 2001 and references therein). Both effects combine to shift the 47 Tuc RGB to the red, relative to Sagittarius, mimicking a metal-poor Sagittarius. It is interesting to note that Whitelock et al. (1996) obtain a value of  $[\text{Fe}/\text{H}] = -0.58 \pm 0.25$  from the slope of the RGB but reject this in favor of the direct comparison with 47 Tuc.

A more natural comparison object for the Sgr dwarf is the LMC. Both objects are apparently dominated by intermediate-age stars, and neither is predicted to be highly  $\alpha$ -enhanced. We overlay the contours of the LMC Hess diagram on our Sagittarius CMD in Figure 4. The contours are logarithmically spaced to highlight the AGB. To make the comparison, the LMC data have been shifted by  $\Delta(m-M) = -1.5$ ,  $\Delta E(B-V) = 0.075$ . Figure 4 shows a remarkable similarity between the two galaxies. The Sagittarius RGB is far narrower than the LMC's; but it overlaps exactly with the red half of the LMC RGB, in good agreement with the metallicity estimates. The slight mismatch in the location of the RGB tip may be due to an error in the relative distance moduli; in the  $(J-K_s, K_s)$ -plane, it is also in the correct sense if the Sgr dwarf reaches a higher metallicity than the LMC. The LMC contours trace an RGB to colors blueward of  $J-K_s = 0.9$ , mapping the extension to the lower metallicities also seen in Sagittarius. Both galaxies contain a population of bright AGB stars and carbon stars, which overlap to a remarkable extent in color and magnitude.

The Sagittarius dwarf galaxy has undergone a high degree of chemical processing, far more than expected given its current lack of gas and small mass. This may support the hypothesis first put forward by Sarajedini & Layden (1995) that Sagittarius may have been a much larger galaxy early in its lifetime and is in the last stages of disruption. Alternatively, it could have captured Milky Way gas during a previous passage through the Galactic disk. It is necessary to obtain spectroscopic abundances for a large number of Sagittarius giants, especially on the blue side of the RGB, in order to trace the variation of abundance and  $\alpha$ -enhancement with time.

This publication makes use of data products from the Two Micron All Sky Survey, which is a joint project of the Uni-

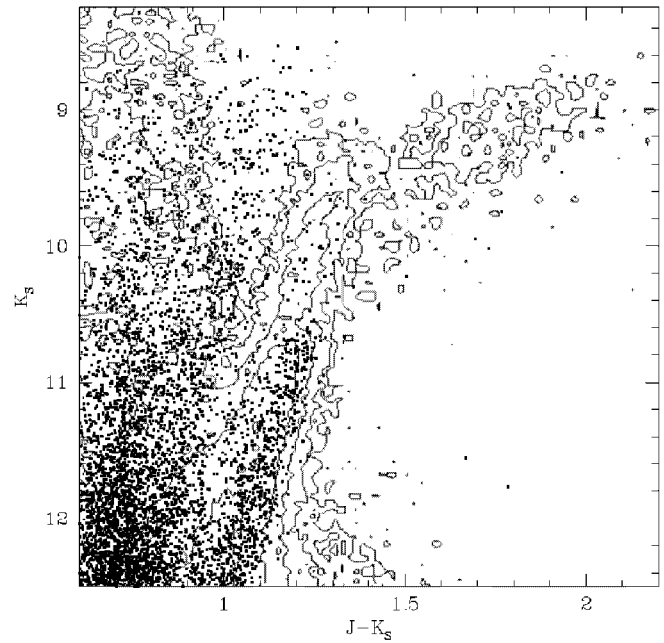


FIG. 4.—The 2MASS CMDs of the Sgr dwarf (*filled squares*) and the LMC (*contours*). The LMC data have been shifted by  $\Delta(m-M) = -1.5$ ,  $\Delta E(B-V) = 0.075$ .

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