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PROSPECTING FOR SPIRAL STRUCTURE IN THE FLOCCULENT OUTER MILKY WAY DISK WITH COLOR-MAGNITUDE STAR COUNTS FROM THE TWO MICRON ALL SKY SURVEY

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ABSTRACT

Using star counts in both color and magnitude from the Two Micron All Sky Survey Second Incremental Release Point Source Catalog, we search for evidence of large-scale nonuniform extinction and stellar population density changes in the Galactic plane. Extinction causes the entire main sequence to shift toward redder colors on a color-magnitude diagram. A local increase in the stellar density causes an increase in the star counts along a line parallel to the main sequence. We find streaks in star count color-magnitude contour plots along the angle of the main sequence that are likely to be caused by distant gas clouds and stellar density variations. The distance of a gas cloud or stellar density change can be estimated from an adaptation of the Wolf diagram or the location of the shift in the star count contours. We identify features in these diagrams that are coherent across at least 10° in Galactic longitude. A series of features is seen at the distance of the expected Perseus spiral arm, 2–4 kpc from the Sun. However, other features as prominent are found at both larger and smaller distances. These structures are over 300 pc in size and so likely to be associated with large-scale coherent structures in the gas distribution such as weak spiral arms. The presence of multiple and weak spiral arms and lack of strong ones suggests that the outer Milky Way is flocculent in its morphology.

Key words: Galaxy: disk — Galaxy: structure

1. INTRODUCTION

It has long been recognized that star counts or the number of stars per magnitude bin per unit area on the sky are strongly affected by extinction, or the absorption of light by dust (e.g., Seeliger 1900; McCuskey 1965). Because extinction is particularly strong in the plane of the Milky Way, it has not been possible to study the spiral structure of our Galaxy deep within the Galactic plane using star counts. However, above the scale height of the gas and dust, at Galactic latitudes outside the "zone of avoidance" or greater than 10° from the Galactic plane, it is possible to measure the distribution of stars in the galaxy. For example, star counts from the Sloan Digital Sky Survey well above the Galactic plane have recently been used to measure the scale heights of the thin and thick stellar disks (Chen et al. 2001) and uncover structure in the halo (Yanny et al. 2000).

Because of the sensitivity to extinction, rather than probe for galactic structure, star counts are often used to measure extinction, as first illustrated with the Wolf diagram (Wolf 1923; Trumpler & Weaver 1953), or to make extinction maps in the visible bands (e.g., Dickman 1978) and at very high levels of extinction in molecular clouds in the near-infrared (e.g., Lada et al. 1994; Cambresy 1999; Lombardi & Alves 2001).

The Two Micron All Sky Survey (2MASS) team has recently released a significant fraction of the sky at a depth of about 15 mag in the K_s band (the Second Incremental Release).[1] Because 2MASS is carried out between 1 and 2 μm, the effect of extinction is greatly reduced compared with that at visible wavelengths. Therefore, 2MASS provides us with a unique opportunity to probe for structure within the plane of our Galaxy. Recent studies that use 2MASS star counts to probe for galactic structure include the study of the galactic bulge by Alard (2001) and measurements of the radial scale lengths of the thin and thick disks by Ojha (2001).

2. NUMBER COUNTS IN A COLOR-MAGNITUDE DIAGRAM

To detect structure in the halo, Yanny et al. (2000) selected stars in a narrow range of color. On the main-sequence, color effectively determines the luminosity of the star, and so its distance can be determined from the observed magnitude. While this technique worked well to uncover structure in the halo, we now explain why it presents difficulties when used to search for structure in the Galactic plane using 2MASS data.

A difference in $J-H$ of 0.1 results in a change in absolute magnitude on the main sequence of about a magnitude (see Fig. 1), and this would correspond to a factor in distance of 1.6. The nearest spiral arms are about 2 kpc away from the Sun (e.g., Vallée 1995) and may only have thicknesses of a few hundred parsecs, so to see an enhancement in the star counts, we can only tolerate distance uncertainties that are less than factors of 1.1. This corresponds to a magnitude uncertainty of less than 0.2, which is difficult to achieve using an infrared color section for stars at the distance where we expect spiral arms. We expect that magnitude uncertainties resulting from the strong dependence of absolute magnitude on color of the main sequence will wipe out any evidence for spiral structure in a given color-selected sample. Furthermore, because of reddening associated with extinction, a color selection will not restrict the stars to a give spectral type or absolute magnitude. As a result, despite the fact that this approach was successful for detecting structure in the halo, if we only search in one color bin it is unlikely to work in the Milky Way disk using 2MASS data.

[1] For information on the 2MASS Second Incremental Release Point Source Catalog, see http://irsa.ipac.caltech.edu.

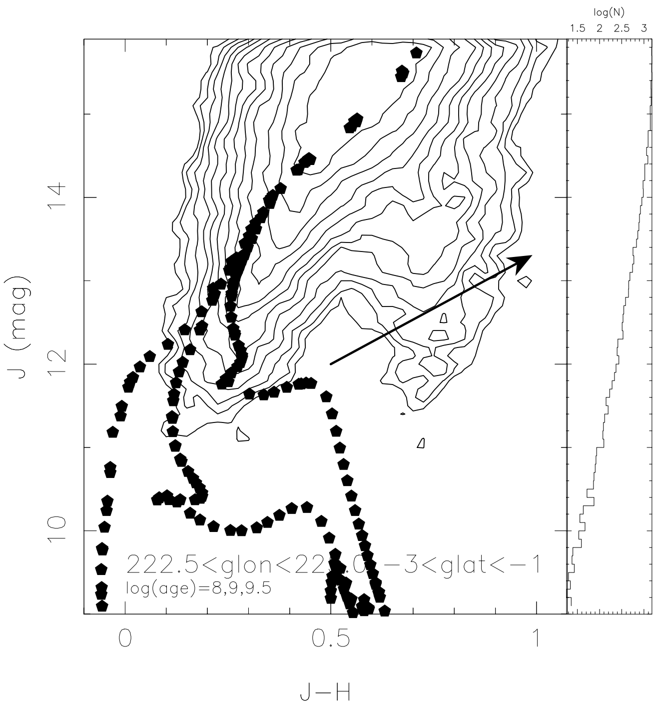

FIG. 1*a*

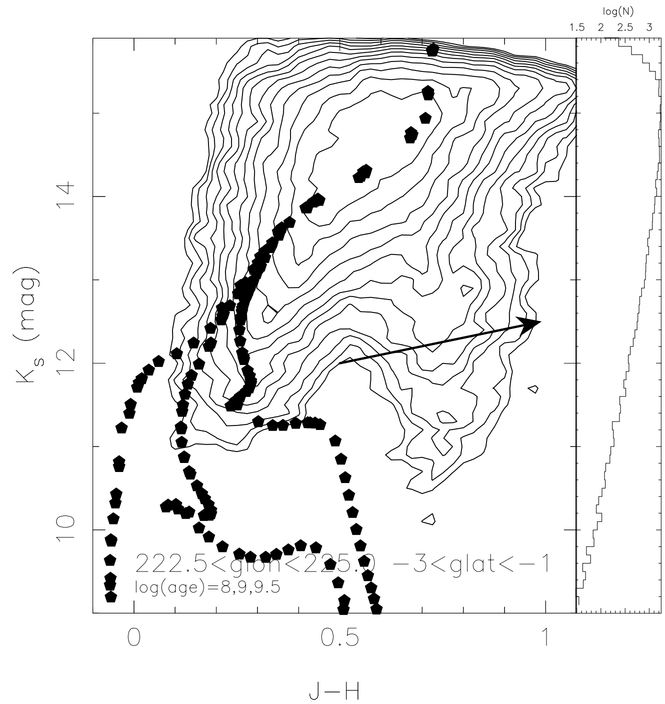

FIG. 1*b*

FIG. 1.—(*a*) Color-magnitude number counts shown for point sources from the 2MASS Point Source Catalog with Galactic longitude $222^\circ\!.5 < l < 225^\circ\!.0$ and latitude $-3^\circ < b < -1^\circ$ for the color $J-H$ (*x-axis*) vs. J (mag) (*y-axis*). Contours are shown at 12 logarithmic levels, with the lowest level set at 10 stars per bin and the highest at the maximum of the counts. As data points, we show the main sequence at three different ages, 10^8, 10^9, and $10^{9.5}$ yr and with solar metallicity assuming a distance of 1 kpc. To plot these points, we have used the stellar evolutionary tracks of Girardi et al. (2000). An extinction arrow is drawn for $A_K = 0.5$, assuming an extinction law from Mathis (1990). As a stellar population becomes more distant, the luminosity function is pushed to higher magnitudes. However, extinction both reddens and decreases the luminosity. A region containing a young population will increase the number of blue stars at a particular magnitude range. Diagonal streaks in the contours can be caused by extinction or an increase in the stellar number density population at a particular distance. Note, for example, the streak that begins at $J \approx 14.5$ and $(J-H) \approx 0.20$ and extends to $J \approx 15.5$ and $(J-H) \approx 0.4$. This streak is also seen in (*b*), beginning at $K \approx 14.2$ and ending at $K \approx 15$. This streak would correspond to enhanced extinction at a distance of about 2.5 kpc. On the right, we show the base 10 logarithm of the number counts per 0.1 mag wide J-band bin integrated over all colors. (*b*) Same as (*a*), except the y-axis is K_s (mag).

So how do we get around this problem? We must use information from stars that cover a range of observed colors. The main sequence provides us with a useful relation between color and absolute magnitude. A change in stellar population caused by recent star formation causes a local increase in the number of blue stars, whereas extinction will cause the entire main sequence to shift toward redder colors on a color-magnitude diagram. If we see features on a color-magnitude number count diagram (number counts per unit color and magnitude bin) that extend along the direction of the main sequence, then we expect that those features are caused by local changes in either extinction or the local stellar population density.

In Figure 1, we show star counts from a 2.5 deg^2 field taken from the 2MASS Second Incremental Release Point Source Catalog with Galactic longitude $222^\circ\!.5 < l < 225^\circ\!.0$ and latitude $-3^\circ < b < -1^\circ$. Stars were counted in an array of bins defined by both color and magnitude. Magnitude bins were 0.1 mag wide in either the J or K_s bands, and the $J-H$ color bins were 0.025 mag wide. To aid the contouring algorithm, we slightly smoothed the array with a smoothing function 3 pixels high and wide that is shaped like a pyramid with half the flux in the central pixel. The minimum contour shown contains five stars per bin, and we show a total of 12 contours spaced logarithmically, with the maximum being the maximum value of counts in the array. For the 2MASS Point Source Catalog, the Level 1 requirements were to achieve a signal-to-noise ratio of $S/N = 10$ at 15.8, 15.1, and 14.3 mag in the J, H, and K_s bands, respectively. The actual achieved limiting magnitudes at this signal-to-noise ratio are about 0.5 mag better than expected. Typical photometric errors are about 0.03 mag for 13, 12.5, and 12.5 mag in the J, H, and K_s band, respectively, and about 0.1 mag for 16.3, 15.5, and 15.0 mag, respectively.

As a stellar population becomes more distant, the luminosity function is pushed to higher magnitudes on this figure. However, extinction both reddens and decreases the luminosity and so affects the entire main sequence along the same vector in the diagram. A region containing a young population increases the number of blue stars at a particular magnitude range or distance. An increase in the stellar density at a particular distance will cause an increase in counts again along an angle parallel to that of the main sequence. This will cause a shift in the contours toward the left. In Figure 1, we have overplotted the main sequence at a solar metallicity and distance of 1 kpc for three different aged populations. Diagonal streaks in the contour levels are observed that are along the same angle as the main sequence but offset in magnitude. Because we see bends in the contours that extend over a magnitude in J and K and 0.2 mag in color, they are likely to be real and not to due Poisson noise. These diagonal streaks are probably due to extinction at a distance exceeding the main-sequence model points. The distance to the gas cloud responsible for the extinction can be estimated from the magnitude shift of the main sequence. A streak in the contours is seen in both J and K_s

versus $J-H$ color-magnitude plots corresponding to an extended enhanced region of extinction or gas cloud at a distance of about 2.5 kpc from the Sun. In this paper, we search for features in the color-magnitude diagrams out to $J = 16$ and $K_s = 15$. At fainter magnitudes the star counts are not complete (see histograms on the right-hand sides of Figs. 1*a* and 1*b*).

3. PROSPECTING FOR SPIRAL STRUCTURE

We now look for coherent structures seen in the color-magnitude diagrams in different locations in the Galactic plane. There are three regions in the Second Incremental Release that contain the Galactic plane ($|b| < 5°$) and not the Galactic center. These regions have Galactic longitudes that range $l = 220°$–$250°$, $50°$–$80°$, and $170°$–$190°$. All three regions should contain the Perseus Spiral arm (see Fig. 2), but in the $50°$–$80°$ region the arm is distant at 5–7 kpc, and so it should be impossible to detect it using main-sequence stars. Furthermore, because the spiral arms increase with distance with increasing Galactic longitude, even weak spiral arms in the region between the Carina and Perseus arms at $l \sim 80°$ should not extend over a large range in galactic longitude. In the Galactic anticenter region between $l = 170°$ and $190°$, the Perseus spiral arm should be roughly equidistant from the Sun at a distance of 2 kpc, but little extinction is evident in this direction. As a result, we begin by concentrating on the region between $220°$ and $250°$.

In Figure 3, we show color-magnitude number count diagrams in regions ranging from $220°$ to $250°$ with Galactic latitudes $b = 0°$ to $-2°$ or $-3°$ to $-1°$. In a few regions, pieces of the sky were not covered by the data release, so the counts were corrected by dividing by the percent of sky area covered. The K_s-band plot corresponding to the J-band plot in Figure 3*a* is not shown, since it is quite similar to Figure 3*a*. In this region between, we see streaks (Fig. 2, *dotted line*) that begin at $J \sim 14.5$ at $l = 220°$ and end at $J \sim 15.5$ at $l \sim 235°$. This feature is also seen in the K_s color-magnitude contour plot (Fig. 3*c*). The location of the streaks is at somewhat larger magnitudes for $b = -3°$ to $-1°$ than for $b = 0°$–$2°$, suggesting that there is a larger smooth extinction gradient with radius at this Galactic latitude than at $b = 1°$. From the location of the feature in the K_s-band plots and how it is offset from the main sequence at 1 kpc (see Fig. 1), we can estimate its distance to be $\sim$2.5 kpc at $l = 220°$ extending to $\sim$4 kpc at $l = 235°$. This corresponds to the expected location of the Perseus spiral arm (see Fig. 2) as extended from our knowledge in existing spiral tracers (Vallée 1995).

We also see evidence for additional structures that have not been identified by Drimmel & Spergel (2001) and H I surveys. See, for example, the indent in contours at $l = 225°$–$235°$ at $K_s \sim 13.8$ to 15, which would correspond to extinction at a distance of 2–4 kpc but inside the Perseus arm, which is expected to be at a distance of 5 kpc at $l = 235°$.

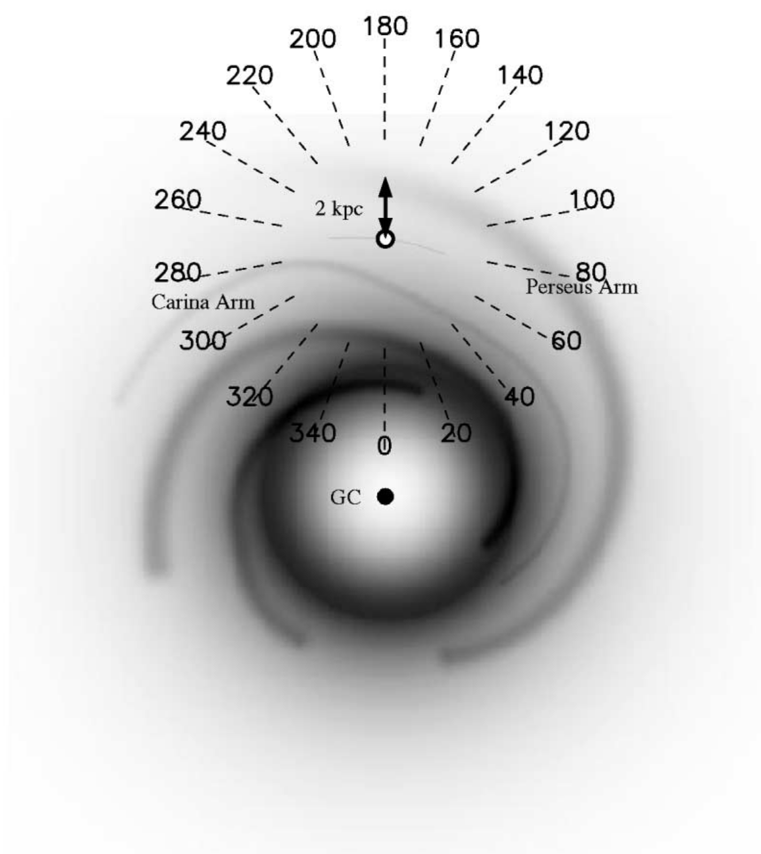

FIG. 2.—Model for the Milky Way spiral arms constructed from dust emission seen in *COBE* DIRBE data by Drimmel & Spergel (2001). We have overlayed Galactic longitudes at the position of the Sun, so that it is clear what spiral arms we expect to see at a given position on the sky and distance from the Sun. Shown as a faint gray line passing through the Sun is the Orion spur, a local ridge of gas and star formation.

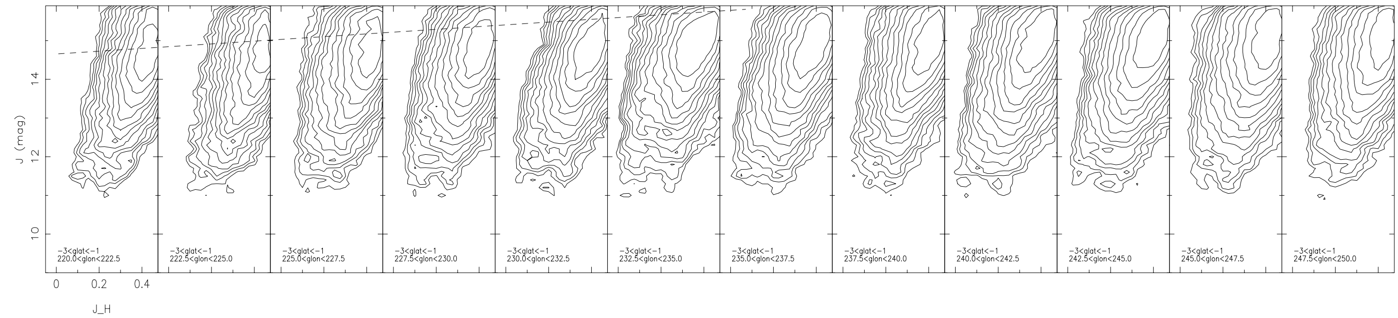

Fig. 3*a*

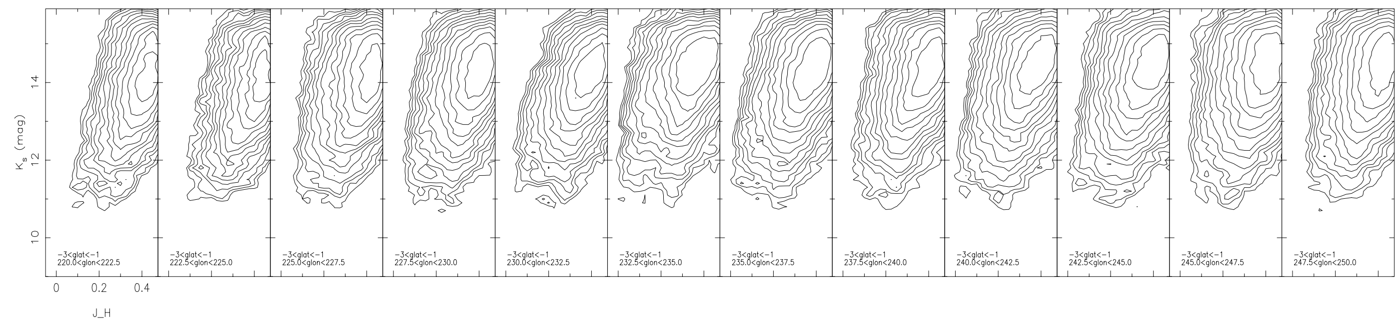

Fig. 3*b*

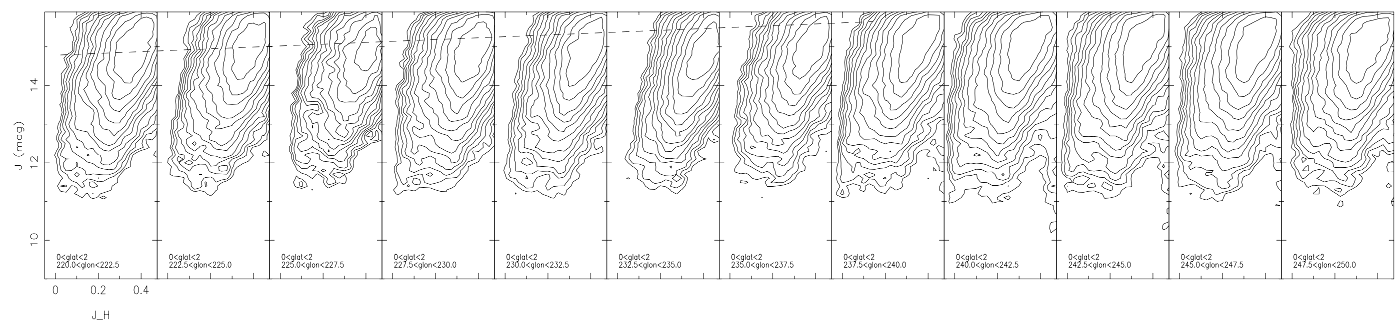

Fig. 3*c*

Fig. 3.—(*a*) Color-magnitude number count diagrams are shown for J (mag) vs. $J-H$ for regions 2°.5 wide in Galactic longitude and for latitude $-3^\circ < b < -1^\circ$. The leftmost panel has $220^\circ < l < 222^\circ.5$, and the rightmost panel has $247^\circ.5 < l < 250^\circ$. Twelve contours are shown at logarithmic intervals with the lowest contour at a count of five stars per 0.1 mag $\times$ 0.025 color bin and the highest contour at the maximum of the plot. A streak in the contours that could be associated with the Perseus spiral arm is shown as a dotted line over the plots from 220°–235°. (*b*) Same as (*a*), but for $0^\circ < b < 2^\circ$. (*c*) Same as (*b*), but for K_s (mag) vs. $J-H$ color.

Structure seen in these star count color-magnitude contour plots appears to be correlated and extended. A streak in the contours at one galactic longitude is likely to be present in the diagram at lower and higher longitude, although systematically shifted toward more higher magnitudes at higher galactic longitudes. This makes sense if the density perturbations in both the gas and stars are spiral in shape or increasing with distance with increasing Galactic longitude (see Figs. 2 and 4).

The structure see in these star count diagrams cannot be solely due to extinction, because local increases in the star counts at higher magnitudes are also seen. This implies that there are also density variations as a function of distance from the sun. Again, this is not unexpected if we remember what other galaxies look like (e.g., see Fig. 4, which displays a *B*-band image of M100).

Although we see strong evidence for local density and extinction variations in the region around $l \sim 230^\circ$, we do not see features associated with extremely strong spiral structure, neither evidence for large variations in the stellar density or local extinction. The most likely explanation for the structure that we do see is that the Milky Way is flocculent in its morphology outside the solar circle. In hindsight, this is not unexpected if we remind ourselves that the Sun is 2–3 disk exponential scale lengths from the Galactic center.

For a spiral arm outside the solar circle, we expect to encounter first an increase in extinction and then an increase in the stellar density as a function of distance from the Sun as a spiral arm is crossed (see Fig. 4). The affect of the extinction is therefore decreased by the increased density following the spiral arm. Stellar density and extinction variations associated with spiral structure should be easier to uncover using star counts in the Carina arm within the solar circle because we expect that blue stars should be nearer than the belt of extinction associated with the spiral arm. This should emphasize features seen in the color-magnitude star count

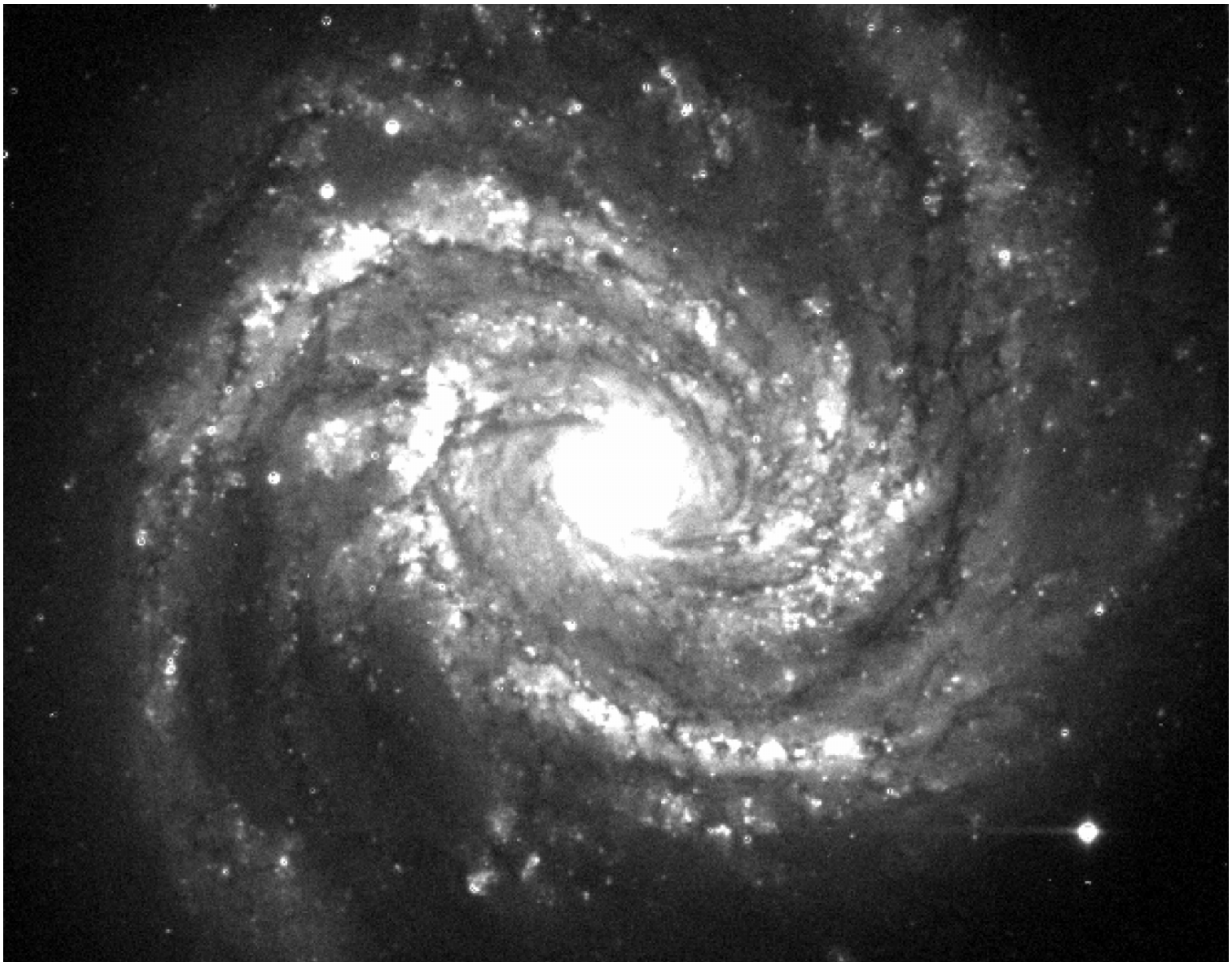

FIG. 4.—This flipped *B*-band image of M100, originally published by de Jong (1996), was retrieved from the NED. Note that for an observer in M100 looking outward away from the Galactic center (as we are when we look at galactic longitudes between 220° and 250°), we expect to see first extinction followed by larger numbers of young blue stars as a function of distance from the observer. Extinction will move the luminosity function to the right in the color-magnitude diagram shown in Figs. 1 and 2, whereas a blue stellar population will move it to the left, countering the affect of the extinction. We expect a larger effect in the color-magnitude diagram when we look at spiral arms that are closer to the Galactic center than the Sun because we expect to see a younger stellar population followed by extinction as a function of distance from the observer.

plots, rather than decrease them as is true when we look toward larger Galactocentric radii. Features associated with these spiral arms may also be easier to detect because these spiral features should have higher gas densities, hence heavier extinction, and stronger stellar density contrasts.

In Figure 5, we show color-magnitude star count plots taken from a strip along $b = 2°–3°$ and between $l = 65°$ and 85°. There is a lot of extinction at $l \sim 80°$, which corresponds to the Dark Nebula LDN 906 (Lynds 1962), which has an area of 15° and must be quite nearby. A number of features are seen in these plots that are probably real because they extend over a fair range on an individual plot. However, we do not find a high level of coherence between the plots. This is not surprising since at this Galactic longitude we are looking between the Carina and Perseus arms and the opening angle of the arms is such that elongated gas clouds will not extend over a large range in Galactic longitude. The large number of features seen in these plots is consistent with a patchy interstellar medium (ISM) and the possibility that the outer Milky Way is flocculent in its morphology.

In Figure 6, we show color-magnitude star count plots taken from strips along latitude $b = -1°$ to 1° and $-3°$ to $-1°$ and between longitude $l = 170°$ and 190°. At $l \sim 170°$–180°, we see evidence for extinction at a distance of about 2 kpc (streaks beginning at $K_s \sim 13.8$). This does correspond to the expected location of the Perseus spiral arm, but the lack of any features at $l \sim 190°$ suggests that it is not continuous. There are also extended features further out at $K_s \sim 14.5$ from $l \sim 180°$ to 190°. We see no dominated feature at the expected location of the Perseus arm but instead a variety of shorter features at both shorter and longer distances.

4. SUMMARY AND DISCUSSION

In this paper, we have presented color-magnitude number count contour plots constructed from the 2MASS Point Source Catalog in the Galactic plane. We demonstrate how streaks observed in these diagrams can be used to estimate the distance of local regions of high extinction. A coherent structure is seen between Galactic longitude 220° and 237°

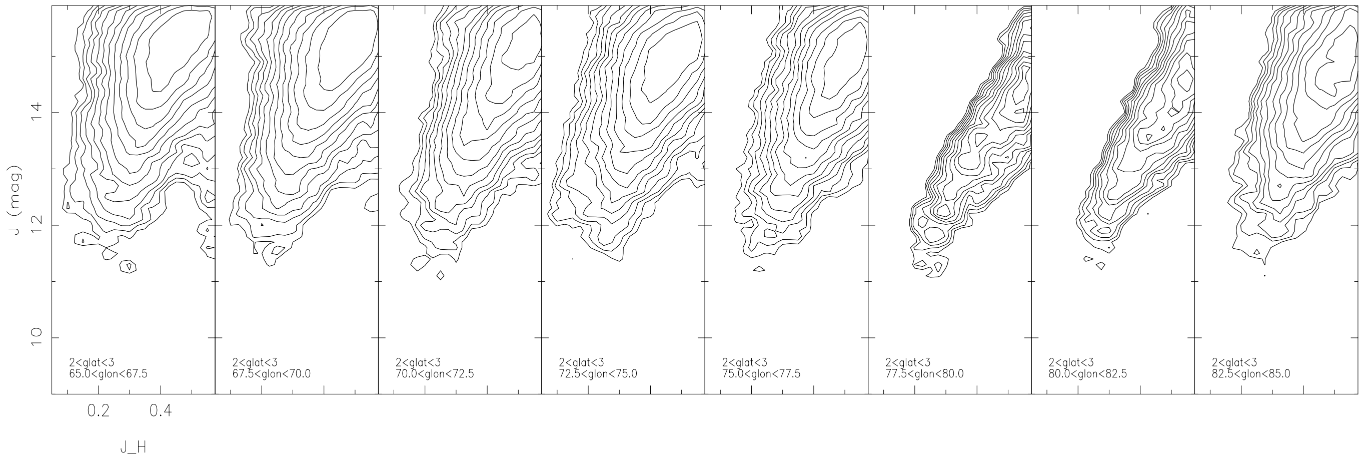

FIG. 5*a*

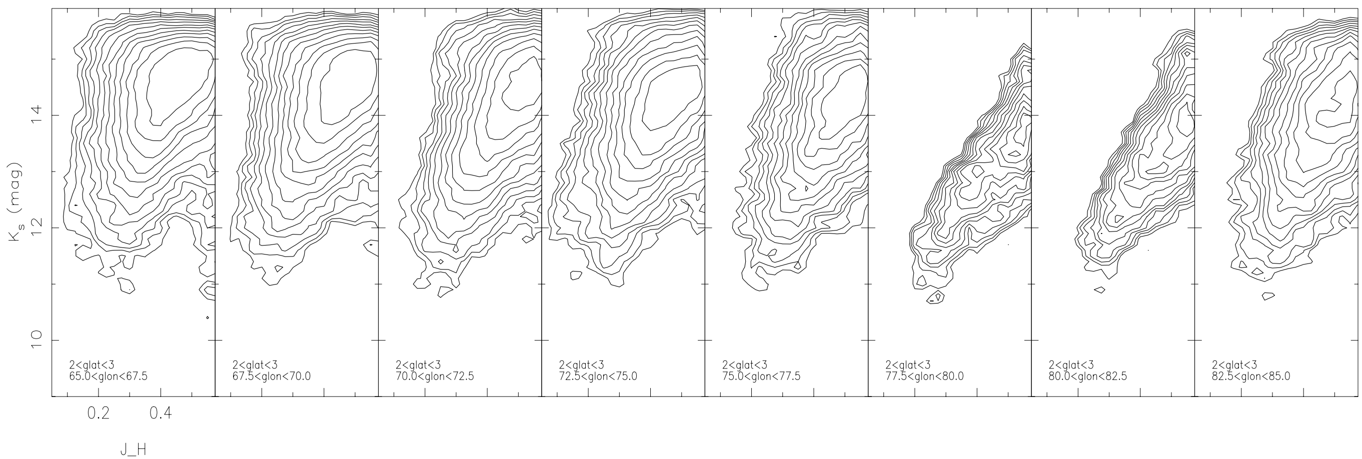

FIG. 5*b*

FIG. 5.—(*a*) Similar to Fig. 2*a*, but for the region $65^\circ < l < 85^\circ$ and $2^\circ < b < 3^\circ$. (*b*) As in (*a*), but for K_s (mag) vs. $J-H$. There is a lot of extinction at $l \sim 80^\circ$ that is caused by the Dark Nebula LDN 906 (Lynds 1962), which has an area of 15° and must be quite nearby. In this direction, we are looking between the Carina and Perseus spiral arms. In this direction, even weak spiral should not extend over a large range in galactic longitude, so we do not expect coherent features that extend from one plot to another. The large number of features seen in these plots is consistent with a patchy ISM and the possibility that the outer Milky Way is flocculent in its morphology.

that corresponds to the probable location of the extension of the Perseus spiral arm. Another coherent structure is seen with a steeper pitch angle between Galactic longitude 230° and 240° at a distance of 2–4.0 kpc and may be a weaker spiral feature. Neither feature is particularly prominent. In the region $l \sim 170^\circ$–190°, we see a feature at the probable location of the Perseus spiral arm but also other coherent features at both larger and smaller distances. Features seen in the star count contour plots are likely to be real because they cover a significant range in color and magnitude in each color-magnitude star count plot and because nearby lines of sight in the galaxy exhibit similar features. At a distance of 2 kpc, a structure that extends over 10° has a length of 350 pc, so the coherent structures picked out from the star counts are likely to be associated with spiral arms. The lack of strong spiral features and the evidence for additional weak features suggests that the outer part of the Galaxy is flocculent in its morphology.

We suggest that color-magnitude number counts could be used to estimate the distances to large-scale gas clouds at distances up to a few kiloparsecs using blue main-sequence stars. It is possible that a similar technique could also reveal structure out to much larger distances using giant stars. Giant stars have the disadvantage that it is not straightforward to estimate the luminosity of the star given its color, but the advantage is that they can be seen much further away than blue main-sequence stars.

Using star counts to measure distances to atomic and molecular clouds is potentially a very powerful technique. However, to do this reliably, we would need to integrate the stellar luminosity function as a function of distance from us and devise techniques to differentiate between patchy extinction, stellar density variations, mean extinction variations, and variations in the mean age of the stellar population. All of these effects should affect the integrated number counts. By combining information available in CO, H I and far-IR images of the Milky Way with 2MASS, it may be possible to make a map of the Milky Way with the detail of that shown in Figure 4 of M100 rather than that currently known, which is represented in Figure 2.

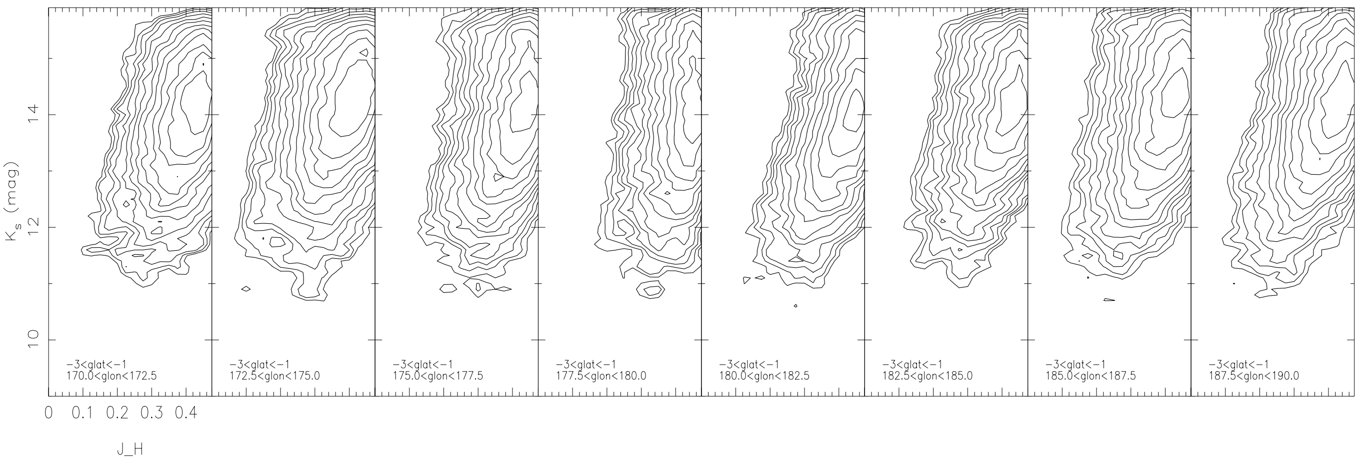

FIG. 6*a*

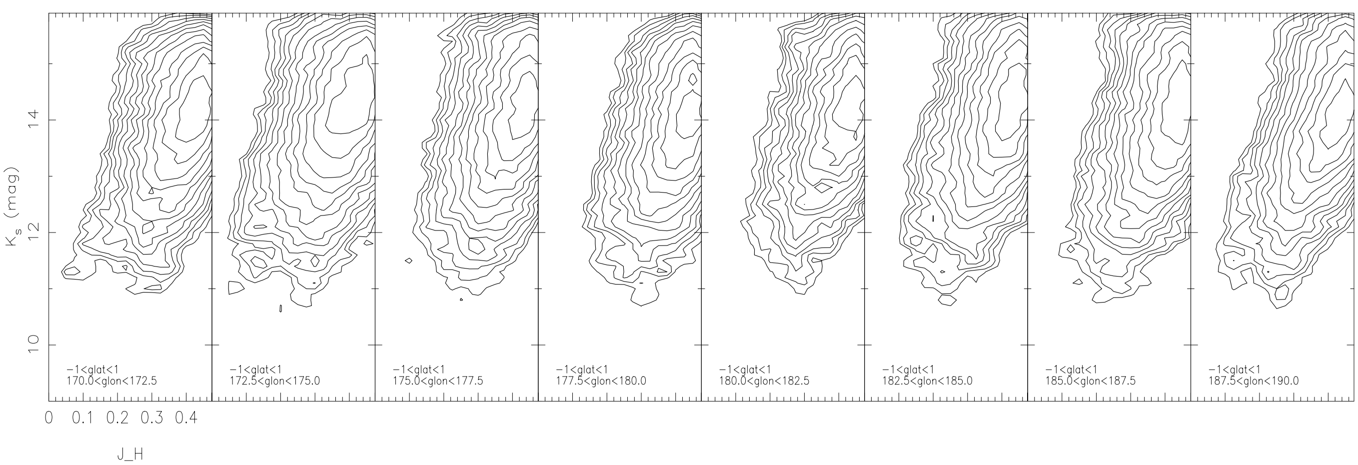

FIG. 6*b*

FIG. 6.—(*a*) Similar to Fig. 2*a*, but for the region $170^\circ < l < 190^\circ$ and $-1^\circ < b < 1^\circ$. (*b*) As in (*a*), but for $-3^\circ < b < -1^\circ$. In the range $170^\circ < l < 177^\circ$, we see features at $K_s \sim 13.8$ mag that would be consistent with extinction located at the expected distance of the Perseus spiral arm at 2 kpc from the Sun. In the range $175^\circ < l < 190^\circ$, we see features at $K_s \sim 14.5$ that would correspond to a band of extinction at about 3 kpc. There is no doubt that features are coherent in the sense that they tend to be visible in the color-magnitude plots in neighboring regions. We do not see evidence for one strong band of extinction associated with a dominant spiral arms, but rather evidence for multiple weaker structures.

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