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WHITHER THE LSR: ANTICENTER CARBON STAR VELOCITIES

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ABSTRACT

We report new radial velocity measurements of 179 carbon stars toward the Galactic anticenter with accuracies of 4 km s^{-1}. We derive distances to the carbon stars from existing K-band photometry and derive an average galactocentric radius of 13.9 kpc for the stars in the sample. Using the new velocities we find that the carbon star sample is moving radially outward with respect to the local standard of rest at a velocity of 6.6 ± 1.7 km s^{-1}. This is in disagreement with the nonaxisymmetric rotation curve model proposed by Blitz & Spergel, which predicts a motion in the opposite direction. We find no systematic difference in the peculiar motion on either side of the anticenter and see no significant trend with distance. The radial velocity dispersion of the sample is 23 km s^{-1} and does not appear to vary with increasing radius.

Subject headings: Galaxy: kinematics and dynamics — stars: carbon — stars: kinematics

1. INTRODUCTION

The typical model used to describe Galactic rotation is axisymmetric with rotation rate varying with radius. It has long been known from H I surveys (e.g., Weaver & Williams 1973; Kerr et al. 1986), however, that the H I gas in the Galactic disk exhibits motions which are inconsistent with a simple axisymmetric model. Recently, Blitz & Spergel (1991a, hereafter BS) proposed a model of the Galaxy which accounts for two features evident in the H I maps: that the gas toward the Galactic anticenter has an apparent inward motion, and that the outer Galaxy gas appears asymmetric about $l = 180°$. They support their model by showing it to be consistent with CO measurements toward the Galactic center, H I column density, and the vertex deviation of the velocity ellipsoid in the solar neighborhood.

A main feature of the BS model is an outward motion of the LSR due to a nonaxisymmetric rotation curve, produced by a rotating triaxial spheroid in the inner Galaxy. (This is distinct from the smaller scale bar at the Galactic center detected by Blitz & Spergel 1991b; Binney et al. 1991; Weinberg 1992; and others.) The rotation curve ellipticity in the BS model decreases outward to about $2.5R_0$ from the Galactic center, where it becomes circular. Thus the gas toward the Galactic anticenter should appear to be moving inward relative to the LSR, increasing in magnitude until $\sim 2.5R_0$ where we should see the full reflection of the radial component of the LSR motion. The outward motion of the LSR is 14 km s^{-1} in the BS model, accounting for the 14 km s^{-1} apparent inward motion of the anticenter gas.

If the LSR has such an outward motion, we would expect to see this motion reflected in stars as well. To detect it one would need a sample of tracer stars toward the anticenter at distances $\gtrsim 1.5R_0$ where the ellipticity of the rotation curve in the model is small. Extinction from dust in the disk is substantial, requiring a tracer that is intrinsically bright. The sample of stars also needs to be large enough to allow a good measurement of the mean velocity: the radial velocity dispersion in the Galactic disk is ≈ 20 km s^{-1} at $1.5R_0$ (Lewis & Freeman 1989). Carbons stars are good candidates for such a tracer population. Though they are not the best of standard candles, they are relatively numerous and are very bright at infrared wavelengths ($M_K = -8.1$ mag), allowing them to be detected at large distances even through absorbing dust. They are also easy to identify on objective prism surveys from strong absorption bands in their spectra.

Fortunately, a significant number of carbon stars have already been identified at the Galactic anticenter. Fuenmayor (1981) found 216 carbon stars in a survey conducted in a region covering ~ 200 square degrees at the Galactic anticenter, complete to $I = 11$ mag. K-band photometry of 211 of these stars was obtained by Jura, Joyce, & Kleinmann (1989), allowing distances of the stars to be determined. This shows that the Fuenmayor stars lie at distances of about 2–10 kpc from the Sun, or about 1.2–$2.1R_0$ from the Galactic center. In addition, Aaronson et al. (1990) measured velocities for 55 of these stars. A preliminary examination of these velocities revealed little evidence of LSR motion, but the sample was too small to draw a firm conclusion. We therefore decided to obtain velocities for the rest of the Fuenmayor stars to allow us to measure the outward motion of the LSR predicted by the BS model.

2. OBSERVATIONS

We obtained spectra for most of the 216 Fuenmayor carbon stars on the nights of 1990 November 27–30 using the Gold Camera on the 2.1 m telescope at Kitt Peak. We used an 831 line mm^{-1} grating in first order centered at 7950 Å, projected onto a Texas Instruments 800 by 800 CCD. This gave a wavelength coverage of ≈ 700 Å at 0.9 Å pixel^{-1}. The region around 8000 Å contains strong bands of CN absorption, which allow the redshift to be measured accurately. We were limited by the internal camera focus of the spectrograph to a resolution of about 3 pixels FWHM with a 1".2 slit. After binning the pixels by 3 in the spatial direction to reduce readout noise, the spatial resolution was about 2.5 pixel FWHM, which corresponded to 6" on the sky. Helium-neon-argon calibration arcs were taken after each stellar spectrum. Though clouds during our observing run prevented us from obtaining spectra for every catalog star, we managed to obtain usable spectra for 179 of the 216 Fuenmayor stars.

The spectra were reduced by rebinning the pixels of each spectrum according to a low-order polynomial fit made to the associated calibration frame. One axis of the resulting image

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corresponded to the normalized spatial direction, and the other to log wavelength. The spectra were then collapsed spatially along the star image and sky-subtracted using pixels away from the star on the same spectrum. The region of the spectrum near 7650 Å contains the telluric absorption *A*-band and was excluded. The redshift between each star spectrum and a reference spectrum of a bright carbon star was then calculated using the Fourier quotient technique of Sargent et al. (1977). Observed relative velocities were adjusted to the heliocentric frame.

Many additional carbon stars were observed to provide a zero-point calibration. These stars were selected from the carbon stars with velocities reported by Aaronson et al. (1990) that were visible during our run. The reference spectrum chosen for computing redshifts was one of a bright carbon star with $K = 3.9$ mag, number 82 in Stephenson's (1989) catalog, for which we obtained a spectrum with a high signal-to-noise ratio. Velocities were computed relative to this template for the program stars and converted to absolute velocities based upon a derived velocity for the template. The template velocity was obtained by measuring a velocity of each of the zero-point calibration stars relative to the template. The difference between this velocity and the star's velocity as reported in Aaronson et al. (1990) gives a measurement of the template's velocity, aligned to their zero point. The measurements are then averaged to obtain the derived template velocity. A total of 62 stars were used to compute our reference template velocity, -32.30 ± 0.51 km s^{-1}. Individual velocities for the template are shown in Figure 1. From this we find a scatter between our velocities and those of Aaronson et al. of 4.0 km s^{-1} (1 σ).

Velocities for 179 anticenter carbon stars are shown in Table 1. The formal errors of the individual velocities from the Fourier quotient are $\simeq 2.0$ km s^{-1}, not including error contributed by the wavelength calibration. The scatter of the velocities used in computing the template velocity gives a good estimate of the total individual measurement error, aside from any overall systematic error. The scatter from Figure 1 is 4.0 km s^{-1}, and using the quoted error for the Aaronson et al. (1990) velocities of 3.0 km s^{-1}, we can calculate an error for our

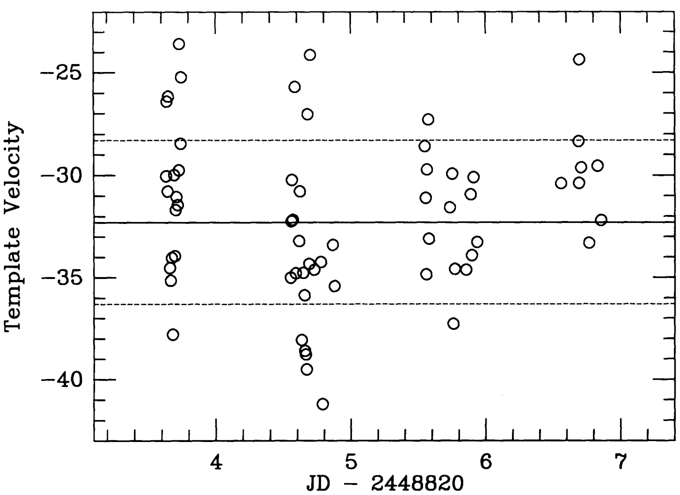

FIG. 1.—Individual measurements of the template velocity vs. Julian date of observation for 62 carbon stars. The solid line shows the mean, used as the velocity for the template, and the dashed lines correspond to 1 σ of the distribution.

individual velocities of approximately 2.6 km s^{-1}. Given the resolution of the detector of 34 km s^{-1} pixel^{-1}, however, we prefer a more conservative error estimate of 3.5 km s^{-1} according to our estimate of the wavelength calibration accuracy. Multiple observations of the same star on several occasions are consistent with this latter estimate. Table 2 shows velocities for non-Fuenmayor carbon stars measured during our run. Stars in Table 2 having velocities reported in Aaronson et al. (1990) were included in the computation of the zero point.

3. ANALYSIS

The first step in the analysis was to determine crude distances to the carbon stars in the sample. Carbon stars have a fairly large intrinsic dispersion in absolute *K* magnitude of roughly 0.6 mag (Schechter et al. 1991; Cohen et al. 1981), corresponding to a 32% error in distance. Distance estimates are further complicated by interstellar absorption. In principle, one might correct for the latter based upon color excesses. Complete photometry for our sample is available only in *I* and *K* bands, however, which gives a single color. Jura et al. (1989) investigated a correction using this color for the Fuenmayor catalog stars. They found that the dispersion in $I-K$ versus K was large, due in part to a wide variation of the intrinsic $I-K$ colors of carbon stars. For this reason, we instead chose to adopt an average extinction gradient.

The use of an extinction gradient leaves significant uncertainty in the unreddened magnitude estimates. Aside from problems with the uneven distribution of extinction in the disk, the extinction gradient in *K* is poorly known. Schechter et al. (1991) report a value corresponding to 0.03 *K* mag kpc^{-1} based on H I column densities, while Jura et al. (1989) use a much higher value of 0.15 mag kpc^{-1}. To further complicate matters, the Fuenmayor catalog stars were a magnitude-limited sample taken in the *I* band, so that stars with large reddenings were preferentially excluded from his catalog. However, Jura et al. (1989) find their high extinction gradient to be consistent with the Fuenmayor sample based in part on the stars' $I-K$ colors.

As a first attempt to check the extinction gradient in our sample, we computed infrared reddenings of the subset of Fuenmayor stars observed in *JHK* bands by Aaronson et al. (1990) using the zero-reddening locus adopted by Cohen et al. (1981). We find an extinction gradient of 0.1 *K* mag R_0^{-1}. This low value is not unexpected as the stars in the subset were selected for bright *V* magnitudes, further excluding more reddened stars.

We can also check an assumed extinction law by comparing the mean $(I-K)$ color of the Fuenmayor stars with the color we would predict a carbon star to have at the mean distance derived for the sample. Combining the *I*-band photometry of Costa (1990) with *K*-band photometry from Frogel (1992) for 62 carbon stars in the LMC, we find a mean $(I-K)$ color of 3.52. The intrinsic color is bluer by about 0.1 mag when corrected for LMC extinction, but Cohen et al. (1981) imply that the Galactic carbon stars are about 0.1 mag redder in $(I-K)$ than the LMC carbon stars (see their Fig. 2). Assuming 0.03 *K* mag kpc^{-1}, we derive (see below) a mean sample distance of 5.4 kpc, corresponding to $A_K = 0.16$ mag. Using the adopted reddening law of Cohen et al. (1981) for the Cousins *I* band, this gives $E(I-K) = 0.92$. We therefore expect the color of a carbon star to be $(I-K) = 4.44$, compared to 4.9 observed for the sample. This method converges to an extinction value of about 0.05 *K* mag kpc^{-1}.

We finally adopted the Schechter et al. (1991) value of 0.03

TABLE 1

FUENMAYOR CARBON STAR VELOCITIES

Star	JD −2,448,220	V_r	V_{model}	Star	JD −2,448,220	V_r	V_{model}
1	3.930	−34.0	7.9	80	5.760	31.6	4.8
2	3.934	8.7	−16.4	82	5.789	19.3	12.2
3	3.938	34.8	−16.3	83	5.811	7.6	7.3
4	3.763	−1.8	−9.6	84	5.827	17.2	13.8
5	3.766	−10.4	−18.7	86	5.806	10.4	3.0
6	3.771	7.5	−17.5	87	5.830	8.9	16.8
8	3.774	14.8	−16.4	88	5.814	27.2	12.0
9	3.779	34.0	−14.1	89	5.839	−37.7	−2.8
10	3.784	49.7	−6.8	90	5.849	−5.7	1.2
11	3.788	−6.6	−8.6	91	5.864	−1.0	10.4
12	3.791	−23.1	−12.7	92	5.853	−36.8	−0.1
13	3.795	−1.2	−14.7	93	5.874	45.4	17.7
14	3.798	18.7	−4.9	94	5.868	9.9	9.5
15	3.803	−20.0	−18.0	95	5.883	12.7	2.1
16	3.806	−30.0	−15.8	96	5.887	−5.7	4.0
17	3.811	7.4	14.9	97	5.879	−4.6	19.6
18	3.815	−25.1	−8.8	98	5.896	−4.7	8.3
19	3.823	6.8	11.1	99	5.909	15.2	6.0
20	3.819	27.7	−7.9	100	6.901	−21.3	12.0
21	3.826	15.4	6.7	101	2.902	−1.1	13.3
22	3.831	11.1	−2.9	103	6.933	8.5	13.1
23	3.835	30.2	−1.1	106	6.937	−0.9	17.4
24	3.841	42.3	10.7	108	6.765	39.0	9.8
26	3.846	−52.5	−18.9	109	6.880	31.5	5.0
27	3.850	0.2	−12.8	110	6.967	23.3	8.1
28	3.854	32.8	−6.0	113	6.828	29.9	4.2
30	3.857	31.3	−12.3	114	6.820	−8.5	1.6
31	3.864	−4.8	−0.4	115	7.010	−23.6	−1.0
32	3.874	−0.1	3.6	116	6.853	−22.4	15.6
33	3.882	40.1	−7.8	122	7.014	38.1	5.9
34	3.895	5.6	−3.9	123	4.842	26.4	8.9
35	3.905	23.6	3.9	124	4.844	28.6	9.0
36	3.910	1.0	2.9	127	4.863	5.9	10.5
37	3.919	−18.1	−8.4	128	4.876	20.8	18.6
38	3.915	−8.7	0.1	129	4.894	23.6	21.3
39	3.925	5.2	−16.8	130	4.872	25.1	11.1
40	3.950	39.6	−9.5	131	4.885	7.9	20.1
41	3.951	−33.9	−14.8	132	4.908	54.0	8.8
42	3.966	19.8	−8.6	133	4.912	−3.0	6.7
43	3.958	35.0	8.4	134	4.917	−0.3	4.7
44	3.975	8.3	1.0	135	4.919	14.0	6.2
45	3.978	−12.9	0.4	136	4.924	16.0	4.4
46	3.988	6.3	12.0	137	4.899	14.7	21.4
47	3.983	−33.5	1.7	138	4.934	8.1	11.5
48	3.993	−27.1	−7.5	139	4.926	12.3	8.1
49	3.996	−3.3	4.9	140	4.938	−27.1	9.2
50	3.999	−19.5	−7.0	141	4.943	−16.4	19.1
51	4.711	20.9	−1.6	142	4.950	32.6	17.2
52	4.005	−35.2	−8.7	143	4.944	20.2	20.0
53	4.715	−2.7	−6.5	144	4.976	48.5	10.7
54	4.725	−5.3	2.1	145	4.982	−1.9	5.8
55	4.738	8.3	−2.3	146	4.988	38.9	0.0
56	4.749	−9.0	−3.7	150	7.004	34.0	8.9
57	4.766	0.8	−8.9	151	4.997	46.1	23.1
59	4.770	29.2	−5.7	153	5.001	22.5	21.1
60	4.776	6.1	0.0	154	5.006	35.0	15.0
61	4.788	−3.1	2.0	155	5.919	33.1	25.2
63	4.802	14.5	−0.7	156	5.929	34.7	10.3
64	4.793	4.3	3.4	157	5.935	48.4	20.2
65	4.811	15.6	7.9	158	5.953	61.3	22.9
66	4.820	49.6	15.2	159	5.963	49.1	12.4
67	4.815	30.4	6.4	160	5.930	30.8	10.7
70	4.832	−39.3	6.8	161	5.944	73.7	19.6
71	4.807	20.0	2.1	162	5.965	6.1	15.3
72	4.835	16.8	7.5	163	5.956	31.5	26.3
73	5.731	12.3	1.3	164	5.982	−20.0	15.0
75	5.751	11.5	6.1	165	5.971	29.9	25.4
76	5.770	25.1	0.0	166	5.976	8.0	31.1
77	5.780	−6.5	11.8	167	5.996	11.2	24.5
78	5.824	32.1	12.0	168	5.987	46.6	13.2
79	5.776	44.4	1.8	169	6.003	−15.8	25.8

TABLE 1—*Continued*

Star	JD −2,448,220	V_r	V_{model}
170	6.011	−8.6	20.1
171	5.998	4.5	26.3
173	6.015	22.0	11.3
174	6.018	−2.4	8.3
176	6.810	72.4	28.9
179	6.771	46.6	11.8
180	6.022	3.3	15.2
183	6.774	10.7	14.2
186	6.031	41.3	6.7
187	6.833	40.8	26.0
188	6.838	19.0	23.7
189	6.844	0.9	25.8
190	6.848	16.1	23.8
191	6.860	8.8	22.7
192	6.864	89.8	22.9
193	6.871	38.0	20.8
194	6.887	52.4	39.9
195	6.874	19.9	22.0
196	6.894	39.3	27.7
197	6.950	47.6	30.5
198	4.030	35.5	4.9
199	6.890	7.7	27.9
200	4.024	49.8	39.1
201	6.959	42.1	23.9
202	6.962	26.3	23.9
203	6.954	26.1	28.8
204	6.971	52.4	38.6
205	6.924	81.0	38.7
206	6.983	−15.1	36.2
208	6.987	82.3	37.9
209	6.929	12.2	17.5
210	6.999	44.8	37.3
211	6.914	26.1	38.5
212	6.993	40.8	40.4
213	6.975	75.4	38.6
214	5.032	9.5	5.6
215	6.996	18.7	27.7

mag kpc^{-1}, to be consistent with their analysis. It is also consistent with the smooth number count distribution we compute below to correct for Malmquist's effect. The difference between distances computed with this value and with 0.05 is less than 5%. The derived motions of the sample with respect to the LSR are fairly insensitive to errors of $\lesssim 0.8$ mag, as the stars are confined to within about 15° in Galactic longitude of the anticenter. Therefore, the difference in adopted extinction would not affect our velocities and changes the mean distances to the stars by only a small amount. Figure 2 shows the location of the sample stars in galactic coordinates. The large difference between our estimated extinction and that found by Jura et al. (1989) is due to a discrepancy in assumed mean $(I-K)$ color. Jura et al. use a value of 2.71 reported by Claussen et al. (1987). We believe the source of the discrepancy stems from the use of different I bands: the Claussen et al. value is for the system of Johnson (1965), which has an I-band filter response that extends to longer wavelengths that the Cousins I (Bessel 1979). Our $(I-K)$ color is based on the Cousins I system, which is closer to the Kron system used by Fuenmayor (1981) for the carbon stars. The extreme red color of carbon stars makes them apparently brighter in the Johnson (1965) system, producing an $(I-K)$ color that is significantly bluer.

To derive distances we applied a correction for Malmquist's effect, using a model disk with an exponential scale length of 4.4 kpc (Lewis & Freeman 1989) and a scale height of 200 pc (Claussen et al. 1987). The K-band luminosity function was assumed to be a Gaussian centered at $M_K = -8.1$ (Frogel, Persson, & Cohen 1980) with $\sigma = 0.6$ mag (Schechter et al. 1987). A Fermi-Dirac function centered at $K = 7$ mag with an effective width of about 1 mag was used as an approximate selection function. Though the selection function is somewhat ad hoc, and the assumption for an exponential disk for the carbon stars is unfounded, the resulting number count distribution function matches the observed distribution well. The correction was computed from the smooth distribution with $\Delta M = -\sigma^2 \, d \ln A/dm$ (Mihalas & Binney 1981), where ΔM is the correction to the carbon star mean absolute magnitude. It is less than ± 0.2 mag for most of the sample, but increases to 0.55 mag at $m_K = 7.3$. We calculated corrections based upon a wide variety of models and found that the derived mean velocity is insensitive to the model chosen. The most significant effect of using the various models is to change the mean distance to the stars, which affects the computed median distance of each quartile of our sample (see below). The effect is largest

TABLE 2

OTHER CARBON STAR VELOCITIES

Star[a]	JD −2,448,220	V_r
caa1	3.699	−29.1
caa2	3.693	−58.9
caa6	3.704	−58.5
caa14	3.709	−20.9
caa21	3.733	−92.7
caa24	3.718	−80.3
caa25	3.728	−55.9
caa36	3.746	−75.3
caa40	3.742	−74.9
caa41	4.698	−75.5
cab13	4.585	−31.9
cab20	4.589	−94.1
cab23	6.695	−122.4
cab30	4.619	−54.1
cad14	4.657	−24.5
cad15	4.653	−20.6
cep5	3.682	−115.7
cep9	6.556	−65.1
cya5	5.601	−71.4
cya6	5.589	−28.1
cya35	5.578	−47.9
cya52	5.572	−2.8
cyb18	5.619	−35.1
cyb26	5.625	−31.8
cyb36	5.647	−92.3
cyb40	5.635	−83.8
cyb69	3.634	−53.5
cyb75	3.639	−34.5
cyc26	5.552	−41.8
cyc28	3.644	−48.5
cyc38	5.548	−54.8
cyc40	3.651	−15.9
cyc41	5.557	−69.6
maa19	4.663	−45.3
maa20	4.668	−55.0
maa21	4.678	−92.0
maa22	4.688	−51.7
ms2	3.686	−21.2
ms64	4.576	−69.3
ms92	4.579	−60.3
ms120	4.624	−62.1
ms128	4.627	−68.0
ms145	4.633	−60.8
ms159	4.643	−60.1
nb246	6.552	−58.5

[a] Designation of Aaronson et al. 1990.

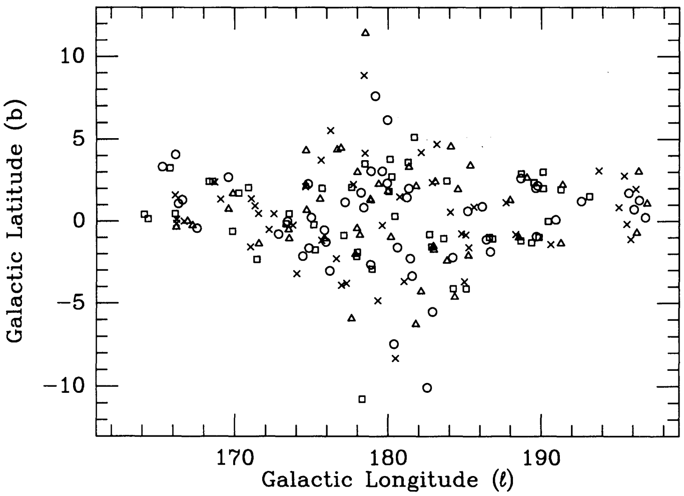

FIG. 2.—Positions of the Fuenmayor stars in Galactic latitude and longitude. Stars in the first through fourth quartiles in distance are shown by triangles, squares, circles, and crosses, respectively.

in the most distant quartile, and widely varying models produce differences of $\simeq 0.2 R_0$ for this quartile.

Figure 3 shows the derived galactocentric distances of the carbon star sample, plotted versus residual velocity from our rotation curve model. Galactocentric distance was computed assuming the unreddened K magnitude of an average carbon star at a distance of R_0, m_0, is 6.3 mag in a volume-limited sample. The residual velocity was computed by subtracting the velocity due to a flat, axisymmetric rotation curve with the standard values $\Theta_0 = 220$ km s^{-1} and $R_0 = 8.5$ kpc (Kerr & Lynden-Bell 1986). Also subtracted from this velocity is the Sun's motion peculiar to the LSR, using a value of 16.5 km s^{-1} in the direction $l = 53°$, $b = 25°$ (Delhaye 1965). Each star's model velocity is shown in the $V_{\rm model}$ column of Table 1. The mean residual velocity for our entire sample is 6.6 ± 1.7 km s^{-1}, in the sense that the carbon star and the LSR are moving apart. Dividing the sample at $l = 180°$, we obtain mean velocities of 8.5 ± 2.3 km s^{-1} for $l < 180°$ and 4.7 ± 2.5 km s^{-1} for $l > 180°$.

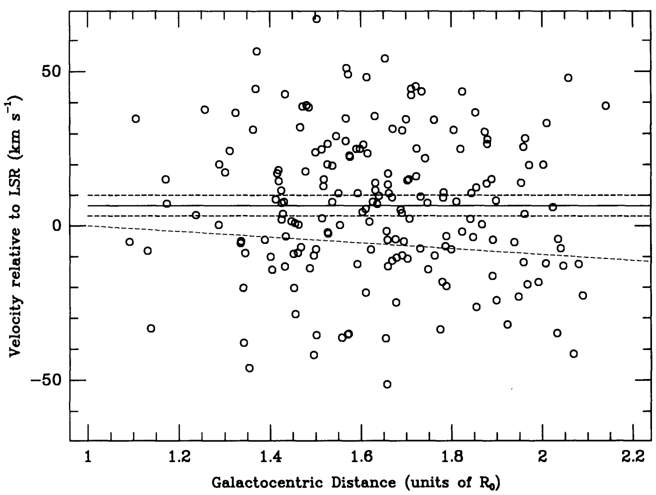

FIG. 3.—Residual velocities of the Fuenmayor carbon stars relative to the LSR after subtracting a flat, axisymmetric rotation curve model, plotted vs. computed distance. The solid line is the mean velocity of the sample, and the dashed lines are offset from this by 2 standard errors of the mean. The lower dashed line shows the mean predicted by the BS model.

Our estimate of the motion of the LSR is most sensitive to the radial component of the Sun's peculiar motion, −9 km s^{-1}. Fortunately, it is fairly well determined: many other estimates of this component agree with this value to within 1 km s^{-1} (Kuijken & Tremaine 1991). The distance errors to individual stars are estimated to be on the order of 50% (of the heliocentric distance, which in units of R_0 is $\simeq R - 1$), including the additional uncertainty in the extinction. The median galactocentric radius for the sample is $1.64 R_0$. No significant trend in mean velocity with distance is evident, and the distance quartiles have mean velocities of 5.2 ± 3.3, 11.2 ± 3.6, 6.5 ± 3.3, and 3.6 ± 3.3 km s^{-1}, at median distances of 1.40, 1.55, 1.70, and $1.92 R_0$, respectively.

We also were able to estimate the radial velocity dispersion, σ_R, using our sample. Since all but 13 of the stars have $|b| < 5°$, we take the observed velocity dispersion to be equal to σ_R. In the four distance quartiles described above, $\sigma_R = 22.5$, 24.8, 22.5, and 22.5 km s^{-1}, respectively, with an error of $\simeq 3$ km s^{-1}. The velocity dispersion for the entire sample is 23.1 km s^{-1}. While we can measure the dispersion in quartiles or as a gradient with distance, the distance associated with each bin is uncertain due largely to the uncertainty in the average extinction gradient for our sample. In addition, if the velocity dispersion σ_R has a significant gradient, as measured by Lewis & Freeman (1989), the scatter due to differential reddening and the intrinsic luminosity function of carbon stars would tend to obscure the gradient.

4. DISCUSSION

The mean velocity of the anticenter carbon stars is 6.6 ± 1.7 km s^{-1} away from the LSR, rather than 14 km s^{-1} toward the LSR as predicted by the BS model. The discrepancy is attributable to the apparent difference in the kinematics of the anticenter gas, upon which the BS model is based, and that of the carbon stars. Lewis & Freeman (1989) see a similar mean velocity in their K giant sample: 13.0 ± 4.2, 16.1 ± 4.6, and 5.7 ± 4.5 km s^{-1} at radii of 12.5, 14.8, and 17.7 kpc, respectively. This is also in the sense that their sample is moving away from the LSR and is roughly consistent with our carbon star velocities.

Another way to test the BS model is to look for asymmetry around $l = 180°$. The mean velocities of $l > 180°$ and $l < 180°$ sample subsets are consistent at the 1 σ level, and the difference between the two is in the opposite sense as one would expect from the BS model. The model predicts only a difference of ~ 2 km s^{-1}, however, so the test is inconclusive using our sample.

From the statistical error alone, the average velocity for the sample is nonzero at a 2 σ level. Can this be accounted for by a systematic error in measurement or analysis? One source of potential systematic error in our adoption of a zero point. We believe, however, that the Aaronson et al. zero point is good to better than 2 km s^{-1}, as their data were taken over a period of several years and corrections for varying zero point from year to year were smaller than this value. We investigated the possibility of systematic error from our choice of template by trying several other template spectra of varying signal level, noise level, and radial velocity. Though the noisier template produced larger scatter in velocity, as expected, no systematic errors were found, and the mean velocity difference was less than 0.5 km s^{-1} in each case.

Another source of systematic error may be that the optical radial velocity of the carbon star does not accurately measure its true center-of-mass velocity. Barnbaum (1992) found that a significant number of carbon stars in her sample had systematic differences between CO and optical velocities, in the sense that the optical velocities were redshifted relative to CO. She also found the presence of a systematic velocity deviation was correlated with variability class and the ratio of flux at 12 μm and 2 μm. Jura et al. (1989) report 2 μm fluxes from their K-band photometry and 12 μm fluxes from *IRAS* point source identifications. Fifty of our carbon stars have log (12 μm/2 μm) > -0.4, identifying them as having potential velocity offsets. This subset of stars has a mean residual velocity of 7.0 ± 3.2 km s^{-1}, and the remaining stars have a mean velocity of 6.5 ± 2.0 km s^{-1}. It is unclear why our sample does not show the effect seen by Barnbaum. Though we cannot rule out the possibility of an optical velocity offset, if present a correction would have to be larger by a factor of 2–3 than measured by Barnbaum to be consistent with the motion of the anticenter gas. Thus even in the presence of systematic errors we examined, we find a significant disagreement between the carbon stars and the anticenter gas, inconsistent with the BS model prediction.

Our measured dispersion agrees well with Lewis & Freeman's (1989) K giant sample. They measure $\sigma_R = 22.4 \pm 3.9$, 22.8 ± 3.3, and 12.7 ± 3.0 km s^{-1}, at galactocentric distances of 12.5, 14.8, and 17.7 kpc, respectively. The first two agree well with our measurement of $\sigma_R = 23$ km s^{-1}, though the third is significantly lower. Our most distant quartile corresponds to a median distance of 16.3 kpc, which while not as distant falls well within the distance error of Lewis & Freeman's 17.7 kpc bin. As discussed in § 3, our 16.3 kpc bin may be contaminated from stars of higher velocity dispersion scattering into the more distant bin, making the dispersion anomalously large. Monte Carlo estimates of this suggest that from our sample the error should be no larger than 5 km s^{-1} or so, though a few outliers make a good statistical estimate difficult. Even so, it would seem to suggest that Lewis & Freeman's well-measured dispersion gradient in the K giants, extending from 0.6 kpc to 18 kpc, may not hold in the carbon stars all the way out to $2R_0$.

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