MACHO PROJECT PHOTOMETRY OF RR LYRAE STARS IN THE SAGITTARIUS DWARF GALAXY

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ABSTRACT

We report the discovery of 30 type a, b RR Lyrae (RRab) stars that are likely members of the Sagittarius dwarf galaxy (Sgr). Accurate positions, periods, amplitudes, and magnitudes are presented. Their distances are determined with respect to RRab stars in the Galactic bulge found also in the MACHO 1993 data. For $R_\odot = 8$ kpc, the mean distance to these stars is $D = 22 \pm 1$ kpc, smaller than previous determinations for this galaxy. This indicates that Sgr has an elongated main body extending for more than 10 kpc, which is inclined along the line of sight, with its northern part (in Galactic coordinates) closer to us. The size and shape of Sgr give clues about the past history of this galaxy. If the shape of Sgr follows the direction of its orbit, the observed spatial orientation suggests that Sgr is moving away from the Galactic plane. Also, Sgr stars may be the sources of some of the microlensing events seen toward the bulge.

Subject headings: galaxies: distances and redshifts — galaxies: individual (Sgr) — galaxies: kinematics and dynamics — Galaxy: halo — Local Group — stars: variables: other (RR Lyrae)

1. INTRODUCTION

The dwarf galaxy Sgr was discovered by Ibata, Gilmore, & Irwin (1994) in the direction of the Galactic bulge. This is the closest dSph, located at about 25 kpc, and moving away from us at 160 km s$^{-1}$. The bulk of the stars in this galaxy are very old, 10$^{10}$ yr, with a range in metallicities of $[\text{Fe/H}] = -0.5$ to $-1.3$ (Mateo et al. 1995a, 1995b; Sarajedini & Layden 1995; Fahlman et al. 1996). Sgr is close to pericenter, and it is being torn apart by Galactic tidal forces, judging from its elongated appearance in the sky (Piatek & Pryor 1995; Velazquez & White 1995). Different numerical simulations aimed at tracing the past history of Sgr give density maps and velocity fields that agree with the available observations (Velazquez & White 1995; Johnston, Spergel, & Hernquist 1995). It has not yet been possible, however, to distinguish among a wide range of orbital parameters and models or to determine the direction of motion of Sgr (i.e., are we observing it pre- or postpericenter, and before or after crossing the Galactic plane?).

The MACHO project has identified more than 38,000 variable stars in the bulge fields from the 1993 data (Cook et al. 1995). Certain variable stars of different types (SX Phb stars, Cepheids, and W UMa, RR Lyrae, and Mira stars) are good distance indicators and can be used as probes to study the density of Sgr and of the different Galactic components along the line of sight toward the bulge. The RR Lyrae stars are by far the best distance indicators for an older population object like the Sgr dwarf galaxy (e.g., Nemec, Nemec, & Lutz 1994), and are the focus of the present study. Our goals are threefold: (1) to identify RRab stars in Sgr; (2) to determine their distance; and (3) to measure the shape, orientation, and total extension of this galaxy.

RR Lyrae stars belonging to Sgr were first discovered by Mateo et al. (1995a, 1995b) in a field centered in the galaxy, adjacent to the globular cluster M54, which is also associated with Sgr (Da Costa & Armandroff 1995). They determined the distance to Sgr, $(m - M)_0 = 17.02 \pm 0.19$, based on nine RR Lyrae stars. More recently, Alard (1996) found more than 300 RR Lyrae stars in a field located in the northern extension of Sgr (in Galactic coordinates), and Mateo et al. (1996) found three RR Lyrae stars in a field next to the globular cluster M55, in the southern extension of Sgr (in Galactic coordinates). The 1993 MACHO fields, located to the north of these previous studies (in Galactic coordinates), add new data, confirming the large extension of Sgr.

2. THE RRab SAMPLE

The system and data collection of the MACHO experiment are described by Alcock et al. (1996a). Here we consider only the first-year data acquired from 1993 February 27 to September 3. There are about 2300 images of 24 bulge fields, containing a total of 12.6 million stars. The photometric measurements are made with SODOPHOT, derived...
from DOPHOT (Schechter, Mateo, & Saha 1993). Light curves for stars identified as variable are phased in order to find periods (Cook et al. 1995). A typical two-color light curve has about 100 points.

The selection of the RRab sample is relatively simple. The variables in the MACHO 1993 data for which a period can be identified are plotted in an amplitude-period plane. RRab stars have periods in the range 0.3–0.8 days, and amplitudes in the range 0.1–1.2 mag. However, for periods smaller than 0.4 days there are larger numbers of RRc variables, with smaller amplitudes and typical light-curve shapes that make them difficult to discriminate from contact binaries. Therefore, our selection included periodic variables with amplitudes greater than 0.2 mag in the MACHO blue band (\(M_{\text{V}}\)), and periods within 0.4–0.7 days. The tighter cut in the amplitudes is imposed to secure good data. About 1700 stars are selected within these cuts. The \(M_{\text{V}}\) and \(V_{\text{MACHO}}\) light curves of all these candidates were inspected in both passbands to decide which ones are bona fide RR Lyrae stars (1173 stars in total). Of these, 44 are duplicates because they are found in the overlap region of MACHO fields. The other 600 stars are mostly contact binaries. Some period aliases are also rejected (see Alcock et al. 1996a). In summary, we have imposed stringent selection criteria that ensure good quality of the sample. The price paid is that the sample is not complete.

Most of the RRab stars in the final sample belong to the Galactic bulge. Their magnitudes peak at \(V \sim 16\), which places them at about 8 kpc. A few, however, are more than twice as far away (30 stars total). Not all of them can be halo RRab stars, according to current halo models (e.g., Saha 1985). These distant RRab’s belong to the Sgr galaxy. Table 1 lists the MACHO catalog of RRab’s in Sgr, containing 30 entries. This table is also available at the WWW address http://wwwmipw.asu.edu. We give the MACHO identification (field and location), the positions in equatorial and Galactic coordinates, the \(V_{\text{MACHO}}\) periods, the \(V_{\text{MACHO}}\) amplitudes, the \(\sigma_V\), the \(\chi^2\) of the light curves, the mean \(V\) and \(R\) magnitudes, and the reddening-independent \(W\) magnitudes (defined in § 4).

3. PHOTOMETRY

The photometric calibration of the large MACHO database is challenging. Only differential photometry is needed for a microlensing search, so individual field zero points and a transformation to the standard system are not priority tasks for the survey telescope. The nonstandard MACHO filters have been calibrated with standard Cousins photometry using Landolt standards transferred to LMC fields. We have used these calibrations in the present work. The \(V_{\text{MACHO}}\) and \(V_{\text{MACHO}}\) magnitudes are transformed to standard Cousins \(V\) and \(R\) magnitudes using the photometry of stars in common with Cook (1987) and Walker & Mack (1986) in Baade’s window (BW).

The 24 fields monitored have zero points that may differ at the 0.15 mag level at most. Cross checks were made with the RRab stars found in the overlapping regions, and with the OGLE data (\(V\) and \(I\) photometry) in BW. However, in order to avoid systematic effects, our analysis will be restricted to a differential approach (i.e., determining relative distances between the bulge and Sgr).

In the regions where two or more fields overlap, we identified a total of 44 bulge RRab stars with 0.4 < \(P\) < 0.7, where \(P\) is the pulsation period in days. Each photometric

### TABLE 1

| Field Location | R.A.(2000) | Decl.(2000) | \(l\) (deg) | \(b\) (deg) | \(P_{V_{\text{MACHO}}}\) | \(A_{V_{\text{MACHO}}}\) | \(\sigma_{V_{\text{MACHO}}}\) | \(\chi^2\) | \(V_{\text{MACHO}}\) | \(R_{\text{MACHO}}\) | \(W_{\text{MACHO}}\) |
|----------------|-----------|-------------|------------|------------|-----------------|----------------|-----------------|----------|----------------|----------------|----------------|

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
measurement is flagged for errors due to crowding, radiation blemishes, array defects, bad seeing, and edge effects. A few of the variables were not found in both overlapping fields (some were rejected a priori for being period aliases; others were not considered as variables, having fewer unflagged points). Using our internal redundancy, we estimate an upper limit of 93% for the completeness of our RRab sample within the period/amplitude cuts selected.

Using the 44 bulge RR Lyrae stars in overlap regions, we have evaluated the internal uncertainty in the photometry $(\sigma_{V_m}, \sigma_{R_m})$, astrometry $(\sigma_x, \sigma_y)$, period $(\sigma_P)$, and amplitude $(\sigma_{A_{V_m}}, \sigma_{A_{R_m}})$ determinations. We obtain the following errors: $\sigma_{V_m} = 0.120$, $\sigma_{R_m} = 0.114$, $\sigma_x = 0.58$, $\sigma_y = 0.37$, $\sigma_P = 0.000054$ days, $\sigma_{A_{V_m}} = 0.12$, and $\sigma_{A_{R_m}} = 0.06$.

The OGLE data in BW (Udalski et al. 1994) provide an independent check on the errors and completeness of our sample. The nine OGLE CCDs cover the same total area as MACHO field 119. In the overlapping field with OGLE, we find 44 RRab's within the same period range. Of these, 25 are in common, and the comparison yields $\Delta x = 0.16 \pm 0.54$, $\Delta y = 0.24 \pm 0.42$, and $\Delta P = 0 \pm 0.0005$ days, where $\Delta = $ MACHO minus OGLE. These values are consistent with the internal estimates obtained from the overlapping regions of the MACHO fields.

The field of Alard (1996) also overlaps with some of our fields. In this overlap region we find 11 RRab’s belonging to the Sgr dwarf, and six in common with Alard (1996). The differences between the samples are not surprising given the different selection criteria adopted. We emphasize that many of the stars that do not pass our initial periodic variable cuts will be recovered when the second- and third-year data are analyzed.

**4. REDDENING**

Figure 1 shows the color-magnitude diagram for all the RRab stars in the MACHO 1993 bulge sample, including RRab’s belonging to the Sgr dwarf galaxy. The appearance of this color-magnitude diagram is largely dominated by reddening. The direction of the reddening vector is indicated. The reddening is patchy in the MACHO fields toward the bulge, ranging from $E(B-V) = 0.2$ in the outer fields, to $E(B-V) \geq 2$ in the most obscured regions. We will then use reddening-independent magnitudes, defined as $W_r = V - 3.97 \times (V-R)$, that assume a standard extinction law for our comparison. These magnitudes are listed in the last column of Table 1. Note that in the most heavily reddened fields some of the faintest variables will be lost. Because we only reliably detect RRab stars that are brighter than $V \sim 19.5$, the distance to which we can detect RRab’s with $0.4 < P < 0.7$ and $A_V > 0.2$ mag depends on the reddening. Note that with the restriction to large amplitudes and RRab variables, the total range in $(V-R)$ should be very small. For $E(B-V) = 0.5$ (typical of the BW field), we would detect RRab’s located well beyond the known distance of Sgr.

In order to avoid the most heavily reddened regions (where $A_V/E_{B-V}$ may be significantly different from 3.1), the relative distances will be measured using only RRab stars with $V-R < 0.82$, and located in fields with $b < -4^\circ$.

**5. PERIODS**

There is a strong dependence of RRab period and luminosity on [Fe/H] (e.g., Sandage 1993a; Jones et al. 1992), in the sense that the more metal-poor RRab stars tend to have longer periods. The effect of metallicity in the period-amplitude plane is clearly illustrated by Figures 10–12 of Jones et al. (1992). There is also a period dependence on $T_{eff}$ (or color) (e.g., Sandage 1993b; Carney, Storm, & Jones 1992), which cannot be investigated with the present data owing to the effect of differential reddening.

These $P-L-Z$ relations have to be taken into account in determining relative distances. Therefore, the relative distance between the RRab stars in the bulge and in Sgr is computed here using only the RRab’s in the bulge covering the same period range as the Sgr RRab’s (i.e., 0.46 days $< P < 0.66$ days).

The bulge RRab stars have a mean $[Fe/H] = -1.0 \pm 0.16$ (Walker & Terndrup 1991). The observed periods listed in Table 1 support the conclusion that the Sgr RRab’s have longer mean periods, and are therefore more metal poor in the mean, than the Galactic RRab’s in these fields (Alard 1996). The period distribution in Sgr resembles that of the LMC, shown by Alcock et al. (1996a). Even though Sgr also has a metal-rich component (Sarajedini & Layden 1995), the bulk of the RR Lyrae stars in this galaxy must be produced by the metal-poor population with $[Fe/H] = -1.3$, as argued by Mateo et al. (1995a, 1995b). The probability of the formation of RR Lyrae stars in a metal-poor population is about a factor of 50 larger than in a metal-rich population (Suntzeff, Kinman, & Kraft 1991).

**6. THE STRUCTURE OF THE SAGITTARIUS DWARF GALAXY**

The distribution on the sky of the RRab stars is shown in Figure 2. Most of the Sgr RRab’s are located in the MACHO fields, which are well off the Galactic minor axis,
FIG. 2.—The 24 fields surveyed by MACHO in the first year of bulge observations. The location of the bulge and Sgr RRab’s are indicated with dots and filled circles, respectively. The position of the field observed by Alard (1996) is marked with the dotted line.

and in the lower latitude fields, with only a few of them in the fields closer to the Galactic center, including BW. The MACHO fields are located in the northernmost extension of Sgr (in Galactic coordinates), reaching 3° farther away from its center than the fields studied by Alard (1996), who found a declining number of RR Lyrae stars in that direction.

The outer contours of Sgr in the discovery paper by Ibata et al. (1994) cover about 10° along its major axis. However, this galaxy is much more extended. In retrospect, perhaps the earliest observational record of Sgr is the excess of blue stars at about $V = 18$ in the luminosity functions of Rodgers & Harding (1989) for a bulge field at $(l, b) = (10°, -22°)$. These stars with $V \approx 18$ and $0.3 < (B - V)_0 < 0.5$ would be horizontal-branch stars at the distance of Sgr. Rodgers, Harding, & Walker (1990) obtained radial velocities and calcium abundances for 18 stars within this color range. Two of these stars (Nos. 2730 and 3844) have heliocentric radial velocities consistent with Sgr membership ($V_{2730} = 162 \pm 38$ km s$^{-1}$, and $V_{3844} = 152 \pm 8$ km s$^{-1}$). Stars associated with Sgr have been found in two other fields next to that of Rodgers & Harding (1989): Mateo et al. (1996) discovered three RRab’s associated with Sgr in a field at $(l, b) = (8°8, -23°3)$, and Fahman et al. (1996) detected a sequence of Sgr stars in their color-magnitude distribution for a field at $(l, b) = (9°, -23°)$. The presence of Sgr RRab’s in the MACHO fields implies that the major axis of Sgr is at least 20° in size, while the minor-axis extension is at least 7° in size.

Figure 3 shows the distribution of distance moduli for RRab stars detected in the MACHO 1993 data. The highest peak, at $W_V = 14.6$, is due to the bulge RRab’s. The second peak, at $W_V = 16.8$, is real and is due to the Sgr members. Adopting $R_\odot = 8$ kpc (see the most recent determinations and discussion by Carney et al. 1995), the difference between these peaks, $\Delta m - M = 2.2 \pm 0.1$ mag, locates the Sgr dwarf at $D = 22 \pm 1$ kpc.

Previous distance estimates to Sgr are listed in Table 2. These mean distance determinations range from 24.0 to 27.6 kpc. The present distance $D = 22$ kpc marks the low end of this distribution. In particular, it is significantly different from the distances of three RRab stars ($D = 26.4, 27.4,$ and 28.2 kpc) on the opposite side of Sgr, measured by Mateo et al. (1996). We argue that the distance spread is real and is due to the fact that Sgr is inclined along the line of sight.

![Figure 3](image-url) — Magnitude distribution of the RRab stars with $0.46 < P < 0.66$, $b < -4°$, and $V - R < 0.8$ in the MACHO 1993 bulge data. The peaks correspond to the Galactic bulge at $D = 8$ kpc, and Sgr at $D = 22$ kpc.

| $l$ (deg) | $b$ (deg) | $m - M$ | $D$ (kpc) | Method | Reference |
|----------|-----------|---------|-----------|--------|-----------|
| 4.0      | -4.0      | 16.71   | 22.0 ± 1.0 | RRab   | MACHO ($R_{bulge} = 8$ kpc) |
| 4.0      | -8.0      | 16.90   | 24.0 ± 2.0 | RRab   | Alard 1996 |
| 5.6      | -14.1     | 16.99   | 25.0      | CMD    | Ibata et al. 1994 |
| 5.6      | -14.1     | 17.00   | 25.1 ± 4.0 | 4 globulars | Da Costa & Armandroff 1995 |
| 5.6      | -14.1     | 17.02   | 25.4 ± 1.0 | RHB-RGBC   | Sarajedini & Layden 1995 |
| 6.6      | -16.3     | 17.02   | 25.4 ± 2.4 | RRab   | Mateo et al. 1995a, 1995b |
| 8.8      | -23.3     | 17.18   | 27.3 ± 1.0 | RRab, CMD   | Mateo et al. 1996 |
| 9.0      | -23.0     | 17.20   | 27.6 ± 1.3 | CMD    | Fahman et al. 1996 |

TABLE 2

DISTANCE ESTIMATES FOR SAGITTARIUS DWARF GALAXY
This distance measurement is relative to the Galactic bulge, and is largely independent of the RRab absolute magnitude calibration. We have checked for a dependence of this distance on metallicity, by dividing the sample into metal-poor and metal-rich RRab stars using the period-amplitude diagram. Even though the Sgr sample is small, both longer period (metal-poor) and shorter period (metal-rich) RRab's yield similar results. Other effects such as a barred bulge or differential reddening would make the distance shorter.

The maximum difference in distances along the line of sight is found between the determinations of Mateo et al. (1996) and the present study. These are two of the most separated fields of Sgr studied so far, about 20° apart. The difference in distance moduli between these two independent determinations is \( \Delta(m - M) = 0.47 \) mag, larger than the estimated errors listed in Table 2. The distance of Mateo et al. (1996) is the mean of the distances of only three RRab's, but it is confirmed by deep color-magnitude diagrams that reach the turnoff of Sgr (Fahlman et al. 1996; Mateo et al. 1996), and therefore it cannot be in gross error. Fahlman et al. (1996) list a range of distances, from 26.3 to 28.9 kpc, depending on the parameters adopted for their main-sequence fit.

Sgr appears very elongated in the plane of the sky, with an axial ratio of 3/1 (Ibata et al. 1994). Two configurations can give rise to such a projected shape: a flat disk seen edge-on, or an intrinsic cigar shape. However, an edge-on disk is ruled out by our observations, since this geometry would yield similar distances at both extremes of the galaxy. Thus, Sgr has a cigar shape. Assuming axial symmetry, the line-of-sight depth of Sgr should be \(~4 \) kpc. This is consistent with the observed FWHM = 0.35 ± 0.05 of the magnitude distribution of RR Lyrae variables (this work; Alard 1996), again ruling out an edge-on disk with line-of-sight depth \(~10 \) kpc.

This elongated configuration is the predicted effect of a close encounter with the Milky Way, "as tidal effects string stars out along the orbit" (Velazquez & White 1995), and as "the sole effect of tides, as seen from our galaxy, is an elongation of the dSph in the orbital plane" (Piatek & Pryor 1995). Numerical simulations of Sgr's past history show that when the galaxy being disrupted is near pericenter, its major axis is approximately perpendicular to the direction of the Galactic center, i.e., parallel to its orbital motion. Taking into account the radial velocity \( V = +160 \) km s\(^{-1}\), assuming that the direction of the elongation traces Sgr's orbit, and projecting this as a straight line (first-order approximation), we find that pericenter occurred at a Galactocentric distance of \( R \approx 13 \) kpc, on the opposite side of the Galactic plane, at \( l, b \approx (0°, 12°) \). Then Sgr is presently moving away from the disk, having crossed the Galactic plane at a Galactocentric distance of about 14 kpc (equivalent to 3.5 Galactic scale lengths \( h_\odot \)).

With the measured radial velocity and projection angles of its tangential motion, the orbit of Sgr is determined. The present analysis agrees with the orbit computed by Velazquez & White (1995), having a transverse velocity of 255 km s\(^{-1}\) directed away from the Galactic plane, with pericenter and apocenter of 10 and 52 kpc, respectively, and orbital period of 0.76 Gyr. Better agreement is found with orbit 1 of Johnston et al. (1995), with 1.08 Gyr period, and pericenter and apocenter of 13.4 and 81.5 kpc, respectively. In this configuration, the globular clusters associated with Sgr (Da Costa & Armandroff 1995) would be leading the orbit.

However, further confirmation of the orbital direction will come with the measurement of accurate proper motions. Preliminary results from a proper-motion survey show that Sgr is moving toward the Galactic plane (Irwin et al. 1996). Assuming that the distances listed in Table 2 are correct, this would indicate that our main assumption that Sgr is elongated along its orbit may not be valid.

7. CONCLUSIONS

We have identified 30 RRab members of Sgr, located at the northern edge of this galaxy (in Galactic coordinates). Their positions, magnitudes, amplitudes and periods are listed in Table 1. The mean estimated distance to these stars is 22 kpc. This is significantly closer than previous distances measured in the center and southern side of Sgr (in Galactic coordinates), as summarized in Table 2. We conclude that Sgr is \(~10 \) kpc long, it has a cigar shape, and it is inclined along the line of sight, with its northern side (in Galactic coordinates) being closer. This information allows us to trace the orbit of Sgr and determine its previous history. Sgr is moving away from the Galactic plane, having passed pericenter, which is located in the opposite side of the plane. Its predicted orbit agrees with previous numerical simulations, although the precise orbit needs to be confirmed with accurate proper motions.

The present work is also another step toward the determination of the line-of-sight distribution of sources for observed microlensing events. In the case of the Sgr dwarf galaxy, its location at 22 kpc makes a very favorable configuration for microlensing by bulge objects at 8 kpc, and since the observed number of microlensing events is about 100, some of these source stars should be in Sgr. However, stars in Sgr cannot explain the high optical depth determined from clump giant sources (Alcock et al. 1996b).

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