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DISCOVERY OF A TIDAL EXTENSION OF THE SAGITTARIUS DWARF SPHEROIDAL GALAXY[1]

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ABSTRACT

We report the discovery of stars associated with the Sagittarius dwarf spheroidal galaxy (Sgr) located nearly 10° from the center of the main body of the galaxy, far beyond the outer boundary defined by the star counts of Ibata and coworkers. The newly discovered stars in Sgr include three RR Lyrae stars found serendipitously behind the Galactic globular cluster M55, red horizontal branch stars, and main-sequence stars identified both in the M55 field and in another field located away from this cluster but still about 10° from Sgr. The photometric properties of all of these stars are perfectly consistent with the previously determined distance, metallicity, and age of the Sgr galaxy. Our results indicate that Sgr is much larger than previously believed and that the stellar distribution in the outer parts of the galaxy is probably quite clumpy. We discuss the implications of our findings on the total luminosity and mass of Sgr and on the characteristics of its most recent past perigalacticon passages.

Subject headings: galaxies: individual (Sgr) — Galaxy: halo — Local Group — stars: individual (RR Lyrae)

1. INTRODUCTION

The recent discovery of the Sagittarius galaxy (Sgr) by Ibata, Gilmore, & Irwin (1994, hereafter IGI) provides a unique opportunity to study in detail the interaction of a dwarf galaxy as it passes very close to the Galactic center. Sgr is currently located 16 kpc from the center of the Milky Way (IGI; Mateo et al. 1995a, b; Sarajedini & Layden 1995) and shows strong evidence of tidal distortion. Sgr is by far the most elongated dwarf spheroidal (dSph) galaxy, and its clumpy internal structure is unlike any of the other dSph systems orbiting the Galaxy (Irwin & Hatzidimitriou 1993). These characteristics are broadly consistent with predictions from generic models describing the evolution of a small satellite galaxy as it interacts with a much more massive parent system (Allen & Richstone 1988; Moore & Davis 1994; Piatek & Pryor 1995; Oh, Lin, & Aarseth 1995). Some recent theoretical studies have focused on the detailed properties of the interaction between Sgr and the Milky Way (e.g., Johnston, Spergel, & Hernquist 1995; Lin et al. 1995; Velazquez & White 1995, hereafter VW).

One robust conclusion of all of these calculations is that tidal debris from Sgr will eventually be strung out along the galaxy's orbital path, both trailing *and* leading the main body of the galaxy (Moore & Davis 1994 explain this effect nicely). In this Letter we report the discovery of stars that we conclude are associated with such a "tidal tail" and located nearly 10° from the center of Sgr. These results demonstrate that Sgr is considerably more extended than previously believed, consistent with the idea that Sgr has probably suffered at least one—and perhaps many—strong tidal encounters with the Milky Way during past perigalacticon passages.

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2. RR LYRAE STARS BEHIND M55

As part of a long-term survey for photometric binaries in globular clusters (Mateo 1995), we obtained a series of V-band and I-band CCD images of the Galactic globular M55 using the Swope 1 m telescope at Las Campanas Observatory. Two different 2048 × 2048 CCDs were used for these observations. About 80% of the data were obtained using a thinned Tektronix CCD (0".59 pixel^{-1}); the remainder were obtained with a thick Loral CCD (0".43 pixel^{-1}). This study is based on the analysis of 76 CCD images obtained during 1993 May/June. A complete log of these data and other observations not discussed here will be presented in a later paper devoted to M55. The data were processed using twilight or dark-sky flats, and the stellar photometry was performed with the DoPHOT photometry program (Schechter, Mateo, & Saha 1993). The photometry described in this paper was calibrated in 1995 July during a run for the OGLE microlensing project (Udalski et al. 1992).

For typical 600 s exposures, the limiting magnitudes were $V \sim 20.0$ and $I \sim 20.5$ in the less crowded outer regions of the cluster. Our technique for searching for variable stars was identical to that described by Yan & Mateo (1994). We successfully identified RR Lyrae stars in M55 (some previously unknown) and some faint eclipsing binaries that are also likely members of the cluster. These stars are the subject of a future paper, but a brief summary of their properties is provided by Mateo & Mirabal (1995). We also discovered three faint variables of special interest. All three have well-determined periods ranging from 0.52 to 0.64 days. Based on their light curves and periods, we classify them as RR Lyrae variables. The mean V-band magnitudes of these stars are restricted to the very narrow range $V = 18.22$–18.36.

These variables are not members of M55. The RR Lyrae stars of the cluster are 3.5 mag brighter than the three fainter variables. Although located near the dwarf Cepheid instability strip in M55 (Mateo 1993), the three faint variables stars are *not* SX Phe stars. On two occasions we obtained continuous time-series data for more than 0.1 days; we can categorically state that all three stars have periods longer than this. All

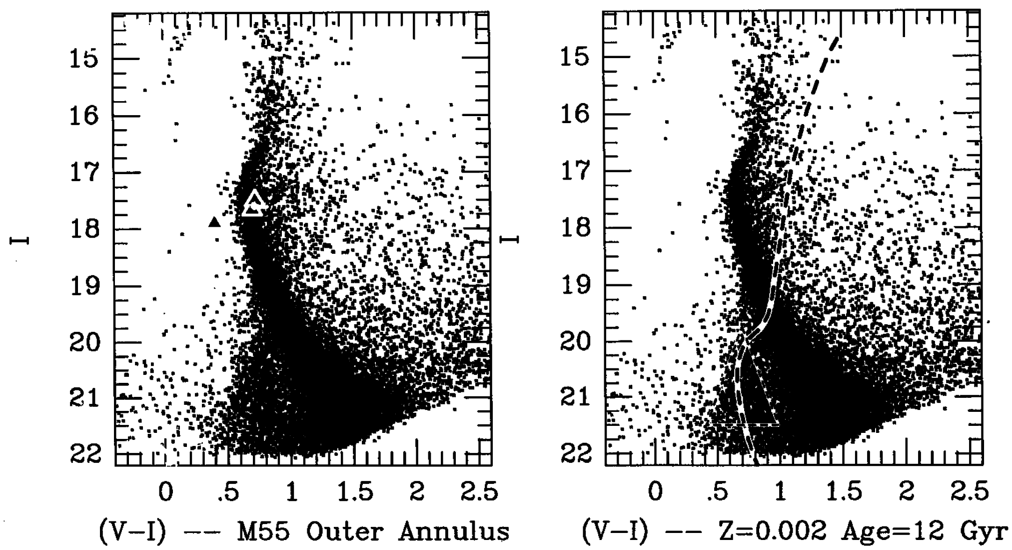

FIG. 1.—*Left*: A CM diagram of the M55 field. Only stars located ≥4′ from the cluster center are plotted. The triangles show the mean colors and magnitudes of the three newly discovered faint RR Lyrae stars in this field. Note the excess of stars blueward of the obvious M55 main sequence at I ≳ 20 and the subtle excess of stars just redward of the M55 main sequence at $I \sim 17.3$. *Right*: The same CM diagram, but now with the isochrone described in § 3 superimposed. The triangle shows the region of the CM diagram used to isolate upper–main sequence stars in Sgr for the star counts described in § 4.

known SX Phe stars have periods shorter than 0.08 days (Nemec, Nemec, & Lutz 1994).

We seem to have discovered three RR Lyrae stars *behind* M55 in a single 20′ × 20′ field. How unusual is this? M55 is located relatively close to the Galactic center: $(l, b) = 8^\circ\!.8$, $-23^\circ\!.3$. Adopting 8.5 kpc as the distance of the Sun to the Galactic center (R_0), we estimate that any bulge RR Lyrae stars along this line of sight would have $V \sim 15.3$, far brighter than the mean magnitude ($V \sim 18.3$) of the newly discovered variables. Interstellar extinction is low in this field and cannot possibly account for this difference (see below). We conclude that all three stars must be located well behind the Galactic bulge, somewhere in the halo. Saha (1985) determined the spatial density of halo RR Lyrae stars as a function of Galactocentric distance. Integrating his model along the line of sight toward M55 and again assuming $R_0 = 8.5$ kpc, we predict 0.3 halo RR Lyrae stars in the M55 field. A posteriori statistics are always suspicious, but we do seem to have found a significant excess of faint RR Lyrae variables in this field.

We can estimate the distances to the three faint RR Lyrae stars as follows. First, we assume $M_V = 0.8$. Second, we adopt $E(B-V) = 0.10$, consistent with the reddening for M55 (Lee 1977) and the Burstein & Heiles (1982) reddening maps. This value is also consistent with our preliminary determinations of the minimum-light $(V-I)$ colors of the RR Lyrae stars in the M55 field (see Mateo et al. 1995a for details). Finally, we adopt $E(V-I) = 1.24\ E(B-V)$, and $A_I = 1.5\ E(V-I)$ (Cardelli, Clayton, & Mathis 1989). The resulting distances of the three variables are 26.4, 27.4, and 28.2 kpc. The mild excess of RR Lyrae stars in *surface density* on the sky is now a striking enhancement in *space density*. From Saha's (1985) model, we would predict only 0.007 RR Lyrae stars in the distance range 26.4–28.2 kpc. Interestingly, the mean distance of the three newly discovered variables—27.3 ± 2.4 kpc—is very close to the distance found for the Sgr dwarf in previous studies (IGI; Mateo et al. 1995a, b; Sarajedini & Layden 1995). The colors, periods, and magnitude range of the newly discovered faint RR Lyrae stars are very similar to what is observed for Sgr RR Lyrae stars (Mateo et al. 1995a; Alard 1995).

3. SGR MAIN-SEQUENCE STARS BEHIND M55

If the distant RR Lyrae stars in the field of M55 are members of Sgr, we should see large numbers of main-sequence stars associated with these variables. We averaged our best-seeing Tek CCD images to produce deep V- and I-band images with effective exposure times of nearly 3 hr each. The data were then reduced using DoPHOT. The resulting "deep" color-magnitude (CM) diagram is shown in Figure 1. Although we have plotted only the photometry of stars located ≥4′ from the center of M55, the most prominent feature in Figure 1 is the cluster's main sequence. This is not surprising, since M55 was centered on these frames and its tidal radius, ∼19′, is much larger than the semidiameter of the CCD. Nevertheless, certain features visible in Figure 1 cannot be attributed to M55. The most obvious is the cloud of objects located blueward of the cluster's main sequence, fainter than $I \sim 20.0$. A more subtle anomaly is the slight excess of stars just redward of the top of M55's main sequence at $I \sim 17.3$ and $(V-I) = 0.9$.

The excess blue objects cannot be attributed to photometric errors. Relative to the number of M55 main-sequence stars, *fewer* of these blue stars are seen in the CM diagram of the inner part of the cluster, where the mean photometric errors are larger and the crowding is more severe. In addition, the color distribution across the CM diagram in the I-band magnitude interval 20–21 is bimodal; this can be perceived in Figure 1 as the slight "gap" at this magnitude range at $(V-I) \sim 0.9$. This odd distribution is quite unlike what is seen in good quality CCD photometry of a single main sequence (e.g., Walker 1994). These faint blue objects are also *not* galaxies. Deep galaxy counts do not reveal an excess of "blue" galaxies until $V \sim 23$ (Tyson 1988), 2.5 mags fainter than the sequence seen in Figure 1.

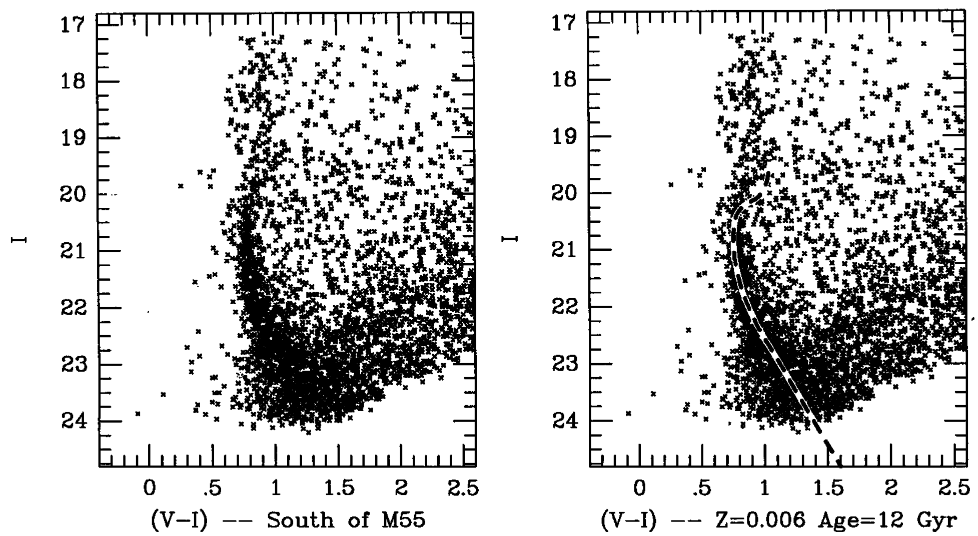

FIG. 2.—*Left*: A CM diagram of the stars in the M55-south field (located 1°.5 south of M55). The obvious sequence of stars corresponds to the main sequence in Sgr. *Right*: The same CM diagram, but now with the isochrone described in § 3 superimposed. This is also the same isochrone as the one shown in Fig. 1, but with a slightly larger adopted reddening.

We suggest that the excess of faint blue objects in Figure 1 are stars associated with the Sgr dwarf. The upper end of this distribution is located at $(I, V-I) \sim (20.0, 0.8)$, just where the upper end of the main-sequence turnoff is seen in Sgr (Mateo et al. 1995b). To underscore this point, we have superimposed a theoretical isochrone from VandenBerg (1985) on the data plotted in Figure 1. This isochrone corresponds to a population with an age of 12 Gyr, [Fe/H] = −0.5, and a distance of 25 kpc. As above, we adopt $E(V-I) = 0.12$. The upper portion of this curve ($I \lesssim 18$) is the fiducial giant branch of 47 Tuc (Da Costa & Armandroff 1990) shifted redward by 0.03 in $(V-I)$ to account for the metallicity difference between this cluster and the isochrone. The curve has not in any way been "fitted" to the data; rather, the parameters were chosen because they are appropriate for Sgr field stars (Mateo et al. 1995b; Sarajedini & Layden 1995). The subtle excess of stars found just redward of the M55 upper main sequence can now be understood as red-clump giants in Sgr (IGI; Mateo et al. 1995b; Sarajedini & Layden 1995), perfectly consistent with the locations of the newly discovered RR Lyrae variables in Figure 1.

To try to improve the visibility of putative Sgr stars in this part of the sky, we observed a "blank" field located 1°.5 south of M55 on 1995 July 31 with a thinned Tektronix 2048 × 2048 CCD on the 2.5 m DuPont telescope at Las Campanas. We shall refer to this as the M55-south field. The exposure times were about 1 hr in both V and I filters. The resulting CM diagram, which goes about 2 mag fainter than the 1 m data, is shown in Figure 2. The obvious sequence of objects visible in this diagram is not attributable to bulge main-sequence stars, which would be seen about 3 mag brighter, nor can they all be associated with the Galactic halo. Reid & Majewski (1993, hereafter RM) produced a deep photographic CM diagram of a bulge field that predicts eight halo stars in the interval $21 \geq I \geq 20$ and $(V-I) \leq 1.0$ [we converted the RM photometry to I, $(V-I)$ using the VandenBerg & Bell 1985 transformations]. This value rises to 24 after we correct for the different lines of sight in this paper and RM. We observe more than 160 stars in this region of the CM diagram, well in excess of the prediction for the halo.

We have superimposed the same isochrone shown in Figure 1 on the M55-south CM diagram (Fig. 2). Again, this is *not* a fit to the data but simply the result of adopting previously determined parameters for Sgr. The only difference from above is that we adopt $E(V-I) = 0.15$ for the M55-south field based on the Burstein & Heiles (1982) maps. We conclude that the prominent sequence of stars visible in Figure 2 corresponds to the upper main sequence of Sgr. A corollary of this is that the parameters adopted for the model shown in Figure 2 (age = 12 Gyr, [Fe/H] = −0.5, distance = 25 kpc) provide a reasonable description of the Sgr stars in the M55-south field. The ages and metallicities of stars in this field appear to be nearly identical to those in the "main body" of Sgr (Mateo et al. 1995b; Sarajedini & Layden 1995).

4. HOW BIG IS SGR AND HOW DID IT GET THAT WAY?

Our results show that Sgr is much larger than previously believed. The outer isopleths of IGI extend ~4° from the highest density region of Sgr (IGI). The two fields we have described in this paper are located 9°.7 from M54, the possible "nucleus" of Sgr (IGI; Da Costa & Armandroff 1995). We have estimated the stellar density of Sgr in our two fields by counting stars within the triangular region of the CM diagram shown in Figure 1, taking into account differences in extinction as needed. This selection preferentially chooses Sgr stars on the upper main sequence. For the M55 and M55-south fields, we find surface densities of 3.0 and 2.5 arcmin^{-2}, respectively. For the Sgr field studied by Mateo et al. (1995b), this procedure was used to derive a surface density of 16.6 arcmin^{-2}, 6 times higher than observed in the M55 and M55-south fields. This result implies that the corresponding surface density of the outermost isopleths of IGI is 2.8 arcmin^{-2}. Either the stellar surface density in Sgr is remarkably uniform—the densities at radial distances of 4° and 9°.7 are nearly identical—or the outer structure of Sgr is very clumpy. The latter conclusion is interesting because most tidal disruption models do not predict significant clumpiness as a satellite is torn apart (Piatek & Pryor 1995; Johnston et al.

1995; however, see VW for an apparent counterexample), yet obvious clumpiness is seen in the inner parts of Sgr (IGI).

The luminosity of Sgr can now be estimated as follows. We adopt the mean V-band surface brightness of the outer parts of Sgr to be $\Sigma_V = 27.3$, which equals $\frac{1}{6}$ the surface brightness of the field studied by Mateo et al. (1995b). If we also assume that the axis ratio of Sgr is 3.0 at all radii (IGI), and approximate the galaxy's structure as an ellipse, the total V-band magnitude of the outer parts of Sgr is 4.8. IGI's results imply that the main body of Sgr has $V = 4.3$ based on a comparison with the Fornax dSph galaxy; thus, $V_{\rm tot, Sgr} = 3.8$. For a true distance modulus of 17.0 (Mateo et al. 1995a), $M_{V,\rm Sgr} = -13.2$, very close to IGI's original estimate. Of course, the luminosity of Sgr may be higher if it is more extended, or lower if the outer structure is sufficiently clumpy. A comprehensive, deep photometric survey is needed to address these uncertainties. However, if we have identified the approximate full extent of Sgr, the galaxy is probably *not* much more massive than Fornax ($\sim 1 \times 10^8\ M_\odot$; Mateo et al. 1991). Thus, the Milky Way might strongly affect the structure of Sgr, but the opposite seens unlikely (Lin et al. 1995).

Given the similarities in the integrated magnitudes of Sgr and Fornax, their dissimilarities become more striking. Recent spectroscopic and photometric abundance estimates imply that the field population in Sgr may be considerably more metal rich than Fornax, perhaps by nearly an order of magnitude (Mateo et al. 1995b; Sarajedini & Layden 1995; Irwin et al. 1995). If confirmed, and if the total luminosity of Sgr is not too much larger than claimed above, Sgr would strongly violate the luminosity-metallicity relation observed for other dSph systems (Caldwell et al. 1992). Sgr is also physically very large compared with Fornax. The diameter of its major axis is about 8 kpc if its structure is roughly symmetric and its projected surface area is about 16 kpc^2. The corresponding numbers for Fornax are 3.4 kpc and 9 kpc^2, respectively. This reinforces a point made by Mateo et al. 1995b), who noted that the central surface brightness of Sgr is abnormally low for its luminosity (Caldwell et al. 1992). Sgr is literally dissolving into the Galactic halo as expected from its strong—and rather one-sided—tidal encounter with the Galaxy (Moore & Davis 1994; Johnston et al. 1995).

Other studies have recently revealed evidence that Sgr is very much more extended than reported by IGI. Alard (1995) finds large numbers of RR Lyrae stars 25 kpc away and located in a field on the opposite side of Sgr from M55. Irwin et al. (1995) have mapped Sgr giants out to M55 and slightly beyond, confirming the features inferred in this paper. Richer (1995, private communication) has detected Sgr main-sequence stars in deep photometry of a field located in M55. Finally, Da Costa & Armandroff (1995) confirm that four globulars are associated with Sgr (see also IGI). Three of these are located as far from the central regions of Sgr as the M55 fields studied in this paper. Taken together, these results suggest that Sgr is at least 20° long along its major axis!

We close by noting one interesting implication of the large angular extent of Sgr. The positive Galactocentric radial velocity of Sgr implies it has passed perigalacticon and is heading out toward apogalacticon. We assume that the most recent perigalactic passage occurred $\lesssim 10^8$ yrs ago and that the orbital period of Sgr is about 1 Gyr (VW). If Sgr began life as a twin of Fornax and if the distortions we now see in Sgr are the result of its last perigalacticon passage, the stars near M55 had to stream away from Sgr at a mean tangential velocity of $\gtrsim 25$ km s^{-1}. Some tidal streaming is expected in an encounter such as this (Piatek & Pryor 1995; Oh et al. 1995), but the typical streaming velocities are ≤ 10 km s^{-1} relative to the center of mass of a low-mass satellite. Streaming would reveal itself as a velocity gradient along the galaxy's major axis, although this is hard to disentangle from the purely geometric velocity gradient that results from the large angular size of Sgr. If these streaming motions were initiated *two* perigalacticon passages ago, the velocities would be much smaller—of order 3 km s^{-1}—and more consistent with model predictions. VW suggested on the basis of their theoretical study that the destruction of Sgr began during its penultimate perigalacton passage; our discovery of remote Sgr stars supports this conclusion.

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