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THE DETECTION OF A 45° TIDAL STREAM ASSOCIATED WITH THE GLOBULAR CLUSTER NGC 5466

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ABSTRACT

We report on the detection in Sloan Digital Sky Survey data of a 45° tidal stream of stars, extending from Bootes to Ursa Major, which we associate with the halo globular cluster NGC 5466. Using an optimal contrast, matched-filter technique, we find a long, almost linear stellar stream with an average width of 1°.4. The stream is an order of magnitude more tenuous than the stream associated with Palomar 5. The stream's orientation on the sky is consistent to a greater or lesser extent with existing proper-motion measurements for the cluster.

Subject headings: Galaxy: halo — Galaxy: structure — globular clusters: general — globular clusters: individual (NGC 5272, NGC 5466)

1. INTRODUCTION

Since the advent of large-scale, digital sky surveys, we have seen a remarkable increase in our ability to distinguish substructures in our Galaxy (Yanny et al. 2003; Majewski et al. 2003; Rocha-Pinto et al. 2004; Johnston et al. 2005). Among the first discoveries in the Sloan Digital Sky Survey (SDSS) data were the remarkably strong tidal tails of Palomar 5 (Odenkirchen et al. 2001; Rockosi et al. 2002; Odenkirchen et al. 2003), spanning over 10° on the sky. Tidal tails of globular clusters are particularly interesting from a dynamical standpoint as they are expected to be very cold (Combes et al. 1999). This makes them potentially useful for constraining not only the global mass distribution of the Galaxy but also its lumpiness (Murali & Dubinski 1999).

Globular cluster tidal tails were first discovered in a photographic survey of 12 southern halo clusters by Grillmair et al. (1995). Leon et al. (2000) and subsequent workers found similar evidence for tidal tails in over 30 other Galactic globular clusters. Once the characteristic, power-law departure at large radius from a King profile was recognized as a signature of unbound stars, evidence of tidal tails was detected in globular clusters as far away as the halo of M31 (Grillmair et al. 1996).

NGC 5466 is an interesting globular cluster in many respects. It has a blue horizontal branch and a large, centrally concentrated distribution of blue stragglers (Nemec & Harris 1987). On the other hand, like Pal 5, NGC 5466 is a low-metallicity ([Fe/H] $= -2.22$), low-mass, and low-concentration cluster. Pryor et al. (1991) determined a very low $(M/L_V)_0 = 1 \pm 0.4$ for this cluster and suggested that it must have lost a significant fraction of its low-mass stars. Combining these factors with NGC 5466's putative orbit, Gnedin & Ostriker (1997) ranked it among globular clusters most likely to have suffered substantial tidal stripping over time. Evidence for the existence of unbound stars around NGC 5466 was first presented by Lehmann & Scholtz (1997). Odenkirchen & Grebel (2004) examined the spatial distribution of cluster member candidates within a degree of NGC 5466 using APM data. Most recently, Belokurov et al. (2005) used SDSS photometry to discover a tidal stream extending 2° from NGC 5466 on either side.

In this Letter we examine a much larger region of the SDSS to search for tidal streams associated with both NGC 5466 and NGC 5272. We briefly describe our analysis in § 2. We discuss our findings for both NGC 5466 and NGC 5272 in § 3, and make concluding remarks in § 4.

2. DATA ANALYSIS

Data comprising u', g', r', i', and z' measurements and their errors for 9.7×10^6 stars in the region $170° <$ R.A. $< 230°$ and $19° < \delta < 51°$ were extracted from the SDSS database using the SDSS CasJobs query system. The data were analyzed using the matched-filter technique described by Rockosi et al. (2002), and the reader is referred to this paper for a complete description of the method. Briefly, we constructed an observed color-magnitude density or Hess diagram for NGC 5466 using stars within 9′ of the cluster center. A star count weighting function was created by dividing this color-magnitude distribution function by a similarly binned color-magnitude distribution of the field stars. The Hess diagram for field stars was created using all stars in rectangular regions to the east and west of NGC 5466, each region subtending ∼150 deg^2. The weighting function was then used on all stars in the field, and the weighted star counts were summed by location in a two-dimensional array.

We used all stars with $16 < g' < 22$. As NGC 5466 has $l = 42°$, $b = 73°$, reddening is not expected to be a significant problem. Nonetheless, variations in foreground reddening across a large field could introduce corresponding variations in sample completeness and possibly spurious structures. We therefore dereddened the SDSS photometry as a function of position on the sky using the DIRBE/*IRAS* dust maps of Schlegel et al. (1998). The applied values of $E(B-V)$ ranged from 0.006 to 0.06 over a field area of 1446 deg^2.

We optimally filtered the $g' - r'$ and $g' - i'$ star counts independently as a consistency check. The $u' - g'$ and $g' - z'$ data were found to be too noisy to contribute significantly to the final signal-to-noise ratio. As expected, the highest filter weight is given to turnoff and horizontal-branch stars, as these populations lie blueward of the vast majority of field stars. However, main-sequence stars contribute significantly by virtue of their much larger numbers.

In Figure 1 we show the final, filtered star count distribution, created by co-adding the weight images generated independently for the $g' - r'$ and $g' - i'$ color pairs. The image has

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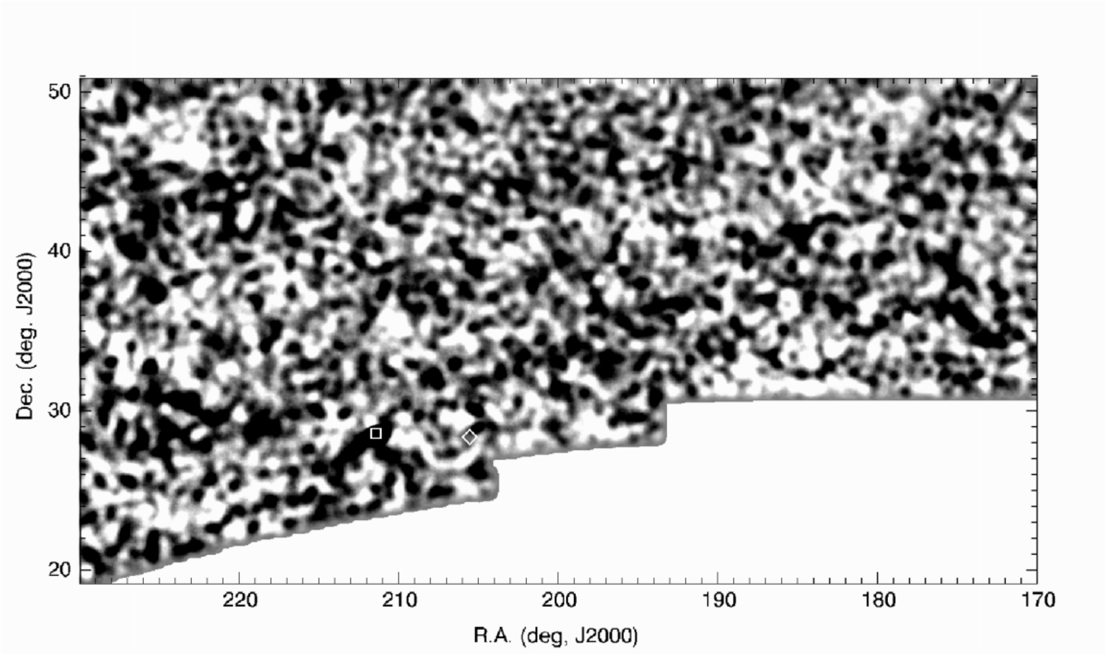

FIG. 1.—Smoothed, summed weight image of the SDSS field after subtraction of a low-order surface fit. Darker areas indicate higher surface densities. The image is the sum of weight images generated independently using the $g' - r'$ and $g' - i'$ color pairs. NGC 5466 is indicated by the open square at R.A., decl. = (211.36, +28.54), while the location of NGC 5272 (R.A., decl. = 205.55, +28.38) is shown by the open diamond. The weight image has been smoothed with a Gaussian kernel of full width 1°. The irregular southern border is defined by the limits of SDSS DR4. The faint, parallel features in the northeastern corner trace the edges of individual SDSS scans and are presumably due to variations in sensitivity and completeness at faint magnitude levels. The putative tidal stream of NGC 5466 extends from the southeastern corner of the image to roughly R.A., decl. = (180, 42).

been smoothed with a Gaussian kernel of full width $\sigma = 1°$. A low-order, polynomial surface was fitted and subtracted from the image to remove large-scale gradients due to the Galactic disk and bulge. We note that there are discernible features running parallel to the SDSS scan directions (or "stripes"), particularly in the northeastern quadrant. These are artifacts introduced by variations in seeing and transparency from one stripe to the next. If we limit our analysis to stars brighter than $g' = 20$, these features largely disappear. However, to improve our signal-to-noise ratio, we maintain a faint magnitude cutoff of $g' = 22$ and disregard features that mimic the scan pattern of the survey.

3. DISCUSSION

Extending ∼3° to the southeast of the NGC 5466 and 2° to the northwest are fairly strong concentrations of stars that are obviously connected to the cluster. These are the features recently reported by Belokurov et al. (2005). Although these tidal arms show little evidence of the S shape characteristic of weak tidal stripping, this would be consistent with our current viewing location very nearly in the plane of NGC 5466's orbit. Extending ∼15° from NGC 5466 toward the southeast and ∼30° to the northwest is an almost linear feature that cuts across several scan stripes. The feature is 1°–2° wide along most of its discernible length. This width is similar to that observed in the tidal tails of Pal 5 and in agreement with the expectation that stars stripped from globular clusters should have a very low velocity dispersion. The stream is not associated with the Sagittarius dwarf debris stream, which runs roughly parallel to the current feature but is much broader and lies 20° to the south of the field shown in Figure 1.

The stream is not a product of our dereddening procedure; careful examination of the reddening map of Schlegel et al. (1998) shows no correlation between this feature and the applied reddening corrections. To be certain, we reran our matched-filter analysis using the original data uncorrected for reddening. Although less strong, the feature in Figure 1 remains quite apparent.

The stream is also not due to confusion between galaxies and stars at faint magnitudes. We have filtered the SDSS Galaxy catalog over the same field area in a manner identical to that used for objects classified as stars. There is indeed evidence of confusion in that there is an obvious concentration of "galaxies" within a few arcminutes of the center of NGC 5466. However, there is no concentration of galaxies coincident with the extended feature in Figure 1.

At its southeastern end, the stream appears to be truncated by the limits of the available data. On the northwestern end, the stream becomes indiscernible westward of R.A. = 180°. Based on the proper motion (Odenkirchen et al. 1997) and assumed orbit of the cluster (see below), the northwestern end of the current tidal stream should be roughly a factor of 2 farther away from us than the cluster itself. In an attempt to trace the stream still farther westward, we reapplied the matched filter after shifting the NGC 5466 color-magnitude sequence fainter by 1.5 mag. However, no evidence for a continuing stream could be detected using the present analysis. While it is conceivable that we are seeing the physical end of the stream (and therefore the very first stars to be stripped from NGC 5466), it seems more likely that our failure to trace the stream any farther simply reflects increasing contamination by field stars at fainter magnitudes and the reduced power of the optimal filter.

In Figure 2 we show the locations of ∼150 stars with colors and magnitudes that would put them on the blue end ($g' - r' < 0$) of NGC 5466's horizontal branch. While the statistics

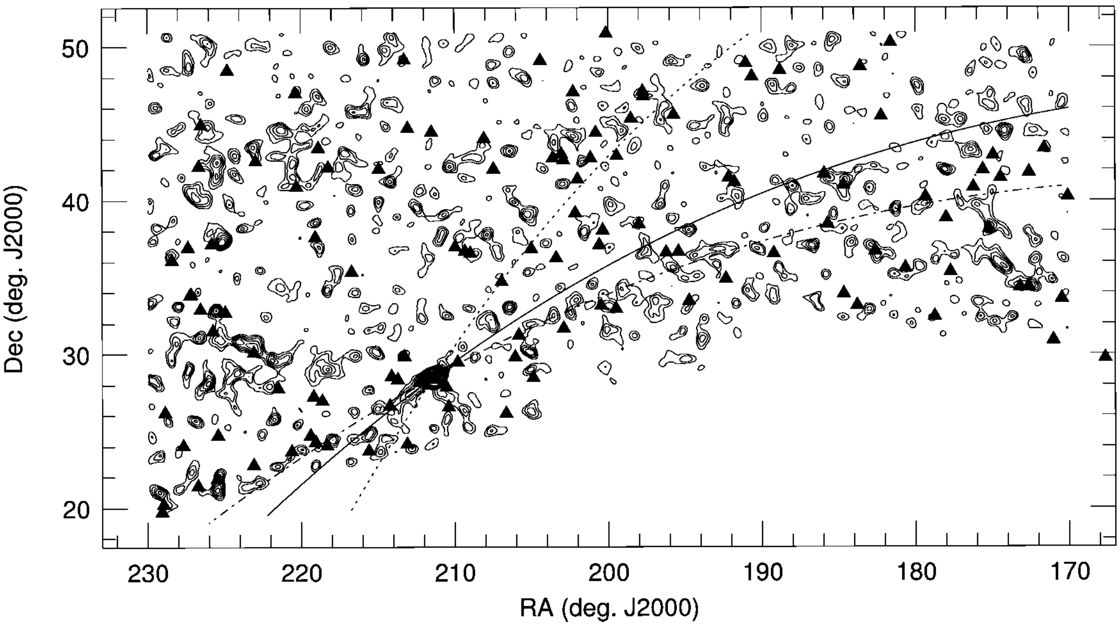

FIG. 2.—Orbit integrations for NGC 5466. Contours are taken from the weight image in Fig. 1 and represent the 2, 3, 4, …, n σ levels. The solid line shows an orbit projection based on proper-motion measurements of Brosche et al. (1991), and the dotted line shows a similar projection using the *Hipparcos*-derived proper motion (Odenkirchen et al. 1997). The dash-dotted line uses $(U, V, W) = (290, -240, 225)$ km s^{-1}. The filled triangles show the locations of stars with colors and magnitudes consistent with those of the bluest horizontal-branch stars in NGC 5466.

are small and while there are interesting groupings here and there across the field, these blue stars show a marked tendency to lie along the tidal stream. Measuring over a radius range of 1°–16° from the cluster, these horizontal-branch stars are between 2 and 3 times more likely to be found within 1°.5 of the center of the tidal stream.

There are seven lines of reasoning that indicate that the feature in Figure 1 is indeed a tidal stream associated with NGC 5466. (1) We know from the work of Belokurov et al. (2005) that NGC 5466 possesses tidal tails extending at least 4° on the sky. (2) Our optimal filter technique recovers the strong, 2° tidal tails found by Belokurov et al. (2005). (3) The projection of the 45°-long feature passes within 30′ of the center of NGC 5466. (4) The feature disappears if the Hess diagrams used to create the matched filters are shifted either blueward or redward of the observed color-magnitude sequence of NGC 5466. (5) The apparent width of the feature is in accord with expectations for globular cluster tidal tails (e.g., Pal 5). (6) Although much noisier, the distribution of candidate horizontal-branch stars also shows a tendency to concentrate along the stream defined by main-sequence/red giant branch (RGB) stars. (7) Given the expectation that the stream traces the orbital path of the cluster, its orientation is consistent with the previously derived space motion of the cluster (see below).

Integrating the weighted star counts along each stream over a width of 1°.4 and beyond 2° from NGC 5466 itself, we find the total number of stars in the discernible streams to be 607 ± 50. Based on a comparison between the observed SDSS luminosity function of NGC 5466 (measured outside the saturated central region) and that of other well-studied globulars, we estimate that between two-thirds and three-quarters of the cluster stars are missing from the SDSS field sample due to incompleteness at $g' > 21$. The apparent stream must therefore contain at least $\sim 2 \times 10^3$ main-sequence stars. If the leading and trailing arms are assumed to be symmetric, then we might expect another thousand stars in the region not covered by the SDSS Data Release 4 (DR4). In total, this represents only about 3% of the current mass of the cluster. However, if the luminosity function of the tails is heavily biased toward low mass (i.e., the missing low-mass stars postulated by Pryor et al. 1991), then both the number of stars and the cluster mass fraction resident in the tidal tails may be much higher.

The surface density of stars fluctuates considerably along each stream. For stars with $g' < 22$, the average surface density is 10 ± 2 stars deg^{-2}, with several peaks along the streams ranging from 20 to over 30 stars deg^{-2}. This may be compared with a total surface density of 7600 field stars deg^{-2} for all stars with $g' < 22$ and illustrates the remarkable power of matched filtering. The tidal tails of NGC 5466 are evidently much more tenuous than those of Pal 5, for which Odenkirchen et al. (2003) found surface densities typically in excess of 100 stars deg^{-2}. However, the relative magnitudes of the surface density fluctuations along the length of the stream are quite similar.

3.1. *On the Orbit of NGC 5466*

Assuming globular cluster tidal streams follow the orbits of their parent clusters (Odenkirchen et al. 2003), we can use the observed orientation of the newly discovered stream to better constrain the orbit of NGC 5466. We use the Galactic model of Allen & Santillan (1991) for orbit integration. Using the Lick-based proper-motion measurements of Brosche et al. (1991), we find a projected orbit as shown by the solid line in Figure 2. Using the Odenkirchen et al. (1997) *Hipparcos*-derived proper motions, we find the orbit projection shown by the dotted line. The uncertainties on the two measurements are similar, and the plate-based measurements are in agreement with *Hipparcos* measurements at the ≈ 1.5 σ level. The orbit projections diverge from one another by $\approx 20°$, and the tidal stream clearly favors the ground-based proper-motion measurement.

Even using the Brosche et al. (1991) proper-motion measurement, the match between the projected orbit and the tidal stream is not completely satisfactory. The northwestern stream does not lie perfectly along any computed orbit and, indeed, appears to depart in places from a smooth curve. This is due in part to small number statistics but could also be due to (1) irregularities in the potential of the Galactic halo, (2) a recent weak encounter between stream stars and a substantial mass concentration in the disk (e.g., a large molecular cloud), or (3) confusion. If we ignore the apparent enhancements westward of R.A. $= 190°$, the stream becomes somewhat less meandering and more closely resembles the computed orbits. If we set $(U, V, W) = (290, -240, 225$ km s$^{-1})$, we arrive at the dash-dotted line in Figure 2. Since our vantage point is very nearly within the plane of NGC 5466's orbit, we would not expect to see a significant offset between the computed orbit and the leading and trailing tails. The U, V, W velocities required to match the stream depart from the proper-motion measurement of Brosche et al. (1991) at the 0.5 σ level, and from the *Hipparcos* measurement at the 2.2 σ level.

All reasonable orbits predict a total length of $\simeq$15 kpc for the northwestern arm, and $\simeq$5 kpc for the southeastern. At the end of the northwestern arm, the orbital path is inclined to our line of sight by some 35°.

3.2. *NGC 5272*

Similar matched filtering procedures were applied to the present data set to search for tidal streams associated with NGC 5272. Based on a color-magnitude sequence that has a somewhat bluer RGB and a brighter turnoff than that of NGC 5466, we expected to be considerably more sensitive to any tidal streams associated with this cluster. However, no evidence for tidal streams could be found. This is in qualitative agreement with the results of Gnedin & Ostriker (1997), who estimated a probability of disruption for NGC 5272 roughly 60 times lower than that for NGC 5466.

4. CONCLUSIONS

Applying optimal contrast filtering techniques to SDSS data, we have detected a tenuous stream of stars roughly 45° long on the sky. Based on several pieces of evidence, we associate this stream with the halo globular cluster NGC 5466.

Verification of the stream and its association with NGC 5466 will require radial velocity measurements of individual stars along its length. Based purely on SDSS colors, there are $\sim$350 candidate stream stars along the length of the tail with $g' < 19.2$ (i.e., above the subgiant branch). Of these, we expect $\sim$20 stars to be bona fide orphans of NGC 5466. Once vetted, these stars will become prime targets for the *Space Interferometry Mission*, whose proper-motion measurements will enable very much stronger constraints to be placed on both the orbit of the cluster and the potential field of the Galaxy.

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Facilities: Sloan

[2] The SDSS Web site is http://www.sdss.org/.

REFERENCES

Allen, C., & Santillan, A. 1991, Rev. Mex. AA, 22, 255
Belokurov, V., Evans, N. W., Irwin, M. J., Hewett, P. C., & Wilkinson, M. I. 2005, preprint
Brosche, P., Tucholke, H.-J., Klemola, A. R., Ninkovic, S., Geffert, M., & Doerenkamp, P. 1991, AJ, 102, 2022
Combes, F., Leon, S., & Meylan, G. 1999, A&A, 352, 149
Gnedin, O. Y., & Ostriker, J. P. 1997, ApJ, 474, 223
Grillmair, C. J., Ajhar, E., Faber, S. M., Baum, W. A., Lauer, T. R., Lynds, C. R., & O'Neil, E., Jr. 1996, AJ, 111, 2293
Grillmair, C. J., Freeman, K. C., Irwin, M., & Quinn, P. J. 1995, AJ, 109, 2553
Johnston, K. V., Law, D. R., & Majewski, S. R. 2005, ApJ, 619, 800
Lehmann, I., & Scholtz, R. D. 1997, A&A, 320, 776
Leon, S., Meylan, G., & Combes, F. 2000, A&A, 359, 907
Majewski, S. R., Skrutskie, M. F., Weinberg, M. D., & Ostheimer, J. C. 2003, ApJ, 599, 1082
Murali, C., & Dubinski, J. 1999, AJ, 118, 911
Nemec, J. M., & Harris, H. C. 1987, ApJ, 316, 172
Odenkirchen, M., Brosche, P., Geffert, M., & Tucholke, H.-J. 1997, NewA, 2, 477
Odenkirchen, M., & Grebel, E. K. 2004, in ASP Conf. Ser. 327, Satellites and Tidal Streams, ed. F. Prada, D. Martinez Delgado, & T. J. Mahoney (San Francisco: ASP), 284
Odenkirchen, M., et al. 2001, ApJ, 548, L165
———. 2003, AJ, 126, 2385
Pryor, C., McClure, R. D., Fletcher, J. M., & Hesser, J. E. 1991, AJ, 102, 1026
Rocha-Pinto, H. J., Majewski, S. R., Skrutskie, M. F., Crane, J. D., & Patterson, R. J. 2004, ApJ, 615, 732
Rockosi, C. M., et al. 2002, AJ, 124, 349
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Yanny, B., et al. 2003, ApJ, 588, 824