Halo Substructure in the QUEST RR Lyrae Survey

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**Abstract.** A survey of 380 sq. deg. of the sky with the 1m Schmidt telescope at the Observatorio Nacional de Llano del Hato and the QUEST camera has found 498 RR Lyrae variables lying from 4 to 60 kpc from the Sun. We describe the halo substructure revealed by these data and the results of measuring some of the stars' radial velocities and metal abundances.

1. Introduction

Recent surveys of the galactic halo have shown that it does not have smooth density contours but a wealth of substructure in the forms of stellar streams and clumps. Several of these over-densities are unambiguously the result of the merger of one or more satellite galaxies with the Milky Way. While the best example of this is the Sgr dSph galaxy and its tidal streams, evidence is accumulating for another merger event that produced large stellar streams that wrap around the sky (Newberg et al. 2002; Yanny et al. 2003; Ibata et al. 2003; Majewski et al. 2003).

These discoveries confirm that the halo of the Milky Way was built up over time by the accretion of smaller systems, as has been suspected for decades from the range in age among halo globular clusters and stars and from the lack of a halo metallicity gradient (see review by Freeman & Bland-Hawthorn 2002). While it is no surprise that mergers happened, the huge tidal streams that have been revealed by the surveys are nonetheless remarkable. Once more of the sky has been surveyed, it may be possible to piece together the merger history of the Milky Way and thereby document the growth of hierarchical structure in the...
Figure 1. The narrow stripe, which is 2.3° wide, is the region covered by the QUEST RR Lyrae survey

local universe. The significance that these results would have for cosmological models is discussed elsewhere in these proceedings.

We discuss the major results of a survey for RR Lyrae variables in the galactic halo. Because RR Lyrae variables are easily recognized by their characteristic light curves and periods, and because they are excellent standard candles, they have been frequently used in the past to map the structure of the halo. The primary difference between our survey and previous ones is that modern technology has permitted us to survey a larger area of the sky and to greater limiting magnitude. The halo substructure that we discuss here could have been discovered long ago if for example the Lick RR Lyrae survey (Kinman et al. 1982 & references therein) had reached ~ 2 mag. fainter.

2. The QUEST RR Lyrae Survey

The QUEST survey for RR Lyrae variables was begun in 1998 as an offshoot of a larger survey for quasars (QUEST = quasar equatorial survey team) that was being conducted with the same instruments, the 1m Schmidt telescope at the Observatorio Nacional de Llano del Hato in Venezuela and a large format CCD camera (Baltay et al. 2002). The major goals of the survey were to search a large area of the sky for RR Lyrae variables and to use these stars to map the substructure, if any, in the halo. Although the Sgr dSph galaxy had been discovered prior to the beginning of the survey, it was not clear whether the accretion of satellite galaxies were infrequent events in the evolution of large galaxies like the Milky Way or was the major process that built their halos. The
survey of the first area of the sky was completed in 2002 (Vivas 2002; Vivas et al. 2001, 2003) and is discussed here. The survey of a second, larger area is nearing completion.

The observations for the survey consisted of long drift scans of the sky that were typically several hours long in right ascension (RA) and 2.3° wide in declination (DEC), centered at $DEC = -1^\circ$. A total of 380 sq. deg. of the sky were covered by the survey. Figure 1 shows the galactic coordinates of the survey, which purposely skipped the region below 10° in latitude, because of its large and variable interstellar extinction and its high density of star images.

Observations in several different filters were obtained depending on the multiple purposes of the data set, but always included the V filter. Along each line of sight of the survey, from 15 to 40 V observations at intervals ranging from one day to several months were obtained. These observations have a saturation limit near $V = 13$ and a detection limit near $V = 19.7$. For RR Lyrae variables, these limits correspond to distances of $\sim 4$ to $\sim 60$ kpc from the Sun. The V observations were used to detect the variable stars and to determine the periods and light curves of the RR Lyrae variables. $V - R$ was used to isolate candidate RR Lyrae variables by color. The huge amount of data gathered for this survey required that many of the data reduction steps had to be automated, including the astrometry and the aperture photometry. However, the final classification of a star as a RR Lyrae variable and the selection of its most likely period was done by examining by eye the light curves produced by the three most probable periods. A few sample light curves are displayed in Vivas et al. (2001). Experiments with artificial variables indicate that the survey is $> 80\%$ complete for type ab RR Lyrae variables and $40 - 60\%$ complete for the lower amplitude type c variables (Vivas et al. 2003). A total of 498 RR Lyrae variables were catalogued in the survey region; $> 86\%$ of them are new discoveries.

In the following discussion, the mean apparent magnitudes of the variables, corrected for the interstellar extinction ($V_o$), are used to gauge their positions along the lines of sight. It should be kept in mind, however, that RR Lyrae variables are not perfect standard candles and that the combination of the stellar evolution from the zero age horizontal branch and the metallicity spread in the halo produces a one-sigma dispersion of $\sim 0.13$ in absolute $V$ magnitude (Vivas et al. 2001). Only on the smallest scales does this dispersion, which is small compared to the ones for other halo tracers, have a significant effect on the spatial distributions inferred from $V_o$.

3. Halo Substructure

In Figure 2, the $V_o$ of the RR Lyrae variables in the major strip of the survey at northern galactic latitudes (see Fig. 1) are plotted against their RA positions. The right-hand axis gives the distances from the Sun, assuming $M_V = +0.55$. There are many small clusterings in this diagram, which may be small groups of variables that have a common origin or, more likely, a consequence of the random fluctuations in the density distribution. We are obtaining spectroscopy of the densest ones to see if some of the stars have similar radial velocities. Three larger features, which are labelled, have high statistical significance, and are discussed in more detail below.
3.1. Sgr Stream

The large over-density of RR Lyrae variables at $V_o \sim 19.2$ and between $RA \sim 200^\circ$ and $230^\circ$ is undoubtedly part of the tidal stream of stars from the Sgr dSph galaxy, which was discovered in this region of the sky (Ivezić et al. 2000; Yanny et al. 2000) prior to the completion of our survey. Since the paper by Vivas et al. in this volume describes this feature and our spectroscopic observations of its stars, it will not be discussed in detail here.

3.2. The $12^h4$ Clump

Near the center of Figure 2, there is a feature that spans roughly $25^\circ$ in $RA$ near $186^\circ$ ($12^h4$) and between $\sim 16.5$ and $17.5$ in $V_o$. The reality of this feature is more obvious from the plots in Figure 3 which show for three $25^\circ$ wide bands in $RA$, which are at high galactic latitudes, the numbers of stars in bins of $V_o$. The most striking feature in Figure 3 is the Sgr Stream which spans the $RA = 200 - 225^\circ$ zone and extends into the $175 - 200^\circ$ zone. From $16.5$ to $17.5$ in $V_o$, there are $35$ variables in the $175 - 200^\circ$ zone, but only $14$ and $10$ in the $150 - 175^\circ$ and $200 - 225^\circ$ zones, respectively. This feature of halo substructure was first recognized in our data for $RA > 195^\circ$ (Vivas et al. 2001) and confirmed later in the Sloan Digital Sky Survey (SDSS) for main-sequence turnoff stars (Newberg et al. 2002), where it is referred to as the feature S297+63-20.0.

This feature may be part of the Sgr stream (Majewski et al. 2003), in which case we expect it be similar in metallicity to the other part of the stream we have observed (Vivas et al. this volume) and to have a radial velocity distribution.
that is consistent with models of the stream. We are obtaining spectroscopic observations to see if indeed this is the case.

3.3. The Pal 5 Region

Figure 2 also reveals a large clump of stars from RA $\sim 225 - 250^\circ$ with $16.6 < V_o < 17.6$. Because this area includes the globular cluster Pal 5, we refer to it as the Pal 5 region (e.g., Vivas et al. 2001). We have been obtaining spectroscopic observations with the 8m VLT, 3.5m WIYN, and 1.5m ESO telescopes to measure the radial velocities and the metallicities of these stars. While much work still needs to be done on this region, we report our results so far for the stars nearest to Pal 5.

The small rectangular area labelled Pal 5 in Fig. 2, which is $4^\circ$ wide in RA and 0.4 mag. wide in $V_o$, contains the previous known RR Lyrae variables in Pal 5, all 5 of which were recovered by our survey. According to our measurements, these Pal 5 variables have a mean of 17.284 in $V_o$ and a one-sigma dispersion of 0.066. This dispersion is consistent with the value expected for RR Lyrae variables of the same chemical composition lying at the same distance from the Sun. Pal 5 is unusual in that all 5 of its variables are type c, which are typically one-third as numerous than the type ab variables in a cluster of the metal abundance of Pal 5.

The rectangle in Fig. 2 contains 5 additional stars (4 type ab and 1 type c), which have not been previously catalogued. The mean and one sigma dispersions of these stars in $V_o$ are 17.277 and 0.034, respectively. These values indicate that the distances to these stars are very similar to each other and to the distance to Pal 5. Even if one ignores the proximity of Pal 5, these stars form such a tight knot in space compared to the general distribution of halo RR Lyrae variables.
that their physical association is highly likely. While two of the 5 lie relatively close to Pal 5 on the sky, the other three lie more than one degree away, far outside the tidal radius of the cluster. Our spectroscopic observations of all 5 of these variables and of 4 of the Pal 5 variables indicate that their radial velocities and metallicities are the same as Pal 5’s to within the errors.

The SDSS has detected two long stellar streams emanating from Pal 5 (Odenkirchen et al. 2001, 2003), which is clear evidence that this cluster is being torn apart by the tidal field of the Milky Way. The rough outline of these streams on the sky and the positions of the 10 RR Lyrae variables in the rectangle in Figure 2 are compared in Figure 4. One can see that two of the 5 stars not previously associated with Pal 5 are close to the cluster, and that one of the three more distant stars lies in the southern stream detected by SDSS, which is preceding the cluster in its orbit (Odenkirchen et al. 2003). It is surprising that the other two distant stars do not lie in the tidal streams, since their distances from the Sun, radial velocities, and metallicities are consistent with membership in Pal 5. There may be a larger system in this area of the sky, of which Pal 5 and its streams are only part. We are exploring this possibility by obtaining spectroscopic observations of more RR Lyrae variables in the Pal 5 region.

3.4. Detection of the Monoceros Stream or Ring?

Using SDSS data, Newberg et al. (2002) discovered a stellar feature in Monoceros, which subsequent work has shown is part of a large ring-like stream that appears to encircle the Milky Way (Yanny et al. 2003; Ibata et al. 2003; Majewski et al. 2003). The part of our survey at southern galactic latitudes (see Fig. 1), overlaps with the SDSS region (S200-24-19.8) where this feature was detected.
Figure 5. The plot of $V_o$ against $RA$ for the survey at southern galactic latitudes. Distances from the Sun are shown on the right. The variables with $V_o \sim 15.5$ might be associated with the stellar ring.

by Newberg et al. (2002) as a main-sequence turnoff in the color-magnitude diagram and where Yanny et al. (2003) confirmed its existence by showing that the stars have very similar radial velocities. The plot of $V_o$ against $RA$ for the RR Lyrae variables in this region is shown in Figure 5. It is important to note that our survey is less complete in this region than at northern galactic latitudes because in general fewer observations were obtained and because the interstellar extinction is large and variable, particularly for $RA > 80^\circ$. While there are no large clumps of variables in Figure 5, their distribution in $V_o$ does not appear to be random. Ten of the 38 variables have values of $V_o$ consistent with distances from 8 to 12 kpc from the Sun, which is more than twice the number expected for a smoothly varying distribution of $V_o$. Yanny et al. (2003) have estimated that in this region of the sky the stellar ring lies from 11.3 to 15.0 kpc from the Sun. This is sufficiently close to the distances of the excess number of RR Lyrae variables that it is likely that they are associated. Since Newberg et al. (2002) also detected the ring at northern galactic latitudes from $RA = 117^\circ$ to $130^\circ$ (feature S223+24-19.4), it is expected to be also present in our data that cover similar latitudes starting at $RA = 120^\circ$. As Figure 2 shows, there is a group of variables at the right $V_o$ ($\sim 15.5$) to be part of the ring. We are obtaining spectroscopic observations to see if these variables and the ones in the $RA = 60 - 90^\circ$ zone have radial velocities consistent with membership in the ring. If confirmed as members, the RR Lyrae variables will provide a precise estimate of the ring’s distance and extent along the line of sight, and a measurement of the metallicities of its oldest stars.

4. Discussion

The results presented above demonstrate that our RR Lyrae survey can detect both large and small substructures. The detection of a dense and large-scale feature, such as the Sgr Stream, is not challenging to a survey for any type of
halo tracer that reaches sufficiently deep. It is of course much more difficult, but nonetheless important for documenting the merger history, to detect low density features that may be the remains of streams from very ancient mergers or the debris from very low-mass systems. The detection of the excess of stars near Pal 5 suggests that our survey has some sensitivity to low-density features. This is due to the combination of the high degree of completeness of the survey and the properties of RR Lyrae variables, which make them excellent standard candles. Particularly in the case of a low-density feature, it is essential to obtain spectroscopic observations to see if the feature is also present in radial velocity space. We are measuring the radial velocities of many of the brighter variables discovered by our survey to see if additional low-density features are present.

The QUEST RR Lyrae survey is continuing, and the next band of the sky, which is centered on $DEC = -3^\circ$, is almost complete. We are also beginning the Palomar-QUEST RR Lyrae survey, which employs the Palomar 48 inch Schmidt telescope and a new CCD camera that has 112 chips. The drift scans produced by this instrument are $4.6^\circ$ wide in DEC and have a limiting $V$ mag. of $\geq 21.0$. For RR Lyrae variables, this limit corresponds to a distance of $\geq 120$ kpc, which is roughly twice the distance limit of the QUEST survey.

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