Keck studies of M31’s stellar halo

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ABSTRACT

We present Keck 10-meter / LRIS spectra of candidate red giants in the halo of M31, located at a projected radius of \( R = 19 \) kpc on the minor axis. These spectroscopic targets have been selected using a combination of \textit{UBRI}-based and morphological screening to eliminate background galaxies. Radial velocity measurements are used to separate M31 halo giants from foreground Milky Way dwarf stars, M31 disk stars, and residual background galaxies. The metallicity of each M31 halo giant is measured using standard photometric and spectroscopic techniques, the latter based on the strength of the Ca II triplet. The various [Fe/H] estimates are in rough agreement with one another. The data reveal a large spread (> 2 dex) in [Fe/H] in M31’s halo; there is no strong radial [Fe/H] gradient. LRIS and HIRES spectra are also presented for red giants in five dwarf spheroidal satellites of M31: And I, And III, And V, And VI, and And VII. There appears to be a significant metallicity spread in And VI and possibly in And I. The new radial velocity data on these outer dwarfs are used to constrain the total mass of M31: the best estimate is under \( 10^{12} M_\odot \), somewhat less than the best estimate for the Milky Way.

Keywords: Andromeda (M31), Keck telescope, dwarf spheroidal satellites, metallicity, dynamics, structure, halo, red giant stars

1. OVERVIEW

This paper describes two ongoing observational programs at Keck unified by a common goal: to investigate the metallicity, structure, and dynamics of M31’s extended stellar halo. The first is a low-resolution spectroscopic survey of field red giant stars in M31’s outer halo \(( R = 10 – 50 \) kpc), while the second aims to combine low-, intermediate-, and high-resolution spectroscopy of giants in dwarf spheroidal (dSph) companions of M31 located at \( R = 50–300 \) kpc. Such dwarfs have long been thought of as basic building blocks in the process of galaxy formation. The metallicity distribution of our target stars serves as as a fossil record of the formation of M31’s halo. Moreover, these stars are good tracers for investigating the internal dynamics of the dwarfs as well as the global dynamics of the M31 subgroup, and hence the dark matter distribution within the Local Group.

2. M31 FIELD HALO RED GIANTS

2.1. Introduction: Motivation and Background

The radial abundance gradient and abundance spread in M31’s stellar halo can potentially discriminate between competing galaxy formation models. The dissipational collapse model\cite{1999ApJ...519..539H} predicts a strong radial metallicity gradient, whereas the accretion model\cite{2000MNRAS.315..401M} predicts no strong gradient. It is important to study both globular cluster and field star populations since they may be dynamically distinct from each other. The Andromeda galaxy (M31) provides a global external perspective of a large spiral much like our own, and yet is close enough for individual stars

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to be resolved. Ref. 25 shows evidence for a weak metallicity gradient in a sample of 150 M31 globular clusters, with a mean iron abundance of [Fe/H] = −1.2, which is slightly higher than the mean value of [Fe/H] = −1.4 for Galactic globular clusters.

The metallicity of M31 field halo stars remains uncertain even after a decade or more of concerted effort using ground-based telescopes. Ref. 25 found a metallicity of [Fe/H] ≈ −0.6 for stars located at a projected distance of \( R = 7 \) kpc along the minor axis and Ref. 22 estimated [Fe/H] ≈ −1.0 at \( R = 8.6 \) kpc also on the minor axis. A study of an \( R = 16 \) kpc field around the globular cluster G219 suggested a large metallicity spread \( \Delta [Fe/H] \) with a mean value [Fe/H] ≥ −1.0, as did the studies described in Ref. 12, Ref. 11 (\( R = 6.7 \) kpc), and Ref. 10 which targeted fields around five M31 globular clusters. Recent Hubble Space Telescope (HST) studies have used its excellent angular resolution to separate field stars from background galaxies and find the mean metallicity at various points in the M31 spheroid to be comparable to that of 47 Tuc: [Fe/H] ≈ −0.7.

The ground-based studies are hindered to one degree or another by sample contamination by distant background field galaxies many of which are compact enough to be mistaken for stars at faint magnitudes. The HST studies, on the other hand, are limited by a small field of view and the lack of comparison field control samples. Studies of the inner halo risk possible contamination by M31 disk stars, while those of the sparse outer halo have to contend with a significant fraction of foreground contaminants, Milky Way dwarf stars at M31’s low Galactic latitude. In general, sample contamination makes it difficult to draw conclusions about the average [Fe/H] of M31’s stellar halo and especially its [Fe/H] spread.

### 2.2. Photometric and Morphological Screening for Red Giants in M31

Our study is based on deep \( UBRi \) images, obtained with the KPNO 4-meter telescope, of a 16’ × 16’ field at \( R = 19 \) kpc (1.6°) on M31’s SE minor axis. This field is further out on the minor axis than the ones used in previous studies, probes at least as far out into the M31 spheroid as the others (based on a 2:1 flattened spheroid), and is the least susceptible to contamination by the M31 disk. Observations of a well-matched comparison field, well away from M31 but at a comparable Galactic latitude, serve as a control data set. Four high resolution \( I \)-band images obtained with Keck, covering most of the field, provide morphological information.

The stars in these fields (M31 giants and Milky Way dwarfs) are outnumbered by the dense background of distant faint blue field galaxies, many of which are too compact to be distinguished from stars on the basis of image morphology alone (even with Keck’s 0.7′′–0.8′′ seeing). We use an alternative method developed in Ref. 10 for discriminating between stars and faint galaxies, one that uses broadband \( UBRi \) color information in addition to morphological information. The technique relies on the fact that stars, even those spanning a wide range of age and metallicity, occupy a narrow, well-defined locus in multicolor space whereas galaxies display a broad distribution due to their mix of stellar populations and redshifts. For an object to be identified as a stellar candidate, its intensity profile must be consistent with the PSF and its \( U - B, B - R, \) and \( R - I \) colors must be consistent (within errors) with the stellar locus defined by model isochrones and empirical data on Galactic globular cluster giants.

This morphological and \( UBRi \) color-based screening is done on all objects detected in the M31 halo and comparison fields. The color-magnitude diagram (CMD) of surviving objects in the comparison field is well described by a superposition of foreground Galactic dwarf stars (in keeping with a standard empirical model of the Galaxy) against a backdrop of residual contaminating faint blue field galaxies, while the M31 halo field contains a clear excess of faint red objects (\( I \sim 20 - 23, B - I \sim 2 - 3.5 \)) in addition to these two components. The location of this population of faint red objects in the CMD is consistent with what one would expect for red giant stars at the distance of M31 (Fig. 1). We have carried out a statistical subtraction between the M31 halo field and comparison field CMDs.

A detailed description of the selection process and results is given in Ref. 36.

### 2.3. Keck Spectroscopy

Of the \( UBRi \)- and morphology-selected sample of objects in our \( R = 19 \) kpc minor axis field, the brightest ones (20 < \( I < 22 \)) serve as excellent targets for follow-up spectroscopy. Spectra of 99 M31 halo red giant candidates have been obtained with the 10-meter Keck telescope and Low-Resolution Imaging Spectrometer (LRIS) around the Ca II triplet (\( \sim 8500-8700 \) Å). In addition, spectra have been obtained of 12 control objects which are known to be significantly brighter than the tip of M31’s red giant branch, and which are thus likely to be foreground Galactic dwarf stars. Five multislit masks were observed for \( \sim 4 \) hr each during 4 nights in the Fall 1996 and 1997 observing
The control sample consists of objects with $I < I_{\text{TRGB}}(M31)$. The model isochrones are from Ref. [41] for (L→R): $[\text{Fe}/\text{H}] = -2.31, -1.41, -0.71, \text{and} -0.30$. Two model curves from Ref. [34] for foreground Galactic dwarfs are shown on the right, while the broad curve to the left is a Gaussian representing M31 halo red giants.

The radial velocity of each target object is determined from its spectrum using standard cross-correlation techniques. This kinematic information is useful for distinguishing among M31 halo giants, M31 disk giants, foreground Galactic dwarfs, and distant background galaxies. Most of the foreground contamination in this low Galactic latitude M31 field ($|b| = 22^\circ$) is expected to be due to dwarf stars in the Milky Way’s disk with heliocentric velocities close to zero, significantly displaced from M31’s systemic velocity of $-297$ km s$^{-1}$. M31 halo red giants are expected to have a large spread of radial velocities due to their random motion in the galaxy’s potential, while M31 disk giants are expected to cluster tightly around its systemic velocity (the line-of-sight component of the disk rotation velocity is expected to be zero as our field is on the minor axis).

In addition to the removal of residual contaminants, spectroscopy allows direct measurement of the metallicity of each star using the near infrared Ca II absorption line strengths, $\Sigma \text{Ca}$ (sum of the three equivalent widths). There has been a lot of work to develop calibration relations based on observations of the line strengths of red giants in fiducial Galactic star clusters with known metallicities. Such relations connect $\Sigma \text{Ca}$ and the brightness of the star $\Delta V$ relative to the horizontal branch to [Fe/H], and have been calibrated over the range $-2.5 \leq [\text{Fe/H}] \leq 0.0$. The line strength, $\Sigma \text{Ca}$, of each of our M31 halo red giant candidates is determined using an empirical linear relation between the relative strength of the cross correlation peak and the directly-measured, but somewhat noisier statistic $\Sigma \text{Ca}$ for selected stars. This derived $\Sigma \text{Ca}$ is then used to calculate the metallicity of each object. A detailed description is given in Ref. [35].

### 2.4. Results

#### 2.4.1. Density of M31’s stellar halo

The surface density of red giant candidates in the $R = 19$ kpc M31 halo field, as derived from the statistically-subtracted, $UBRI$ color- and morphologically-selected sample, is coupled with the $HST$ studies in Ref. [24]. The data indicate that M31’s stellar halo is much denser and/or larger than that of the Galaxy: $(\rho_{M31}/\rho_{MW})(\Lambda/1.5)^{-\nu} \sim 10$, where $\Lambda$ is the ratio of the radial scale lengths of M31 and the Galaxy and $\nu = -3.8$ is the assumed power law index of the density profile. The density of M31’s inner halo may be even higher than this estimate: while we have
adopted a single power law profile for M31’s halo, the outer profile is known to steepen both from the counts in our \( R = 19 \) kpc field and from Ref. 33 which finds that the profile is better fit by a de Vaucouleurs law than a power law. A refined estimate of the halo density profile and flattening are underway based on a spectroscopically-selected sample of an additional 50–100 secure M31 halo red giants at various locations on the major and minor axes. Radial velocities and line strengths derived from this sample should enhance our knowledge of the dynamics and metallicity of M31’s halo, respectively (see Sec. 2.4.2 and 2.4.3 below).

2.4.2. M31 halo kinematics and residual sample contaminants

The radial velocities measured from the > 100 Keck spectra presented in this paper display a bimodal distribution with one component centered on M31’s systemic velocity \( (v_{\text{sys}} = -297 \) km s\(^{-1}\)) and another component centered at \( \approx 0 \) km s\(^{-1}\) (Fig. 2). We use an empirical star count model of the Galaxy (IASG model)\(^3\) to estimate the expected distribution of line-of-sight velocities of foreground dwarfs. The spectroscopic control sample consists of 12 stars with \( I < 20 \), which is brighter than \( I_{\text{TRGB}} \) at the distance of M31 (Fig. 1); these stars are thus exclusively foreground dwarfs. The IASG model matches their velocity distribution very well (dotted histogram in Fig. 2).

A linear combination of the IASG model \( v \) distribution and a Gaussian centered on M31’s systemic velocity is fit to the data; the best fit Gaussian width is \( \sigma = 150^{+30}_{-20} \) km s\(^{-1}\) and the fraction of M31 halo stars in the sample of 99 targets is estimated to be \( \sim 50\% \). Note, with this normalization of the Galactic dwarf \( v \) distribution (see Fig. 2), almost all the stars with \( v > -50 \) km s\(^{-1}\) are likely to be foreground dwarfs. The model results may be used to estimate the foreground contamination fraction for various velocity cuts in the sample—e.g., \( v > -150 \) km s\(^{-1}\) corresponds to \( >50\% \) contamination in all velocity bins, while \( v < -210 \) km s\(^{-1}\) corresponds to \(<25\% \) contamination. The different symbols in the CMD plot (Fig. 1) are based on these velocity ranges. The lack of a significant concentration of objects at the exact systemic velocity indicates a negligibly small degree of contamination by M31 disk giants. Selecting stars with \( v < -210 \) km s\(^{-1}\) yields a secure sample of M31 halo red giant stars.

2.4.3. Radial gradient and spread in metallicity

The secure sample of M31 halo red giant stars with \( v < -210 \) km s\(^{-1}\) is particularly useful for investigating the mean [Fe/H] and spread. The iron abundance of each of these stars is measured using two independent methods: the star’s location in the \( B - I \) vs. \( I \) CMD and the strength of the Ca II absorption lines, \( \sum \text{Ca} \). The CMD-based photometric method compares each star to model isochrones calculated over a range of metallicities.\(^3\) The line
Figure 4. The metallicity distribution of spectroscopically-selected secure M31 halo red giant stars. From left to right, the upper panels show [Fe/H] estimates derived from the Ca II line strength with ZW and CG97 calibration relations and from the $(I, B − I)$ CMD. The histogram and curve in the lower left panel show unweighted and luminosity-weighted [Fe/H] distributions of Local Group dwarf galaxies, respectively. The weighted distribution takes the [Fe/H] spread within each dwarf into account; it is dominated by a few dwarfs (LMC, SMC, M32, NGC 205, etc.). The lower middle panel shows the unweighted distribution of M31 globular clusters. The lower right panel shows chemical enrichment models with steady gas loss.
strength $\sum \text{Ca}$ is calibrated to [Fe/H] using two independent calibration relations [38, 39], labeled “ZW” and “CG97”, respectively, following the designation in Ref. [38]. The photometric estimate of [Fe/H] is in reasonable agreement with the spectroscopic estimates within the calibrated range of each method, especially for the CG97 calibration (Fig. 3).

Measuring the abundance gradient versus radius in M31’s halo involves comparison of the mean [Fe/H] in our data set to $HST$-based photometric determinations of [Fe/H] at $R = 7$ and $11$ kpc on the minor axis [31, 32] and at $R = 40$ kpc on the major axis [32, 33]. Both of our $R = 19$ kpc samples of halo red giants, the large $UBRI$- and morphologically-selected statistically-subtracted sample and the smaller but cleaner spectroscopically-selected secure sample, yield $\langle[Fe/H]\rangle$ in the vicinity of $-1.6$ to $-1.3$ using various ways to estimate [Fe/H] (photometric and spectroscopic). This mean abundance is roughly consistent with the results of the $HST$ studies indicating that M31 lacks a strong radial gradient in metallicity. However, the use of heterogeneous samples, different [Fe/H] determination methods, and possible sample contamination (M31 disk stars) in the inner halo fields, makes this conclusion uncertain. We are in the process of isolating clean samples of halo red giants at a variety of radii in M31 and determining [Fe/H] in a uniform way with the help of Keck LRIS spectra (Sec. 2.4.1).

The secure sample of M31 halo red giants in the $R = 19$ kpc field displays a large spread in [Fe/H] ($\sim 2$ dex), independent of the metallicity measurement method (upper panels of Fig. 4). The metallicity distribution among M31 field halo stars is similar to the distribution of mean [Fe/H] values of M31 globular clusters and Local Group dwarf satellite galaxies (Fig. 4). The observed [Fe/H] distribution in M31’s halo can be explained in terms of chemical enrichment models with steady gas loss from the system (see details in Ref. [33]).

3. M31’S DWARF SPHEROIDAL SATELLITES

3.1. Introduction: Basic Building Blocks of Galaxy Formation

Dwarf galaxies, the most numerous type of galaxy, are considered to be major building blocks for the formation and evolution of more massive galaxies [1]. Among dwarf galaxies, the least luminous, least massive morphological type known is the dwarf spheroidal subclass. Almost all known dSphs are found in close proximity to more massive galaxies, and are therefore particularly useful as tracers of the gravitational potential of the “parent” galaxy as well as for the study of environmental effects on dwarf galaxy evolution. While the nine dSph companions of the Milky Way have been studied in great detail, similar studies of the M31 dSphs have only recently become feasible thanks to large-aperture 8–10-meter class telescopes and efficient modern-day spectrographs [2]. Large area surveys in search of low surface brightness objects have led to the discovery of three new M31 dSph galaxies in the last couple of years, bringing the census to six dSph galaxies. The present set of M31 dSph galaxies cover the same range of galactocentric distances as the Milky Way companions. Thus it should be possible to make a direct comparison of environmental effects on these two sets of dSphs.

We present initial results from a Keck spectroscopic survey of five of the six M31 dSph companions, And I, And III, And V, And VI, and And VII. The first four have been studied with LRIS using a similar multislit Ca II triplet setup as for our M31 field halo star survey (Sec. 2.3); the fifth dSph has been observed with the High-Resolution Echelle Spectrometer (HIRES) —see Sec. 3.2.4 below.

3.2. Preliminary Results

3.2.1. Integrated radial velocity

Integrated stellar velocities of the five M31 dSph companions are listed in Table 1. In each case, this is based on the mean radial velocity of 15–25 member giants. The quoted uncertainty is the $1\sigma$ error of the mean, derived from the observed rms dispersion of velocities among member stars (combination of measurement error and internal velocity dispersion); it does not include possible systematic error in the measurements. Note, the signal-to-noise ratio of the And III data is substantially lower than that of the other dSphs and this is due to truncation of the exposure time.

It is interesting to compare the velocity measurements in Table 1 with a recent neutral hydrogen survey described in Ref. [40]. The HI cloud tentatively detected in the vicinity of And III has a radial velocity of $v_{\text{LSR}} = -337 \pm 6$ km s$^{-1}$ in the radio 21 cm line, which is within $1\sigma$ of the optical velocity measurement. If this low significance HI detection at And III is confirmed, it likely represents gas that is physically associated with the dSph. By contrast, the 21 cm velocity of the HVC 368 cloud in the direction of And V is $v_{\text{LSR}} = -176 \pm 1$ and this is clearly inconsistent with the optical value. As originally suspected, this cloud is likely to be a fragment of a larger neighboring gas cloud (complex ‘H’) that happens to be superposed on And V.
Figure 5. Color-magnitude diagrams for four dSph companions of M31 zoomed in around the tip of the red giant branch showing the full photometric data sets (smallest black dots) from which the LRIS spectroscopic targets are drawn. The slightly bolder black dots in the two upper panels represent giant candidates identified on the basis of Washington DDO51 photometry. Spectroscopic targets can be divided into: dSph members (filled red circles), field/foreground interlopers (open green circles), and failed velocity measurements (open blue triangles). The brightest of the And VI member stars (filled red circle with square) was included as a mask alignment star; it is slightly brighter than the giant branch tip. See Ref. 22 for details.
Table 1. Mean heliocentric velocities for five M31 dwarf spheroidal galaxies

| Name                  | $v_{hel}$ (km s$^{-1}$) |
|-----------------------|--------------------------|
| And I                 | $-369.5 \pm 2.2$         |
| And III               | $-352.3 \pm 13.6$        |
| And V                 | $-387.0 \pm 4.0$         |
| And VI (Peg dSph)     | $-340.7 \pm 2.9$         |
| And VII (Cas dSph)    | $-306.7 \pm 2.3$         |

Figure 6. Distribution of [Fe/H] among the member red giants in four M31 dSph companions from Keck/LRIS observations. These [Fe/H] estimates are based on the Ca II absorption line strength calibrated via the CG97 formula given in Ref. 39. The And VI spectra have the highest signal-to-noise ratio of the four, while the And III spectra have the lowest signal-to-noise.

3.2.2. Metallicity

Figure 5 shows CMDs of four of the M31 dSphs, the ones we have targeted for LRIS spectroscopy (targets marked by special symbols). The slope and width of the red giant branch traced by member stars are indicative of the mean metallicity and metallicity spread of the dSph, respectively. For example, the And V red giant branch is significantly closer to vertical than And I's or And VI's indicating a lower metallicity. This is confirmed by the spectroscopic [Fe/H] estimates for these galaxies (see Fig. 6).

Perhaps an even more striking aspect of Fig. 5 is the variation of the width of the red giant branch from one dSph to another. It is convenient to compare And V to And VI since their CMDs are based on photometric data of near-identical quality: short $V$ and $I$ band exposures with LRIS in 0.6$''$–0.8$''$ seeing conditions. While the And V member giants define a very narrow track, the And VI members display a substantial spread in color that is significantly in excess of the photometric error; this is most easily explained in terms of a metallicity spread in And VI. The spectroscopically-determined [Fe/H] histograms (Fig. 6) support this hypothesis: despite the fact that it has the highest signal-to-noise spectra of the four, the And VI histogram shows a prominent tail towards high metallicity and a spread in excess of 1.5 dex. Similarly, the And I red giant branch is broader than that of And III (Fig. 5), perhaps due to an intrinsic metallicity spread in the former galaxy. The large spread in spectroscopic [Fe/H] values observed for And III (Fig. 6) is likely a result of measurement error caused by the low signal-to-noise ratio of its spectra.
3.2.3. Dynamical mass estimate for the extended M31 halo

Dwarf companions can be treated as test particles in a large galaxy’s gravitational potential. Ref. 14 presents the most up-to-date and thorough dynamical analysis of the M31 halo using available radial velocity and distance data for several classes of tracers: gas and stars in the rotating disk, globular clusters, planetary nebulae, and dwarf satellites. The recent discovery of distant dSphs around M31, some almost 300 kpc from the parent galaxy, has breathed new life into this subject. The most distant tracers provide the best constraints on the total mass of the halo. An update of the M31 dynamical analysis, including radial velocity data for all of the dSphs presented in this paper, yields the best total mass estimate to date: $\sim 8 \times 10^{11} M_\odot$. Surprisingly, this M31 value is somewhat lower than the best estimate for the total mass of the Milky Way halo. However, the large uncertainty associated with each determination means that one cannot rule out the possibility that the two galaxies have the same mass.

3.2.4. Internal dynamics of And VII: Multislit HIRES experiment

The HIRES observations of And VII red giants presented in this paper were carried out in an unusual manner. Special purpose multislit masks were designed and fabricated to enable simultaneous observations of multiple red giants. Each mask contains 5–6 slitlets, with lengths in the range $1''$ to $2.5''$, so that the sum total of all slitlet lengths is $\leq 11''$ in order to prevent overlap of adjacent echelle orders. Needless to say, there is not much blank “sky” area available on the typical slitlet. Instead of the usual method of sky subtraction, we synthesize a single sky spectrum for each multislit mask by coadding blank pixels from all the slitlets on that mask. The experiment was made doubly difficult by the fact that our typical target star is very faint by HIRES standards: $V \sim 22–23$. Nevertheless, it is possible to reliably extract velocities for most of the 21 stars (Fig. 7). The observed rms dispersion is $\sigma_v = 9.4$ km s$^{-1}$, quadrature sum of the dSph’s internal velocity dispersion and the velocity measurement error. These data are being used to probe the dynamics and mass-to-light ratio of And VII.

4. SUMMARY

4.1. Main Points: M31 Halo Red Giants

The first part of this paper describes a study of field red giant stars in the outer halo of M31:

- A new color-based screening technique, using deep $UBRI$ photometry obtained with the KPNO 4-meter telescope, is combined with traditional morphological star-galaxy separation based on high resolution $I$-band images obtained with the Keck 10-meter/LRIS. This enables us to isolate M31 halo red giant stars in a field located at a projected distance of 19 kpc from the galaxy’s center along the minor axis. After screening for stars, this field displays a clear excess population relative to a well-matched comparison field, plausibly red giants at the distance of M31.

- These data, taken together with $Hubble Space Telescope$ studies of the inner halo, suggest that the density of M31’s stellar halo is about $10 \times$ higher than that of the Milky Way halo at comparable radii.

- Follow-up Keck LRIS spectra are presented for 99 M31 halo red giant candidates and a control sample of 12 foreground Galactic dwarf stars. Kinematical information derived from the spectra allow elimination of residual contaminants: foreground Galactic dwarfs, M31 disk giants, background galaxies.

- Metallicity measurements are made on a star-by-star basis using two independent methods: the strength of the $Ca II$ absorption lines and the location in the $B - I$ vs $I$ color-magnitude diagram. Various calibration schemes are tried in deriving spectroscopic $[Fe/H]$ estimates. The photometric and spectroscopic $[Fe/H]$ estimates are in reasonable agreement with each other.

- The mean metallicity of M31 field halo giants, $\langle [Fe/H] \rangle$, is in the range $-1.6$ to $-1.3$ depending on the metallicity measurement method, in rough agreement with the mean value of the Milky Way halo. There does not appear to be a strong radial abundance gradient in M31’s halo: the mean $[Fe/H]$ in this $R = 19$ kpc halo field is similar to (possibly slightly lower than) $HST$ findings for the inner parts of the halo ($R = 7–11$ kpc).

- There is a spread of at least 2 dex in $[Fe/H]$ even for the spectroscopically-selected sample of secure M31 halo red giants, independent of the method used to measure $[Fe/H]$. This is comparable to the $[Fe/H]$ spread among M31 globular clusters and Local Group dwarf satellite galaxies.
The velocity distribution in the $R = 19$ kpc minor axis halo field is well fit by an equal mix of foreground dwarfs (drawn from a standard Galactic model) and giants in M31’s halo represented by a Gaussian of width $\sigma_v \sim 150$ km s$^{-1}$ centered on its systemic velocity ($v_{\text{sys}} = -297$ km s$^{-1}$).

4.2. Main Points: M31’s Dwarf Spheroidal Satellites

The second part of the paper presents initial results from an ongoing Keck survey of red giants in dwarf spheroidal satellites of M31, including three newly discovered members:

- We present spectra of about 100 red giant candidates in five M31 dSph companions: And I, And III, And V, And VI (Peg dSph), and And VII (Cas dSph). The first four have been observed with LRIS and the last one with HIRES. This fall, we plan to carry out observations with ESI, the new, intermediate-resolution, high-throughput spectrograph on Keck.

- The mean stellar radial velocities of the dSphs are compared to recent velocity measurements of neutral hydrogen clouds seen in the direction of some of these dwarfs. The stellar and HI velocities are in good agreement in the case of And III, indicating a physical association, but not in the case of And V (probably a chance superposition).

- Color-magnitude diagrams of spectroscopically-confirmed dSph member giants suggests the presence of a significant metallicity spread in And VI and possibly in And I, but little or no spread in And III and And V. Spectroscopic estimates of the metallicity distribution in these four dSph galaxies, based on the strength of the Ca II triplet in member red giant stars, appear to be consistent with this finding.
The And VII observations are based on a novel multislit (5–6 stars at a time), echelle spectroscopy technique using HIRES. Accurate radial velocity measurements have been obtained for a total of 15–20 member giants. The observed rms velocity dispersion is about \( \sigma_v \sim 9 \text{ km s}^{-1} \) (uncorrected for measurement error).

Using our new radial velocity measurements of these outer dSph satellites in combination with other dynamical tracers, the total mass of M31's extended halo is estimated to be a little under \( 10^{12} M_\odot \), comparable to or smaller than that of the Milky Way halo.

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