The Velocity Dispersions of Star Clusters in Andromeda

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Abstract

Globular clusters are the oldest known stellar systems and provide good models for understanding the dynamics and evolution of stars. The clusters in our own galaxy have been studied extensively and many interesting correlations have been observed between different physical parameters. The velocity dispersion is one parameter that correlates very well with many other physical properties. It is not known whether this is true in other galaxies, so the goal of this project is to measure the velocity dispersions of a few extragalactic globular clusters. A Keck sky survey collected detailed spectra from 25 globular clusters in Andromeda and its neighbors and these were analyzed in detail. Using Fourier cross-correlation methods, the velocity dispersions of these clusters were determined and can now be used in conjunction with other properties observed with the Hubble Space Telescope to gain a better understanding of globular clusters and stars in general.

Introduction

In 1918, Harlow Shapley used the distances to globular clusters to first find the center of our galaxy. Since the 1950's the ages of GC's has been the lower limit on the age of the universe. Since the beginning of modern-day astrophysics, GC's have provided invaluable information and served as models for understanding stellar dynamics. In the 1960's, theories on the dynamics of GC's were first developed and these were refined with more observations in the 80's and 90's. Current models for the evolution of globular clusters are well accepted and fit well with observations from our own galaxy. However, very little is known about the GC's of other galaxies.

Globular clusters are homogeneous populations of stars in a densely packed spherical aggregate. There are about 150 known GC's in the Milky Way galaxy. They are composed of from thousands to hundreds of thousands of stars, and date back to the formation of the galaxy. Unlike the majority of stars in the Milky Way, globular clusters lie outside the galactic plane. They orbit the nucleus of the galaxy in highly inclined orbits and, with their wide distribution, outline the shape of the galaxy. There are a few clusters visible to the naked eye: Omega Centauri and 47 Tucanae in the southern skies, and M13 in the northern sky.

The study of globular clusters focuses on finding correlations between different observable parameters. Using various telescopes, a variety of morphological and photometric data can be obtained from astronomical objects. In previous studies of GC's in the Milky Way, several clear correlations have been identified between cluster parameters. Although there are no good correlations with luminosity, one of the easiest parameters to obtain, there is some tendency for more luminous clusters to have smaller and denser cores. More condensed cores are also more likely to be found towards the center of the Galaxy. A stronger correlation is observed between metallicity and mass-to-light ratio. However, some of the best correlations for globular cluster parameters involve velocity dispersion.

The velocity dispersion of a globular cluster describes the spread in the motions of the stars in the cluster. Although a cluster moves around the galaxy at some average velocity, the stars within the cluster are also moving with respect to each other. Since the clusters are bound by gravity, it is the kinetic energy from these motions that keeps the cluster in dynamical equilibrium. In some sense, the stars in a globular cluster can be viewed as molecules in a cloud of gas, and the velocity dispersion as the kinetic temperature.

In studies of the Milky Way, the velocity dispersions of globular clusters have correlated well with a number of parameters. Luminosity, surface brightness, mass, radius, and density all show good correlation with velocity dispersion. Physical properties of a cluster's core are often also involved in these correlations as a second parameter. The relationships between velocity dispersion and these other parameters have been well established in studies of the Milky Way, and this has helped constrain the models for globular cluster formation and development. With those models, astrophysicists have been able to gain a deeper understanding of star formation and of the structure of the entire galaxy. However, the accepted models of globular cluster development have never been tested on clusters in other galaxies.

Extragalactic globular clusters were not observable before the advent of the Hubble Space Telescope, but now, the physical parameters of many clusters in nearby galaxies can be extracted from HST images. The HIRES instrument on the Keck-I telescope can collect detailed spectroscopic data for each of these GC's, from which the velocity dispersions and metallicities are extracted. A study of this sort, correlating parameters of extragalactic clusters, has never been done before.

Since Andromeda is structured very similarly to the Milky Way, so the properties of its GC's are expected to be comparable. Preliminary analyses of a few clusters in the data set have shown this to be the case: Correlations between velocity dispersions, magnitude, and luminosity have the same coefficients as data from the Milky Way. This may not be true of the data from the elliptical galaxies, and by finding and analyzing the differences, a lot could be learned about globular clusters, and stars in general.

Materials and Methods

The primary focus of this project is the extraction of velocity dispersions from the Keck spectra. There are 25 globular clusters in this data set from 4 neighboring galaxies. 11 are in Andromeda (M31) and the rest in its companions: 9 from the Triangulum Galaxy (M33), 4 in the dwarf elliptical NGC185, and 1 in the dwarf elliptical NGC205. The data from each cluster encompass the visual spectrum from 4100 to 6600 angstroms, which is divided into 33 echelle orders.

The first step in analyzing these spectra is a correction for the Doppler shift induced by the radial velocities of the clusters. This is important, because the atomic lines spectral lines need to be shifted to their expected wavelengths. Being able to identify them conclusively is vital to any spectroscopic analysis. Determining metallicities and velocity dispersions relies exclusively on measurements of the widths of these spectral lines.

The process of correcting the spectra has several steps, and is accomplished using a program called the Image Reduction and Analysis Facility (IRAF). This software was developed at the National Optical Astronomy Observatories in Tucson, Arizona. IRAF is organized into several packages that include a myriad of programs, called tasks, for astronomical image processing. The spectra from Keck are organized in 33 echelle orders, which are analyzed individually in IRAF. Each step in this process must be repeated 33 times for each echelle order.

The first step is a smoothing of the spectra using an IRAF task called splot. A screen shot from splot can be seen in Figure 1. The smoothing process reduces the noise in the spectra and allows easier identification of atomic lines. The next step is to identify prominent spectral lines in order to measure the amount of Doppler shift using a task called rvidlines. This is the only nontrivial step in this process, and involves a bit of discretion on the part of the researcher. The strongest and widest lines in the spectrum of any star are generally the Hydrogen lines. Thus, a preliminary estimate of the Doppler shift can be ascertained from the position of H-alpha, which should be found at 6562.808 angstroms. If the H-alpha line lies between echelle orders for a particular globular cluster, H-beta, at 4861.342 angstroms, can be found. Finding the offset of these lines from their vacuum wavelengths provides a guideline for a more precise measurement of the radial velocity. In each of the clusters in the sample, there are a series of strong metallic lines between 5162 and 5193 angstroms. Since these are all in the same echelle order, it is convenient to use them for a more precise measurement of the radial velocity. The IRAF task rvidlines averages the displacements of these lines, yielding values ranging from 50 to 500 km/s with errors of about 1 km/s. Using this measured radial velocity, the spectra are then shifted accordingly so that the atomic lines appear at their expected vacuum wavelengths.

Since globular clusters are really groups of many stars, this measured radial velocity is really the average of the velocities of all the stars in the cluster. Each star in the cluster, with its own radial velocity, will emit an atomic line with a different Doppler shift. Thus, when an atomic line is observed in the corrected cluster spectrum, there isn't a single line, but a distribution of lines, appearing as a curve centered on the expected wavelength. Since this phenomenon is caused by the different velocities of stars in the cluster, the width of this distribution represents the velocity dispersion. However, even single stars do not show distinct lines in their spectra, since a star is actually composed of many individual atoms each emitting their own lines. Thus, to find how the width of the atomic lines in the cluster spectra relate to the velocity dispersion between individual stars, the clusters must be compared to templates of individual stars.

Six template stars relatively close to the earth were chosen for comparison to the clusters. Each cluster was grouped with a template star that had similar properties and similar spectral features. Using the same HIRES instrument at Keck, spectra of these template stars were taken in a format that would be easily comparable with the existing data. As with the clusters, these template stars also had Doppler shifts caused by radial velocities, and using the same techniques, these spectra were also shifted to the rest frame.

Instead of comparing the widths of individual spectral lines of the clusters to those of the templates, an average of comparisons between all the lines can be done using Fourier transform methods. This technique is called cross-correlation and can be accomplished with the IRAF task xcsao, which is part of the add-on package rvsao, developed at the Smithsonian Astrophysical Observatory Telescope Data Center.

The goal of the cross-correlation process is to compare the widths of lines in one spectrum to those of another. The method in which this is done, however, is not so simple. First, the continuum must be subtracted out of each spectrum. For this sort of analysis, only the atomic lines are needed and any background radiation needs to be removed. The xcsao task (Figure 2) accomplishes this by fitting a polynomial to points in the spectrum that are roughly horizontal. The continuum-subtracted spectra of the cluster and the template are then Fourier-transformed and convolved together. Since the cluster and template should have similar spectral features, they should also have similar Fourier transforms. When they are convolved together, this should result in a resonance peak. If the atomic lines in the cluster are wider with respect to the template, this will increase the range over which resonance can occur, and thus widen the resonance peak. Since Fourier transforms take into account all the atomic lines in their range, this method effectively compares the widths of all the lines in a single echelle order. Thus, the width of the cross-correlation peak represents an average of all these widths.

However, the width of the cross-correlation peak only gives a relationship between the template star and the globular cluster; it does not give the true velocity dispersion. To convert peak widths to velocity dispersions, a calibration curve must be generated for each template. Convolving the template spectrum with different Gaussian functions can simulate globular clusters with specific dispersions. The width of the Gaussians represents the velocity dispersion. When a star is convolved with a Gaussian with a width of x meters, this represents a cluster of those stars with a dispersion of $x*c/\lambda$ meters-per-second. These convolved spectra can then be cross-correlated with the original template spectrum, giving a resonance peak width. By using Gaussian widths at regular intervals, a calibration curve can be constructed relating the cross-correlation peak widths to velocity dispersions. Thusly, the velocity dispersions can be extracted from the data.

The cross-correlation process must be performed individually on each echelle order in a cluster spectrum, and this gives a set of up to 33 independent measurements of the velocity dispersion. Thus, after measuring the radial velocities of all the clusters and templates, shifting them to the heliocentric rest frame, cross-correlating them, and converting the results via a calibration curve, the primary results of this study are obtained.

Results

The velocity dispersions of 23 different clusters were successfully measured. Three echelle orders, the 6th, 18th, and 30th, were analyzed for each cluster (see Table 1). Because of high noise and other factors, a good dispersion measurement could not be obtained from each order; this is indicated in the table. Every echelle order in clusters R14 and G287 were analyzed, giving 32 independent measurements of the velocity dispersion.

There is a wide range of values for the velocity dispersions, but they are consistent with measured dispersions of other clusters in the Milky Way and other galaxies. There is a rather large variation between different echelle orders, and this causes a large standard deviation value for many clusters. Plotting the different echelle order measurements against each other (Figure 3), it can be seen that the 6th echelle order produces consistently higher dispersions than the other two orders. In Figure 4, this is even more apparent in the residuals between the 6th echelle order and the average of the 18th and 30th orders. This might imply that the choice of echelle orders is introducing some bias into this measurement.

The visual magnitudes of many of the clusters were available through Hubble Space Telescope data, and they are also listed in Table 1. Since the distances to each cluster were different, the apparent magnitudes were adjusted to the distance of m31, making the values comparable to each other. These magnitudes are plotted against the base-10 logarithm of the velocity dispersions in Figure 5.

Discussion

The velocity dispersions for the extragalactic clusters show a clear correlation with the visual magnitudes of those clusters. This implies that extragalactic clusters behave in a similar way to those in the Milky Way, which will allow for broader generalizations about stellar dynamics.

The choice of three echelle orders proved to be slightly flawed in that the 6th order was consistently higher that the average value. In the two cases where all available echelle orders were analyzed, this also proved to be the case. Thus, before this data can be validated, more echelle orders of the different clusters must be analyzed. Also, since the clusters from m33 and n185 had very noisy spectra, a good velocity dispersion measurement was impossible to extract from some echelle orders. An investigation of more orders will also provide better data on the clusters that were harder to resolve.

Whether the correlation between magnitude and velocity dispersion is comparable to the corresponding relationship in the Milky Way is yet to be seen. There are also many other parameters, such as mass, radius, or density, that have been known to correlate well with velocity dispersion. The data from this study, once complete, will be compared with these other parameters as well. The results of that analysis will further extend the understanding of globular cluster evolution, and stellar evolution, in general.

Conclusion

Twenty-three different extragalactic globular clusters were investigated to measure their velocity dispersion. A Fourier cross-correlation method was used to take these measurements, comparing the clusters with nearby template stars. For most of the clusters, a sample of three echelle orders was investigated to make the measurement. The velocity dispersions measured were within reasonable expectations and in a sample comparison, correlated well with visual magnitude.

It is yet to be seen how well these measurements correlate with a host of other parameters, but the results of this study imply that the correlations will be similar to those found in the Milky Way. There was some bias introduced in the choosing of a small sample of the data, so further analysis is needed for an accurate measurement of the velocity dispersions. However, the preliminary results of this study show hope for the study of extragalactic globular clusters; they will soon add considerably to the available data set for studying GC dynamics in general.

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Bibliography

1. De La Rosa, Ignacio G.; De Carvalho, Reinaldo R.; and Zepf, Stephen E. "The Fundamental Plane of Elliptical Galaxies in Compact Groups". *The Astronomical Journal*, 122:93-102. July 2001.

2. Djorgovski, George. "The Dynamic Lives of Globular Clusters". *Sky & Telescope*. October, 1998.

3. Djorgovski, S.G. "Dynamical Correlations for Globular Clusters in M31". *The Astrophysical Journal*, 474: L19-L22, January 1, 1997.

4. Djorgovski, S. "The Fundamental Plane Correlations for Globular Clusters". *The Astrophysical Journal*, 438: L29-L32, January 1, 1995.

5. Djorgovski, S. "The Galactic Globular Cluster System". *The Astronomical Journal*, Volume 108, Number 4. October 1994.

6. King, Ivan R. "Globular Clusters". *Scientific American Magazine*. June, 1985.

7. Motz, Lloyd. Astrophysics and Stellar Structure. Ginn and Company. 1970.

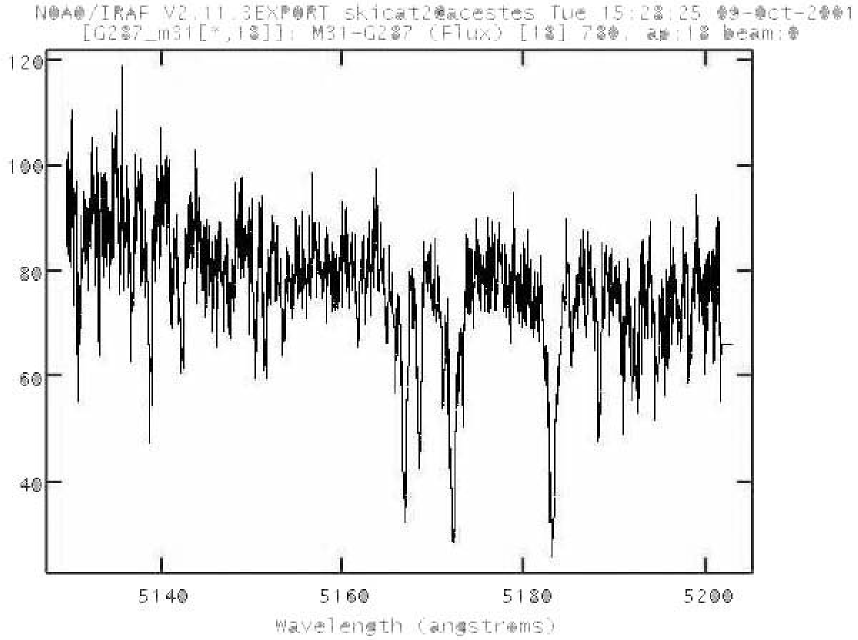
8. Novotny, Eva. Introduction to Stellar Atmospheres. Oxford University Press. 1973.

9. "RVSAO Radial Velocity Package for IRAF". http://tdc-www.harvard.edu/iraf/rvsao/ . SAO Telescope Data Center. October 6, 2000.

10. van den Bergh, Sidney. "Updated Information on the Local Group". *Publications of the Astronomical Society of the Pacific*. 112: 529-536, April 2000.

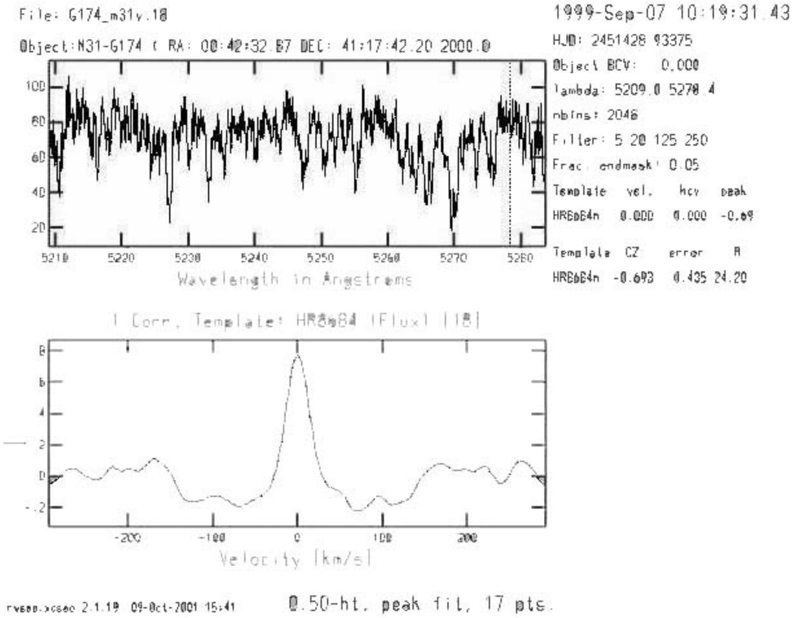
Tables and Figures

Figure 1: Echelle Order Spectrum from IRAF



This is the 18th echelle order of the cluster G287 as displayed by the IRAF task splot.

Figure 2: Cross-Correlation Peak



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Object:M31-G174 ( RA: 00:42:32.87 DEC: 41:17:42.20 2000.0

1999-Sep-07 10:19:31.43
HJD: 2451428.93375
Object BCV:   0.000
lambda: 5209.0 5278.4
nbins: 2046
Filter: 5 20 125 250
Frac. endmask: 0.05
Template   vel.   hcv   peak
HR8684n   0.000   0.000  -0.69

Template   CZ    error    R
HR8684n  -0.693  0.435 24.20

rvsao.xcsao 2.1.19  09-Oct-2001 15:41       0.50-ht. peak fit, 17 pts.
```

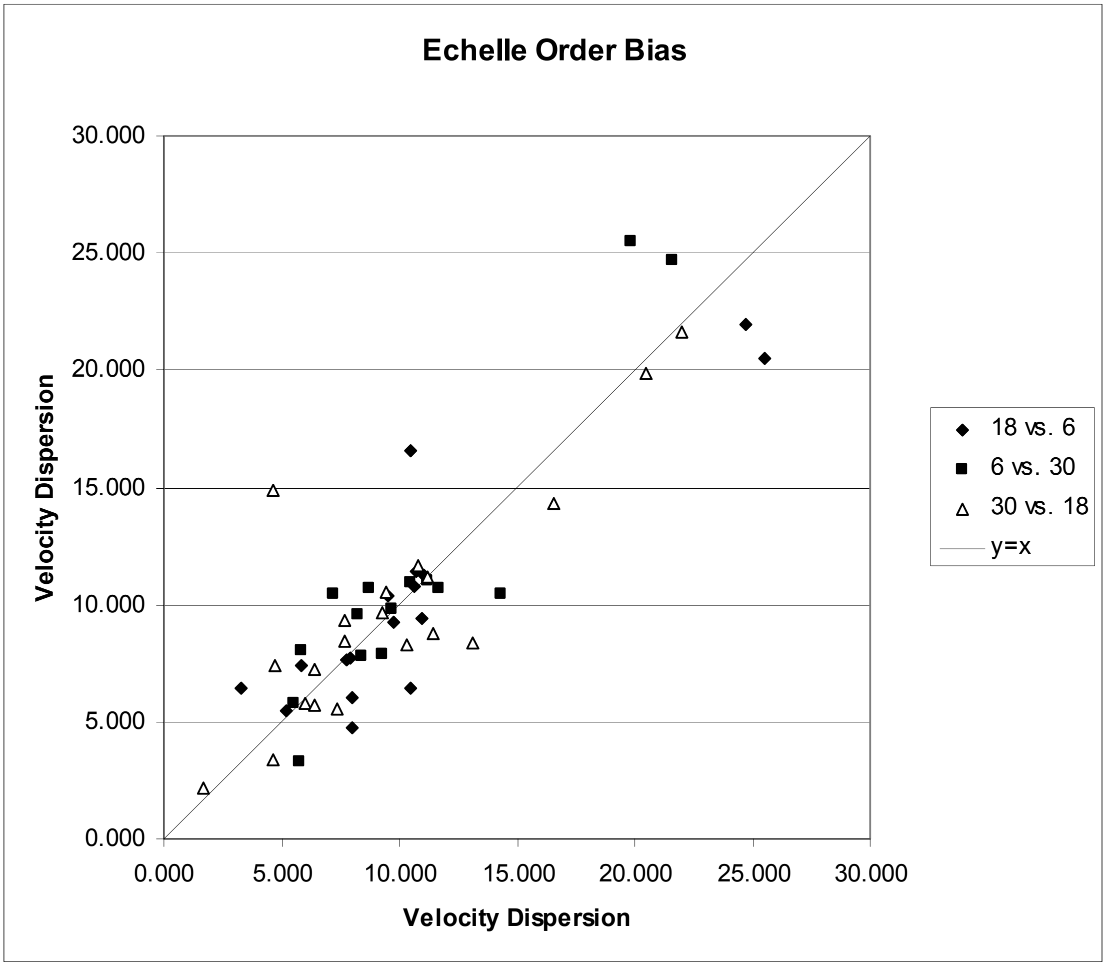
This is the output from the IRAF task xcsao, showing the cross-correlation peak between cluster G174 and the template HR8684n7.

Table 1: Velocity Dispersions

Template	Cluster	Galaxy	RV (km/s)	echelle orders	**Velocity Disp.**	Error	Log (σ)	Error	Visual Mag.	Adj. (m31)
HR8684n6	G33	m31	-470.97	3	**13.8**	1.03	1.139	0.032	15.500	15.500
HR8684n6	G87	m31	-246.84	3	**10.3**	0.47	1.013	0.020	15.700	15.700
HR8684n6	G287	m31	-33.41	32	**9.6**	0.26	0.982	0.012		
HR8684n6	G327	m31	-232.61	3	**5.0**	0.14	0.696	0.012		
HR8684n6	G185	m31	-486.86	3	**22.0**	1.03	1.342	0.020	14.520	14.520
HD12929n6	G172	m31	-196.54	3	**22.8**	0.57	1.357	0.011	15.060	15.060
HR8684n7	G11	m31	-460.03	3	**8.0**	0.71	0.905	0.038	16.360	16.360
HR8684n7	G170	m31	-576.77	3	**8.3**	0.29	0.919	0.015	16.450	16.450
HR8684n7	G174	m31	-234.92	3	**9.4**	0.35	0.973	0.016	16.360	16.360
HR8684n8	G198	m31	-101.02	3	**11.16**	0.03	1.048	0.001	15.980	15.980
HR8684n8	G177	m31	-559.94	3	**11.0**	0.17	1.043	0.007	15.910	15.910
HR8684n6	U49	m33	-116.19	3	**6.6**	0.40	0.821	0.026	16.250	16.166
HR8684n6	R14	m33	-178.51	32	**9.2**	0.09	0.964	0.004	16.480	16.396
HR8684n6	M9	m33	-212.84	2	**5.3**	0.08	0.727	0.007	17.120	17.036
HD12929n7	R12	m33	-182.18	3	**6.2**	0.33	0.796	0.023	16.380	16.296
HD12929n7	H38	m33	-205.25	3	**5.1**	0.55	0.711	0.047	17.250	17.166
HD12929n7	U77	m33	-187.91	3	**4.0**	0.44	0.601	0.048	17.190	17.106
HR8684n8	C20	m33	-117.93	1	**5.2**	N/A	0.720		17.670	17.586
HD26162n8	C38	m33	-83.69	2	**6.1**	0.95	0.785	0.068	18.100	18.016
HD26162n8	H10	m33	-186.65	2	**10.8**	1.68	1.032	0.068	18.230	18.146
HR8684n7	FjjIII	n185	-186.07	2	**9.8**	3.64	0.989	0.162	16.800	16.410
HR8684n7	FjjV	n185	-116.73	2	**1.9**	0.17	0.277	0.039	16.700	16.310
HR8684n8	FjjI	n185	-161.46	2	**6.4**	1.16	0.805	0.079	18.400	18.010

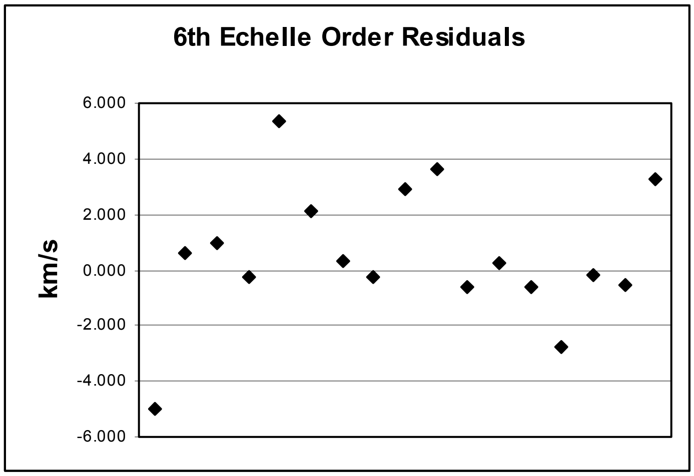
Every cluster investigated is shown in this table. The number of echelle orders used in the measurement of velocity dispersion is shown. Those clusters where more echelle orders were investigated should have more reliable data. The visual magnitudes were adjusted for the different distances to the clusters so that they could be compared with the logarithm of the velocity dispersion

Figure 3: Echelle Order Bias



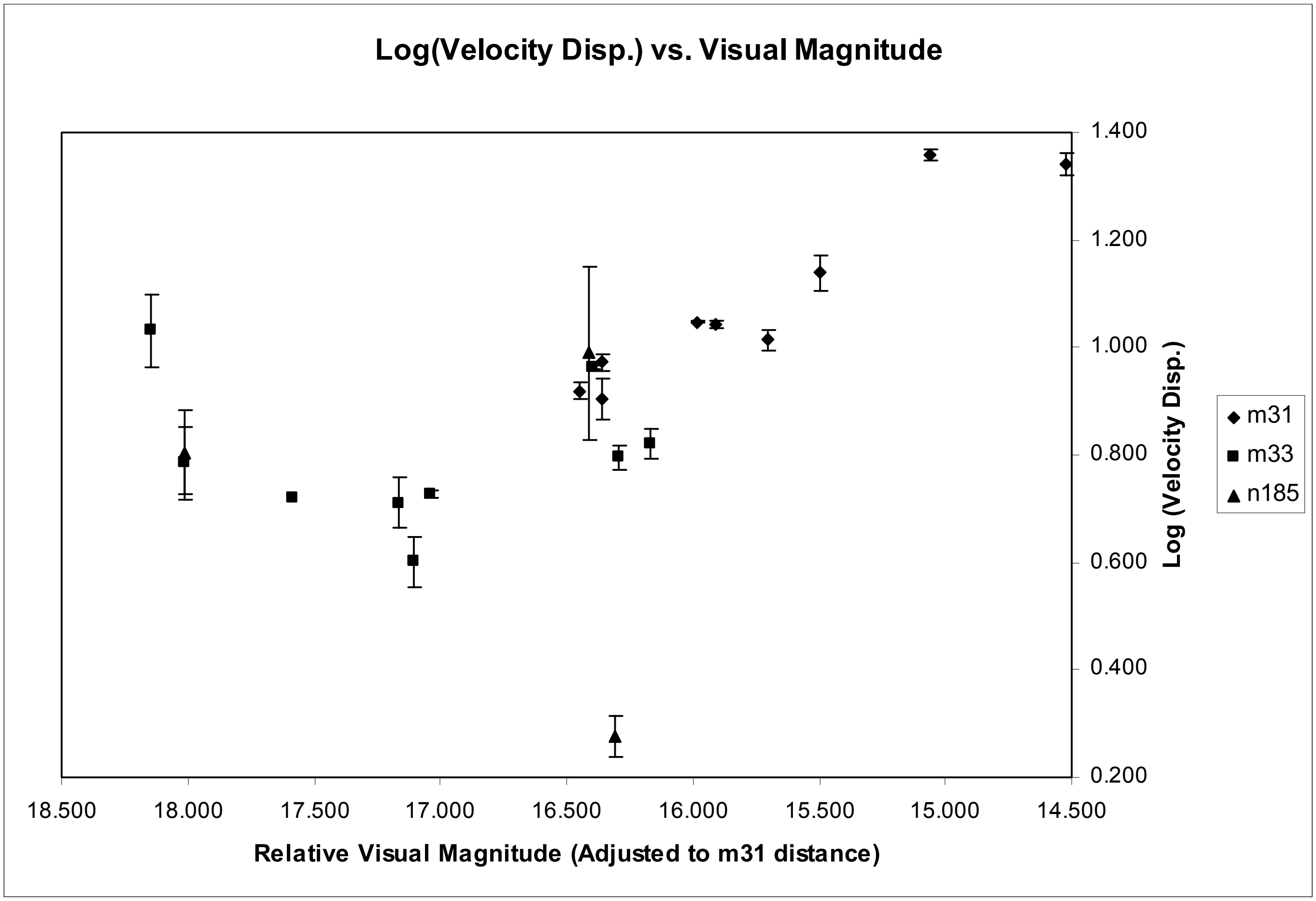
Plotting the velocity dispersion measurements from each order against each other, it is clear that while the 18th and 30th orders give very consistent measurements, the 6th echelle order is giving higher dispersions than the other two.

Figure 4: 6th Echelle Order Residuals



Except for the first point, the 6th echelle order shows a clear trend toward higher dispersion measurements than the average of the other two orders.

Figure 5: Log(Velocity Dispersion) vs. Magnitude



This figure plots the base-10 logarithm of velocity dispersion against the relative visual magnitude of the clusters. The magnitude of each cluster was adjusted to represent the magnitude at the distance to m31. There is a clear correlation between these two parameters. The two obvious outliers were both measured with only two echelle orders and are more susceptible to noise.