DETERMINING GALAXY INCLINATIONS FROM KINEMATICS

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ABSTRACT

The distribution of inclinations of spiral galaxies in any area in the sky is expected to be completely random in an isotropic universe. Surprisingly, we find that this is not the case when using inclinations determined from the projected shape of the galaxy or photometric inclinations. We have compared photometric inclinations with kinematic inclinations, which are derived from the distribution of Doppler shifted velocities in the galaxy as measured by the 4.1m SOAR telescope and Goodman spectrograph. We also compare results from two different codes for measuring kinematic inclinations. The first code is called DiskFit, and it takes a number of points in discrete elliptical annuli and fits based on the averages of velocities within those annuli. The second is one that we developed that uses all data points simultaneously, called Velocity Field Fitter (VFF). We quantify the differences between the two fitting methods to determine the success of their application as a function of galaxy size and shape.

1. INTRODUCTION

1.1. *The RESOLVE Survey*

In the UNC-led REsolved Spectroscopy Of a Local VolumE (RESOLVE) survey, all galaxies in a nearby volume are observed regardless of size or luminosity in what is considered to be a volume-limited fashion. This is much more statistically representative of the composition of our universe on a larger scale than the classical approach that is limited by apparent brightness, where one obtains data for only the brightest galaxies, ones which are not very common in the universe. Though these surveys give us a good idea about the large scale structure of the universe, it is also pertinent to our understanding of the universe that we explore the small scale details that make this up. The RESOLVE team members at UNC are well-situated to observe local environments because UNC, as a partner, is guaranteed a portion of time every year and competes nationally for more time on the 4.1 meter SOAR telescope, which has been erected in Chile and is capable of taking highly-resolved (0.22 arc seconds per pixel) spectra of galaxies. With the large number of observed galaxies in the RESOLVE survey, we can determine how photometric properties might change in the RESOLVE survey with the expectation that most of them should be random in the volume-limited sample. When examined, the distribution of photometric inclinations were not as expected.

1.2. *Photometric Inclination*

Inclinations are defined as the projected tilt of a disk galaxy ranging from 0 to 90 degrees, or from face-on to edge-on. We have analyzed the galaxies photometrically, using the axial ratio of the projected ellipse to determine its inclination by the classic formula from Hubble (1926)

$$i = cos^{-1}(((q^2 - q_0^2)/(1 - q_0^2))^{1/2}) \quad (1)$$

where q is the major to minor axial ratio and q_0 is the ratio at an inclination of 90 degrees. Since disk galaxies are not flat, q_0 must be greater than 0, and is taken to be 0.2, as determined by Holmberg (1958). We find that the distribution of photometrically determined inclinations for disk galaxies is not random, as can be seen in Figure 1.

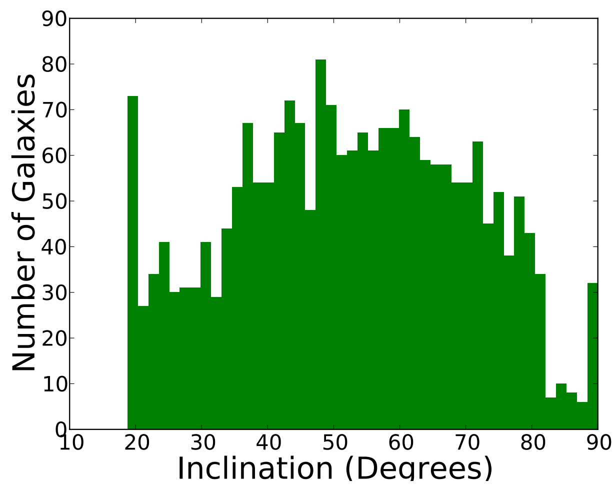

Fig. 1.— The distribution of photometric inclinations in the RESOLVE survey. If the measurement was truly random, this distribution should be fairly flat.

We are interested in finding why this is the case, since we would expect there to be no preference in a volume-limited survey. The root of this problem may lie in either the way that photometric inclinations are calculated or in our understanding of the intrinsic shapes of disk galaxies. I have been working towards ruling out one of these options in answering the question: Is our current method of photometric inclination determination sound, and if not, what photometric properties cause this error? This is an important question to tackle because galactic astronomers have for almost a century been using a simple equation which assumes a lot about the shape and structure of a galaxy, and has not yet been tested vigorously for robustness. Luckily, there is another way to determine the inclination of galaxies that assumes much less about the structure.

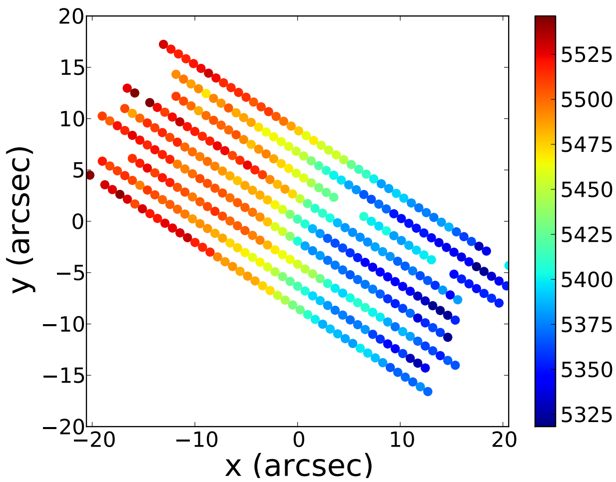

Fig. 2.— An example of the velocity field of a nearly face-on galaxy with three pointings from the fall catalog of the RESOLVE survey, with velocities given in km/s.

1.3. *Kinematic Inclination*

Kinematic inclinations are inclinations found from the observed velocity fields of spiral galaxies. These galaxies are rotating about a central point, and the line-of-sight velocities from Doppler shifting can be detected by a spectrograph to determine the average velocities of baryonic matter in the line of sight. Using the maximum velocity calculated from luminosity as described by Tully & Fisher (1977), one may determine how far from edge-on a galaxy is. This can be done because an observed edge-on galaxy would have almost all of its velocity in the line of sight, whereas a face-on galaxy would show only the cosmological redshift at most of the points in the galaxy. One may model the continuum of possible inclinations based on the velocity fields. This can be seen in the equation relating projected velocities with inherent velocities described by Teuben (2002)

$$V = V_{sys} + V_{rot}(R)\cos\theta\sin i + V_{exp}(R)\sin\theta\sin i \quad (2)$$

where θ is the angle of the deprojected galaxy, and i is the inclination from (1). We believe that the kinematic method of inclination measurement is more accurate because it makes less assumptions about the intrinsic properties of a spiral galaxy. There are processes which can tidally disturb the velocities in some regions of galaxies, but the effects appear to be minimal when determining the inclination on a larger scale. With two different ways of measuring inclination, we have made a comparison of measurements using the two methods and how their differences relate to other properties of galaxies to see where these differences might come from. With the belief that the kinematic method provides a more accurate representation of a galaxy's true inclination, this also means that we might expose faults in the measurement of photometric inclinations.

2. DATA

We observe galaxies using the 4.1m SOAR telescope and collect spectra using it's GOODMAN spectrograph with a custom-built spectrograph image slicer that allows up to three nearby spectra to be taken at once without

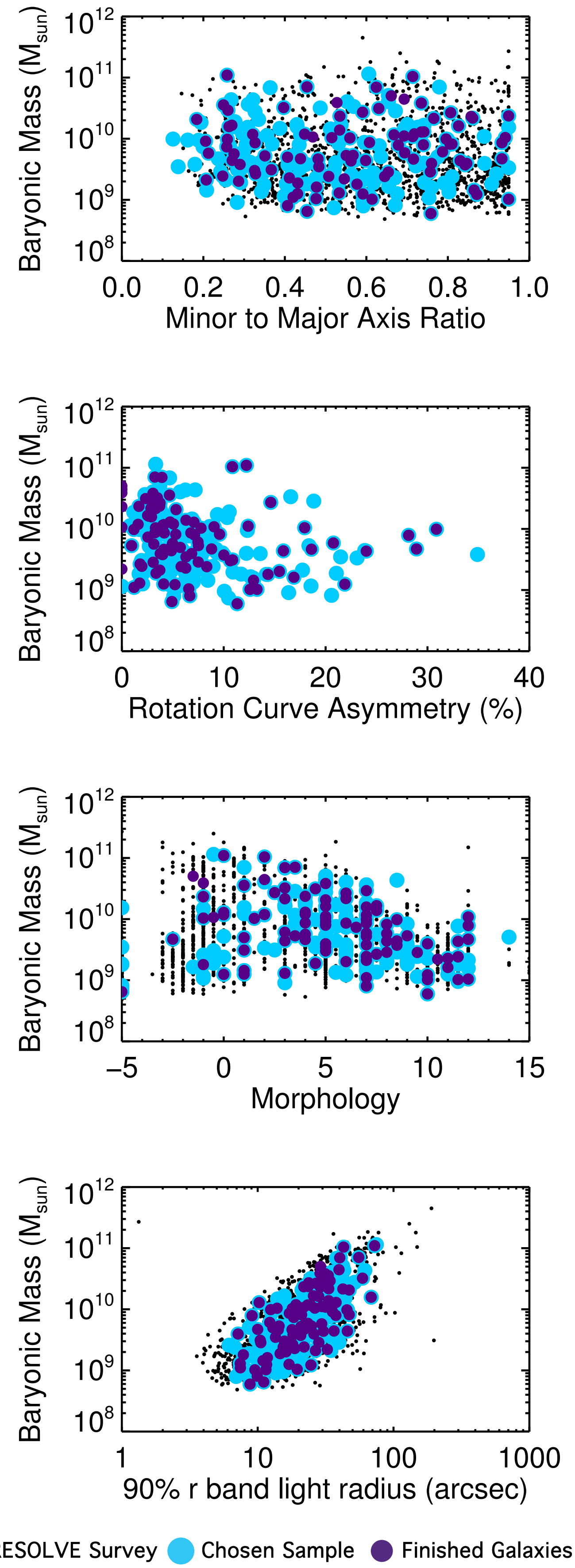

Fig. 3.— Baryonic mass against axial ratio, rotation curve asymmetry, morphology, and 90% r band light radius.

overlap. All data is reduced through a pipeline created by the RESOLVE team. Of the galaxies in the survey, a subsample including all previously reduced data was selected for the comparison of photometric and kinematic inclinations. To ensure that the sample was representative of the larger survey, we checked various properties of interest based on what we would expect might have an effect on the two dimensional projection of a galaxy and what might have an effect on the observed velocity field, which would in turn affect the photometric and kinematic inclination measurements respectively. Properties that we decided would have an effect are the galaxy's morphology, rotation curve asymmetry, and radius at which 90 percent of the galaxy's r-band light is contained within. For statistical reasons, we also made sure to have a representative distribution of all the axial ratios found within the survey.

3. KINEMATIC VELOCITY FITTING METHODS

3.1. *DiskFit*

A publicly available code called DiskFit (Barnes & Sellwood 2003) is capable of fitting the velocity field data that we have to a model profile given initial guesses to the position angle and galaxy center. Using DiskFit to model velocity fields for ∼100 galaxies, we have found there to be no clear link between the differences in inclination measurements and galaxy properties such as total baryonic mass, rotation curve asymmetry, 90% r-band radii, or morphology, but we did find some problems fitting small, asymmetric, or barred structures in the disk-fitting algorithm. This makes sense because the model requires many points in order to fit at many annuli and the program assumes the rotation curve to be inherently smooth, but perturbations might easily be misinterpreted, especially with the weight they would have in a small annulus.

3.2. *Velocity Field Fitting*

To remedy this, we have created a new algorithm that uses all of the data simultaneously, without the necessity of fitting disk annuli to it. We first find the center of kinematic rotation in the Doppler velocity field, then we use equations from Teuben (2002) that provide a translation from projected velocities to rotational velocities. Next, we map out the rotation curve of the galaxy and fit the rotation curve to the functions described by Courteau (1997) using minimum chi squared minimization techniques described by Markwardt (2009) in Python. We have found that there is a distinct advantage in doing this for small galaxies that do not have enough data in each annulus to make a clear disk but still have enough information to give a reasonable kinematic profile. So far, we have found that kinematic inclinations are more random than their photometric counterparts, but we still have not compared the differences with other photometric properties, as we did before with the DiskFit models.

4. RESULTS

We employed various tests on VFF to see whether it holds up well to different problems in fitting velocity fields. Most of these tests involve making a perfect profile, introducing effects, then re-examining the ability for the code to recognize the original profile.

4.1. *Perfect Fields*

As a zeroth order test, we made sure that the reexamination of a perfect field gave exactly the right inclination, and the correlation was a perfect one-to-one for well-sampled fields with no turbulence or other large perturbations in the field. DiskFit performed just as well in this test.

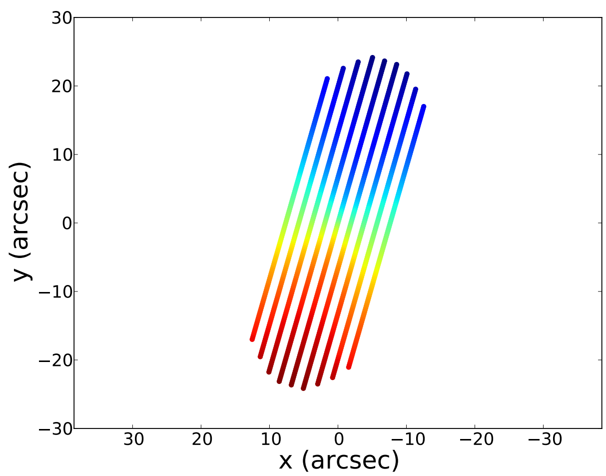

Fig. 4.— An example of a velocity field generated to perfectly fit the photometrically determined properties of a galaxy in the sample with three pointings.

4.2. *Fields with Turbulence*

Next, we introduced random Gaussian noise across the perfect velocity field to model turbulence. The reexamination for 60, 120, and 200 km/s yielded a one-to-one correlation with the original dataset. HOW DOES VFF PERFORM VS DISKFIT? PLOT IT

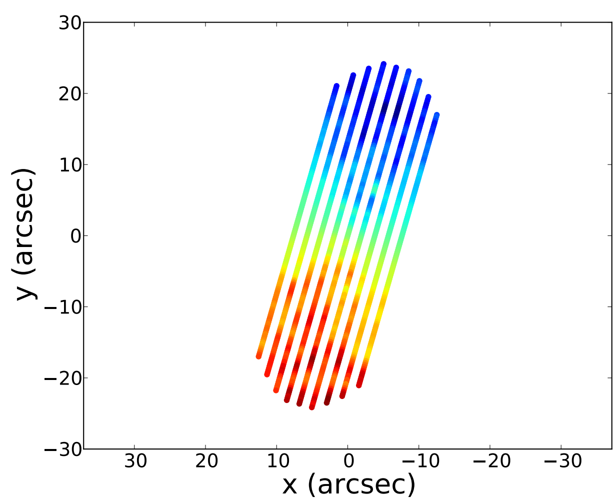

Fig. 5.— The same field from Figure 4, but with 120 km/s Gaussian noise added to the velocity. This models the effects of dust and atmosphere missed by the ADC.

4.3. *Binned Down Perfect Fields*

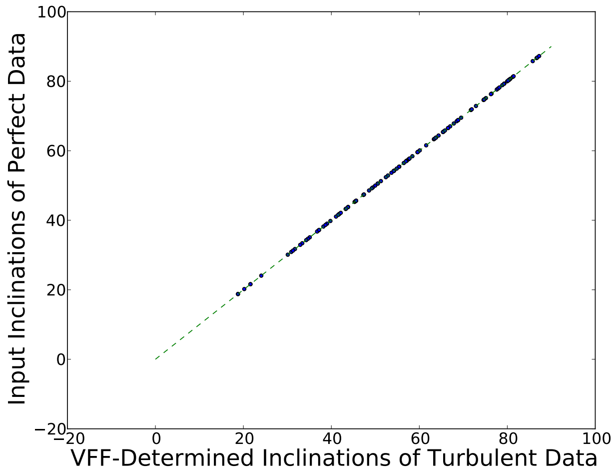

FIG. 6.— The one-to-one correlation with input parameters and output parameters from VFF after 60 km/s turbulence was added.

This test attempted to determine how the fitting process holds up against binned down data from the perfect fields to simulate the resolution of a realistic observation of a galaxy. In fact, for each galaxy we binned at the locations of the actual data from the RESOLVE survey, and used the distance between it and its nearest neighbor as the binning radius. This test gave DiskFit a lot of trouble, making half of the galaxies fail the Fortran fitting procedure that it employs (BRENT). VFF fit all of the galaxies that this test included, but it did not give a one-to-one correlation to the original properties, and fit on average to a lower inclination than the input. This effect is still being investigated in regards to a possible problem with longslit data, but it is promising that the routine does not give up so easily as DiskFit.

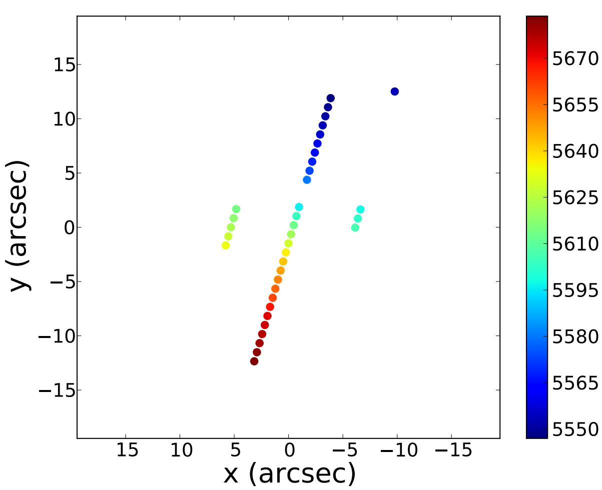

FIG. 7.— The field from Figure 4 with velocities binned to the resolution of the SOAR telescope for direct comparison.

4.4. *Binned Down Turbulent Fields*

This is the ultimate test, and will determine if VFF does okay in the worst case possible, but most realistic.

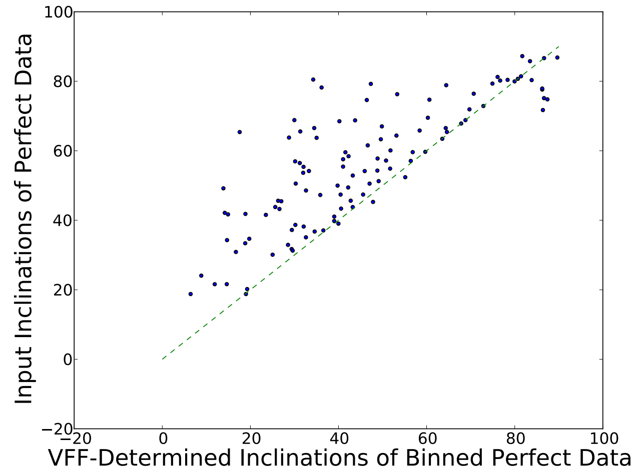

FIG. 8.— A comparison of the input inclinations and the inclinations determined from much more poorly sampled perfect velocity fields.

DO THIS TEST AND PLOT THE RESULTS!!!

4.5. *Real Data*

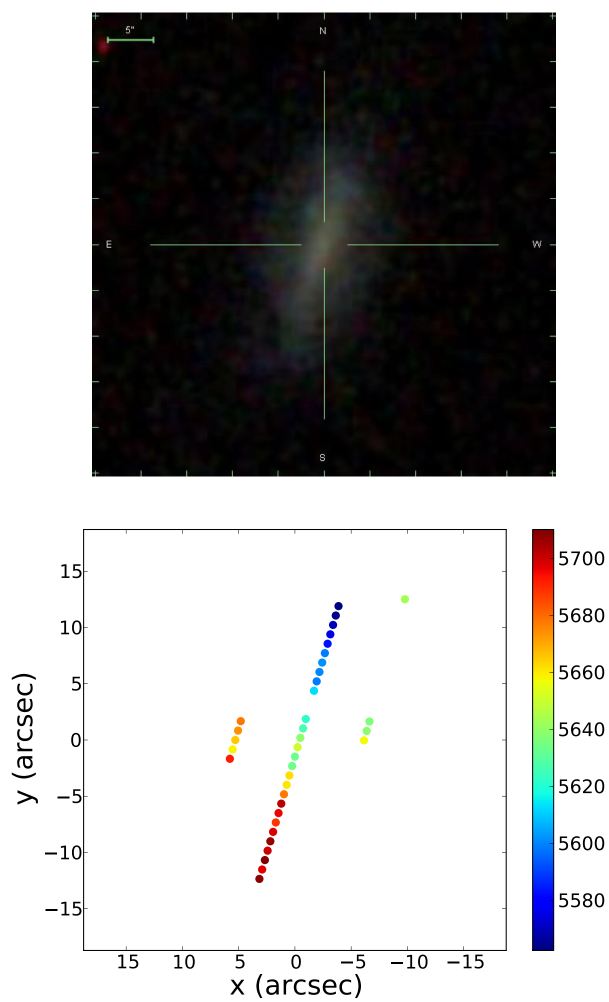

FIG. 9.— The SDSS image and the SOAR spectrum of a galaxy in the survey.

With real data, VFF fits similarly to DiskFit, but with a larger degree of variance from the photometric counterparts. PRESENT AN ANALYSIS OF REAL DATA AND PHOTOMETRIC PROPERTIES TO BE DISCUSSED IN DISCUSSIONS AND CONCLUSIONS.

5. DISCUSSION

6. CONCLUSIONS

7. ACKNOWLEDGEMENTS

REFERENCES

Barnes, E. I., & Sellwood, J. A. 2003, AJ, 125, 1164

Courteau, S. 1997, AJ, 114, 2402

Holmberg, E. 1958, Meddelanden fran Lunds Astronomiska Observatorium Serie II, 136, 1

Hubble, E. P. 1926, ApJ, 64, 321

Markwardt, C. B. 2009, in Astronomical Society of the Pacific Conference Series, Vol. 411, Astronomical Data Analysis Software and Systems XVIII, ed. D. A. Bohlender, D. Durand, & P. Dowler, 251

Teuben, P. J. 2002, in Astronomical Society of the Pacific Conference Series, Vol. 275, Disks of Galaxies: Kinematics, Dynamics and Peturbations, ed. E. Athanassoula, A. Bosma, & R. Mujica, 217–228

Tully, R. B., & Fisher, J. R. 1977, A&A, 54, 661