Astronomical Databases: Quasar Clustering in SDSS DR7, and Novice/Expert Characteristics in Learners

Andria C. Schwortz
Advisors: Dr. Andrea Burrows, Dr. Adam Myers

Department of Physics and Astronomy, University of Wyoming, 1000 E. University Ave., Laramie, WY, 82071

aschwort@uwyo.edu

ABSTRACT

The analysis of large databases is of increasing importance in astronomy as current surveys such as the Sloan Digital Sky Survey (SDSS) and future surveys such as the Large Synoptic Survey Telescope collect more data than can be processed object-by-object. For my thesis research, I propose attacking databases in astronomy from two fronts: on the astronomy science side, I will investigate quasar clustering properties in SDSS Data Release 7 (DR7), while on the astronomy education side I will characterize novice and expert characteristics in college Astronomy 101 students, K-12 teachers, and science / science-fiction writers, as they work on an astronomy activity, and in college calculus-based Physics II students in an action research project. Preliminary work with SDSS DR7 has confirmed that previous results within DR5, such as the stronger clustering of radio-loud quasars than of radio-quiet quasars, persists in DR7. Early analysis of the education data reveals that the activity does result in learning of both the astronomy content and dataset skills, and that K-12 teachers exhibit some expert characteristics such as recognizing the importance of "big picture" thinking in working with astronomy datasets.

Contents

1. Science Project: Quasar Clustering in SDSS DR7

Presented at 225th Astronomical Society Meeting, in prep for publication in the Monthly Notices of the Royal Astronomical Society.

1.1. Introduction

The name "quasar" comes from a shortening of the term "quasi-stellar radio source" (Chiu 1964): these objects typically appear as point sources in images of the sky, much like stars, but their actual spectra do not resemble those of stars. In addition, it was later discovered that not all quasars have radio emission, therefore "quasi-stellar object", or QSO, is the more recently coined term for them. Redshift information also revealed that quasars were at great distances (Schmidt 1963), and thus could not be stars.

Quasars are very bright sources located in the cores of galaxies far from the Milky Way, or equivalently, existing long ago. The sizes of quasars are smaller than the Solar System, and it is believed that they are powered by hot gas spiraling into supermassive black holes (SMBHs) present in the cores of all galaxies. However not all galaxies possess quasars, and the most popular model is that the merger of two large galaxies is what causes the material to migrate in towards the center of the galaxy where the supermassive black hole is located.

Because of the distance to quasars, the nuclear region of these galaxies (and in many cases the entire galaxy as a whole) is unresolved, so all the information we have comes from spectra and the brightness at different wavelengths. When we look at quasars in different types of light, we find that in the optical we see something that is extremely bright and hot (presumably the gas as it approaches the black hole). When we look in the radio, we find that some of the sources are bright in radio emission, and we call these radio-loud quasars (RLs). Based on the shape of the radio spectrum, we know that this is due to synchrotron radiation: relativistic charged particles spiraling around a magnetic field. Today it is well-accepted that the geometry of quasars and related active galactic contains many parts, and that in many parts of the spectrum, the viewing angle controls much of what we see. In the core is the SMBH surrounded by an accretion disk which serves as the optical continuum source, as well as the source for UV and x-ray luminosity (Elvis 2000). A warm highly ionized medium flows out from the accretion disk, and viewing this causes narrow-line and broad-line absorption (Elvis 2000). And a gap in the accretion disk and winds along the axes allows the escape of gas jets comprised of outflowing material entangled with magnetic fields (Blandford & Payne 1982; Begelman et al. 1984; Antonucci 1993). While the physics of the emission from the jets is well-known, the details of how the jets themselves are formed is not well understood, and thus understanding RLs will help us to clarify this picture. In addition, the vast majority of quasars ($\sim 90\%$) have no detected radio emission; this category is called radio-quiet quasars (RQs).

There are two main competing hypotheses regarding the categories of RL and RQ. One says that there are two physically distinct types of quasars, formed in different environments or through different processes, and that each type is constant in time - RLs are always RLs, and RQs are always RQs. The other hypothesis is that all quasars go through phases of being RL and RQ. These transitions could happen stochastically, or in a periodic fashion that could be described by a duty cycle.

One way to study quasars is to look at their environments. It has been known for a while that RLs live in more dense environments than RQs (Shen et al. 2009): if we study individual quasars, we find that there are more nearby galaxies if the quasar is RL than if the quasar is RQ. Since the distribution of luminous matter (that is, galaxies) traces the underlying distribution of dark matter, this implies that RLs are found in environments with more massive dark matter halos than are RQs. More recently large catalogs of quasars such as those from the Sloan Digital Sky Survey (e.g., Schneider et al. 2007 for DR5, Shen et al. 2011 for DR7) have allowed us to statistically analyze the distribution of large number of quasars - to study how quasars cluster. For example, Schmidt (1968) represents some early work into the clustering properties of quasars with redshift, while more recently Richards et al. (2006) examined quasar properties in SDSS Data Release 3. In contemporary works, clustering is quantified with the correlation function, essentially measuring the average excess of quasars that are at a particular distance from each other - see Figure 1 on the right, each blue circle indicates a certain distance from a given quasar, or Figure 2, each data point indicates the average excess of pairs of quasars at each separation. Clustering results from previous authors (e.g., Shen et al., 2009) also imply that RLs form in more dense environments and thus are intrinsically distinct from RQs due to their formation process.

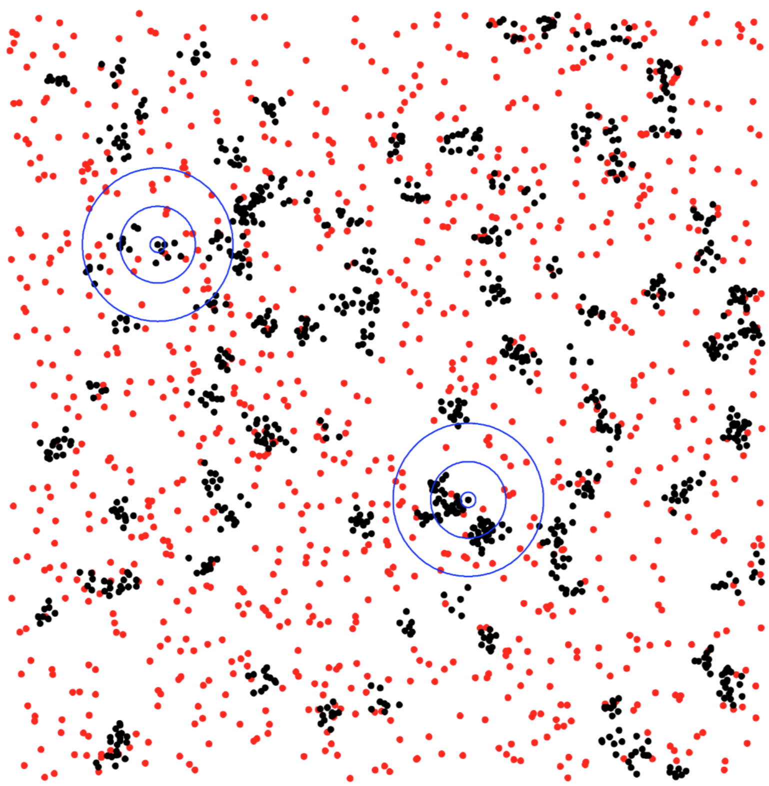

Fig. 1.— Black dots represent clustered quasars while red dots are randomly placed. Blue circles serve as guides to visualizing clustering. Myers c/o DiPompeo.

Additional physical mechanisms have also been proposed to distinguish RLs and RQs (e.g., Richards et al. 2011: RLs tend to have CIV emission that is less blueshifted than that in RQs. Some of the CIV emission may arise from winds originating from the disk around the SMBH, which would result in a blueshift (that is, the observed motion of these winds is towards the observer because the receding winds are blocked from view by the disk). RLs appear to have weaker blueshifted CIV

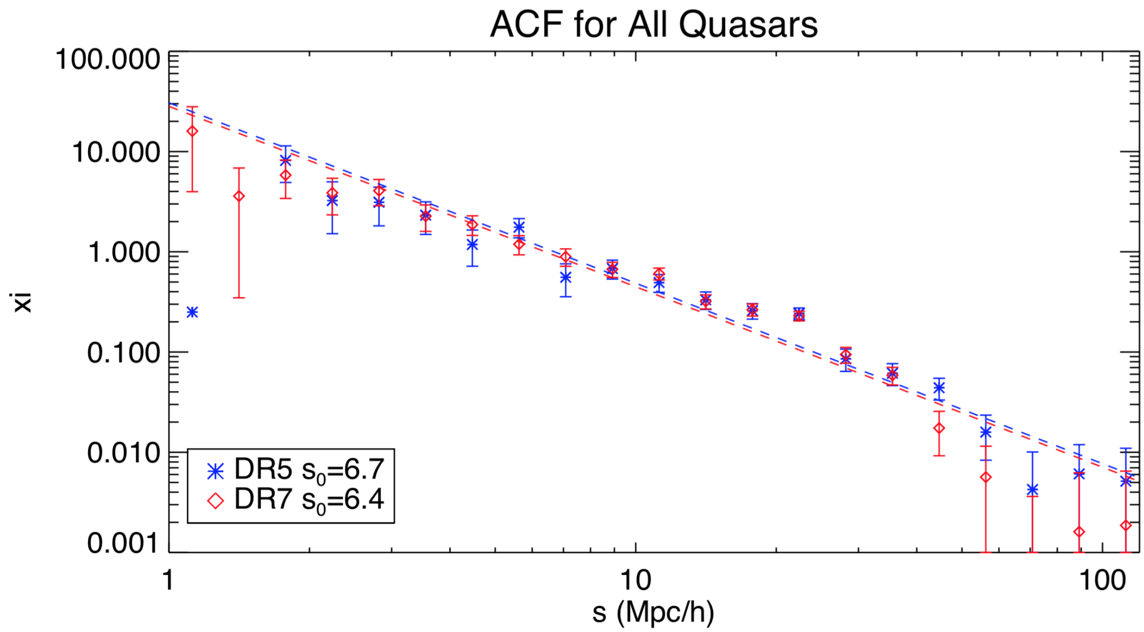

Fig. 2.— Autocorrelation function for DR5 and DR7.

emission suggesting that although they possess stronger jets than RQs, they may have weaker disk winds than do RQs, or possibly non-existent winds.

If this were the extent of the data however, then we would not have anything to research. In fact though, Richards et al. (2011; in particular, Figure 7) have noted that there exist some quasars without radio emission and thus are traditionally categorized as RQs, but which also do not possess strongly blueshifted CIV emission, a characteristic we expect from RLs. As a result, we are calling these RQRL quasars. We do not at this time know whether these specific objects have clustering tendencies more similar to that of RLs (tightly clustered) or RQs (less tightly clustered).

This project seeks to further explore how the clustering properties of RL and RQ quasars correlate with CIV emission. If we determine that RQRLs are as tightly clustered as are RLs, then this will imply that they could be RLs which are in an "off" portion of their duty cycle. If we determine that RQRLs are as loosely clustered as RQs, then we will need to seek another reason why they possess blueshifted CIV emission.

I have confirmed the findings of Shen et al. (2009) using DR5 and expanded upon it using the larger DR7 catalog. We find that at lower redshifts quasar clustering depends weakly on luminosity. Autocorrelation of FIRST detected (radio-loud) and non-FIRST detected (radio-quiet) quasars indicates that radio-loud quasars cluster more strongly than do radio-quiet quasars. We agree with the conclusion that radio-loud quasars reside in more massive and denser environments, implying the possibility that it is physical mechanisms correlated with the density of environment which determine a quasar?s radio loudness, rather than simply whether a quasar's radio jets are pointing towards our Galaxy.

1.2. Methods

The Sloan Digital Sky Survey (SDSS, York et al. 2000) is a survey using ground-based telescopes located in New Mexico. Data Release 7 (DR7) of the SDSS covers ∼11,663 deg^2 of the sky in imaging and ∼9,380 deg^2 of the sky using spectroscopy (Abazajian et al. 2009). The sample of quasars that were spectroscopically confirmed in SDSS DR7 and that were targeted by applying a uniform selection algorithm to SDSS imaging are shown in Figure 3. Figure 3 compares these SDSS DR7 quasars to the earlier uniform sample from SDSS Data Release 5 (DR5), which is the state-of-the-art sample used for quasar autocorrelation clustering measurements over the redshift range of approximately $0.8 < z < 2.2$.

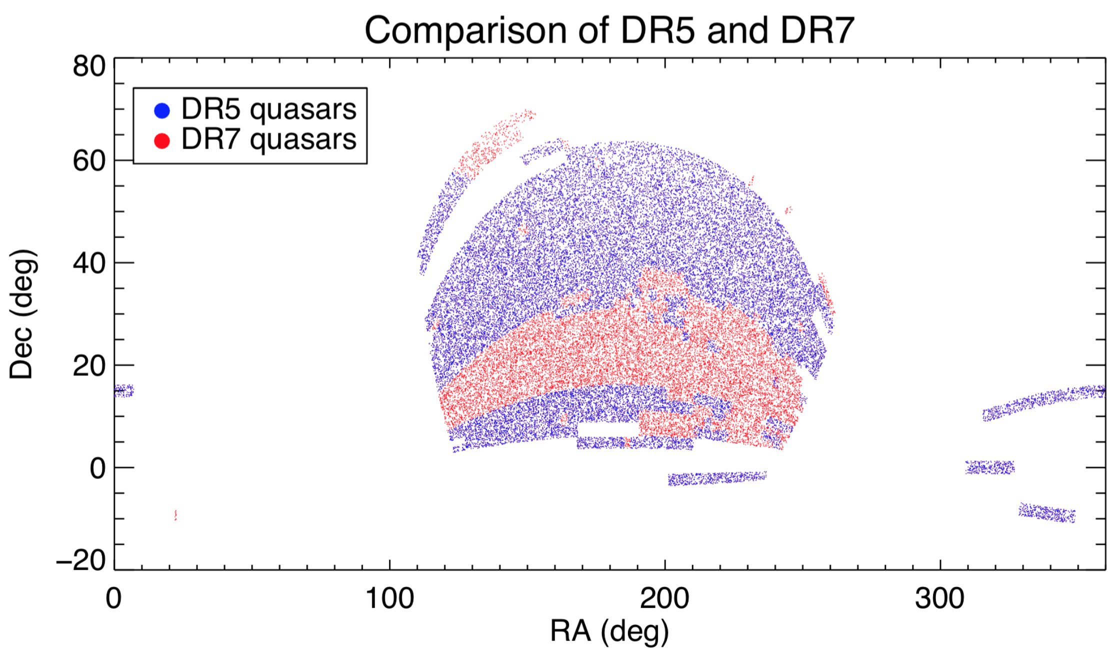

Fig. 3.— Sky coverage of DR5 and DR7. DR5 quasars are represented by blue points; DR7 includes all the blue points plus all the red points.

Data for this part of the project comes from SDSS DR7, and I have this data via our collaborators Yue Shen and Nic Ross. Shen et al. (2009) characterized quasar clustering in DR5, including exploring dependencies upon assorted physical characteristics, such as radio loudness (FIRST detection), brightness, virial mass, and redshift.

Data Release 5 of the Sloan Digital Sky Survey (SDSS DR5) contains 77,429 sources identified as quasars (Schneider et al. 2007), while DR7 contains 105,783 spectroscopically confirmed quasars (Schneider et al. 2010). We will use a subset of uniformly selected DR5 and DR7 quasars to match our random catalog, which restricts our sample to 37,303 DR5 and 58,680 DR7 quasars. These catalogs include information from the VLA FIRST radio survey. Separating our samples based upon whether or not they are detected in FIRST, the DR5 quasar catalog contains 34,809 RQ sources and 3,214 RL sources, and DR7 contains 53,533 RQ and 5,147 RL sources, which are consistent with previous findings that approximately 10% of quasars are RLs.

I have developed an autocorrelation routine using the estimator of Landy & Szalay (1993), and I am also working on a cross correlation routine. Autocorrelation compares each source to another source in the same sample (e.g., comparing RLs to RLs), while cross correlation will compare a given sample to all quasars (RLs to all quasars) - this allows us to highlight differences between the RQ and RL samples while leveraging the larger complete sample size. This routine will measure the 3D correlation function, which (described as a possible estimator by Landy & Szalay 1993) is given by the expression

$$\xi(s) = \frac{< DD > -2 < DR > + < RR >}{< RR >}$$

where $< DD >$ indicates the suitably normalized (or ”average”) number of data-data pairs at a comoving separation of s, $< DR >$ indicates the suitably normalized number of data-random pairs, and $< RR >$ the suitably normalized number of random-random pairs.

Currently error bars for each ACF point have been calculated using Poisson statistics. A simple χ^2 fitting routine steps through the different possible values for s_0 in the power-law model for clustering represented by the below equation:

$$\xi(s) = \left(\frac{s}{s_0}\right)^{-1.8}$$

1.3. Preliminary Results

To date I have confirmed that the autocorrelation function for all uniformly selected DR7 quasars agrees with the results found by Shen et al. (2009) for DR5 quasars, as shown in Figure 2. As Figure 4 shows, our results for the radio-loud vs. radio-quiet quasars are also consistent in that the bias is higher for radio-loud quasars. And we find a mild trend in the evolution of the scale-length with redshift, as shown in Figure 5. The summary of these preliminary results is presented in Table 1.

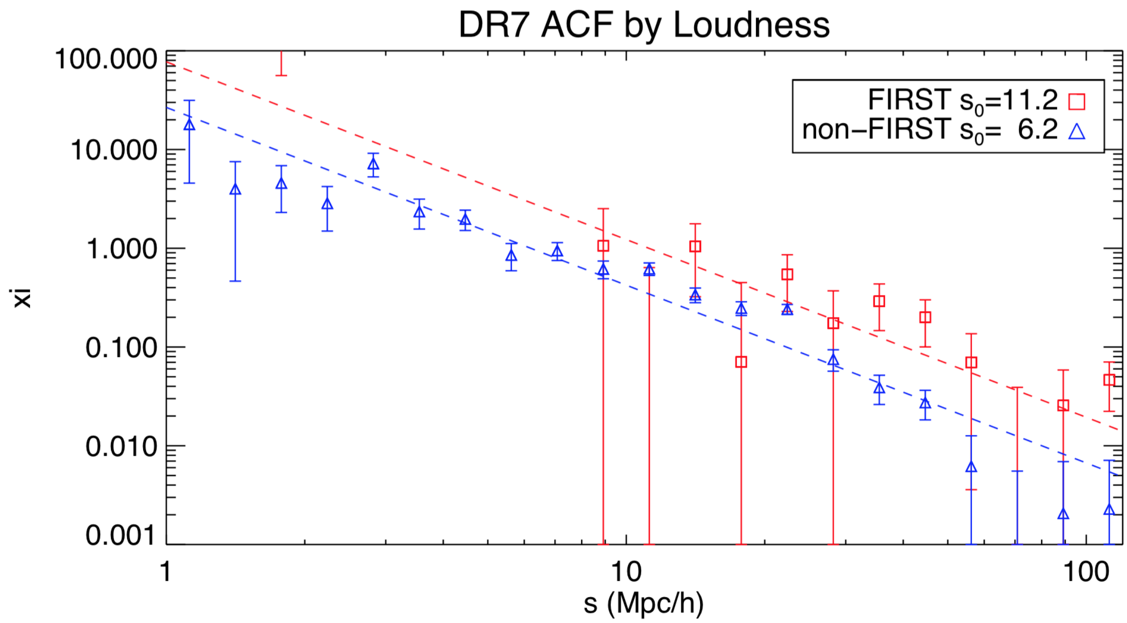

Fig. 4.— Autocorrelation function split by FIRST detection and non-detection.

Sample	N_{QSO}	$\bar{z}$	$\log_{10} \bar{L}_{bol}$ (erg s^{-1})	$s_0\|_{\gamma s=1.8}$ (h^{-1} Mpc)
All luminosities				
$0.1 < z < 0.8$	11748	0.51	45.61	6.0
$0.8 < z < 1.4$	15484	1.12	46.33	6.9
$1.4 < z < 2.0$	17421	1.68	46.66	6.0
$2.0 < z < 2.5$	5968	2.20	46.96	8.0
$0.4 < z < 2.6$				
All	47008	1.38	46.43	6.4
FIRST-auto	4073	1.30	46.47	11.2
non-FIRST	42935	1.38	46.43	6.2

Table 1: Preliminary results of χ^2 fitting to find $s_0|_{\gamma s=1.8}$.

1.4. Next Steps

Additional physical parameters will be examined as well, for example I may look at splitting the sample by the reddening ($\Delta(g-i)$), or by the i-band brightness ($M_i(z=2)$).

I will measure the error bars for the ACF using jackknife error sampling, a standard Monte Carlo approach. To do this, I will split the region into 16 equal area sections on the sky and recal-

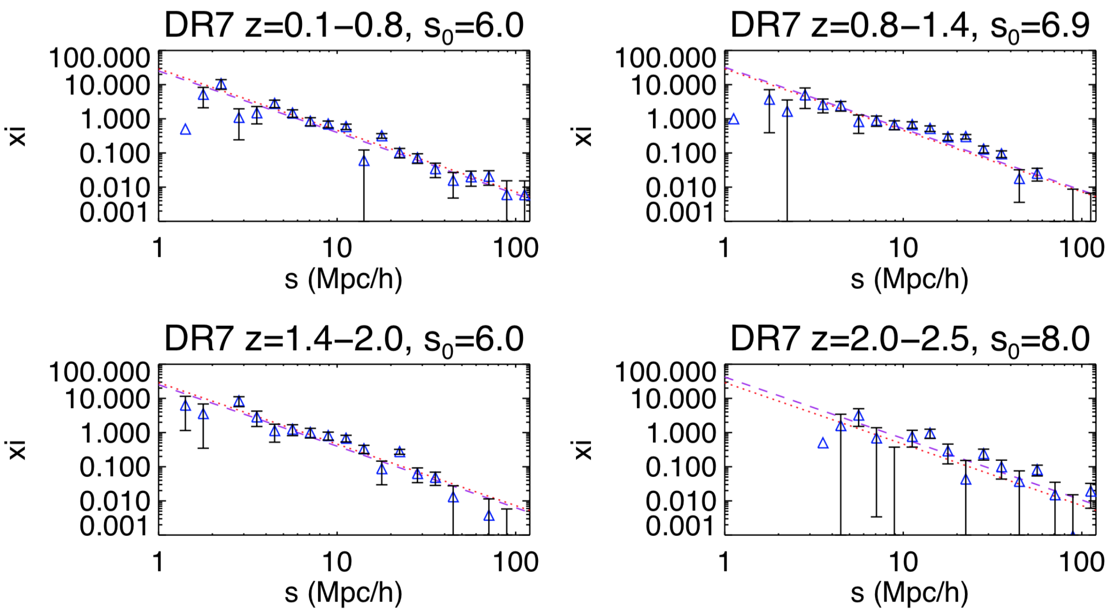

Fig. 5.— Autocorrelation function split by redshift. The red dotted line is for $s_0 = 6.5$ to guide the eye, while the purple dashed line is for the fit indicated in the titles.

culate the cross- correlation after successively removing each sample. The chi-squared power-law fit to the correlation function does not yet have error bars, and after doing so the fits will be compared to not only the previous work by Shen et al. (2009). We will also fit more physical clustering models of the quasar bias (how much more strongly quasars cluster compared to underlying dark matter) and of the mass of the dark matter halos hosting quasars (e.g., Sheth et al. 2001, Smith et al. 2003). We may also attempt to confirm the power law slope of -1.8, though this has been well accepted by previous works.

A stretch goal, which may not be completed for this specific project, is to identify those sources which Richards et al. (2011) found to be radio-quiet but possessing CIV lines similar to those of radio-loud quasars, and determine their ACF or CCF. Depending upon the difference in the amplitudes of the correlation functions, we'll determine whether we have two categories of quasars, RL and RQ, and into which of these two categories the RQRLs fall.

2. Education Project Description: Novice and Expert Characteristics

2.1. Introduction

It is well known within the field of education research that novices and experts exhibit distinct patterns of how they approach problem solving. Bransford et al. (2000), for example, describes six characteristics which distinguish experts from novices: (1) recognition of meaningful patterns, (2) organized knowledge, (3) contextualized knowledge, (4) knowledge retrieval, (5) pedagogical content knowledge and peer instruction, and (6) adaptability and metacognition. Although these traits are recognized, what's less well known is how novices acquire these traits.

In the field of physics education research (PER), most investigations into novice/expert traits have been focused on the solution of individual problems such as would be on a freshman mechanics homework problem set (see, for example, Larkin et al. 1980). There is a dearth of research into either novice/expert traits in astronomy learners, or in learners working with datasets rather than with individual problems. Thus the gap in the literature which I am working to fill is that of determining the process by which people transition from novices to experts when learning to work with datasets in astronomy.

As educators and faculty in physics and astronomy, our goal is to help students to advance along the path from being novices, towards becoming experts and our eventual peers. The exact course that students chart along this path remains a key open question in the realm of science education. As part of my Ph.D. thesis I have begun a program of research into how introductory astronomy students and K-12 teachers approach working with a moderate sized dataset of 200 entries.

I am uniquely positioned to study this problem. As a former community college professor, I have classroom experience working with students who are learning astronomy content, and in physics classes learning to work with datasets. My academic training includes not only the coursework typical for any Ph.D. in Physics and Astronomy, but also courses in both education research at the University of Wyoming, and in science education pedagogy at the University of Massachusetts Amherst. And perhaps most importantly, I have extensive content expertise in the field of astronomical databases: I am also working on a project using data from a massive survey known as the Sloan Digital Sky Survey (SDSS).

Because this project is being split into multiple papers for publication, I have organized the content into the three papers currently in prep. Section 2.2 discusses the mixed-methods paper about the teacher participants (N=14); Section 2.3 is about the quantitative analysis of all participants (N=77); Section 2.4 discusses the action research studio physics project (N=29).

2.2. Novice and Expert Characteristics in Teacher Professional Development with Astronomy Databases

Presented at 2015 Association for Science Teacher Education Meeting, in prep for publication.

2.2.1. Sample

I have characterized the novice and expert behaviors of in-service K-12 teachers who self-selected to attend two astronomy-themed professional development workshops at a large research university in the Rocky Mountains. Fourteen unique individuals attended the workshops and participated in a computer-based activity involving a large astronomy dataset: six workshop A only, five workshop B only, and three attended both workshops A and B. Of the fourteen individuals, six were female and eight male. The activity involved working with 200-entry databases in astronomy using Google Spreadsheets, with limited information about a random set of quasars drawn from SDSS DR5.

2.2.2. Methods

This is a mixed-methods study, including pre-/post-test scores, free responses on the pre-/post-test, artifacts from the activity, audio/video recordings of the activity and transcriptions thereof, and one-on-one interviews. Quantitative data had pre-/post-test means, gains, effect size (Cohen's d, Cohen 1988), and standard deviations calculated both for the group as a whole, and for the women and men separately. P-test and T-tests were performed to determine whether any groups were distinct from the majority. Individual questions were examined to determine which questions had statistically significant improvement.

2.2.3. Preliminary Results

Figures 6 and 7 indicate the quantitative data found for scores, gains, and effect size. In-service K-12 teachers benefit from professional development combining astronomy content and dataset skills while working in groups, though the men teachers demonstrated greater learning ($p<0.05$) than did the women. The three "repeater" participants showed improvement in their second iteration, indicating that even repeating the same professional development is of use to teachers. Nine out of 14 teachers exhibited awareness that a "big picture" exists and is important during data analysis in astronomy. Interestingly, some of the teachers exhibited awareness that the big picture was important, even though they were not themselves aware of what that big picture actually was.

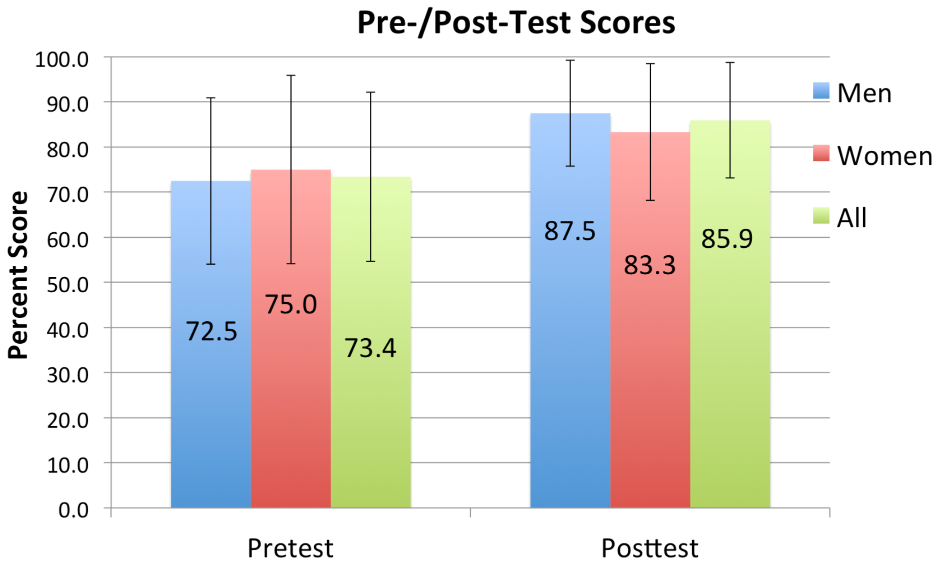

Fig. 6.— Pre- and post-test scores for all teacher participants, and split by gender. Black bars indicate standard deviation.

2.3. Quantitative Analysis of Science Educators' and Students' Pre-/Post-Tests

Presented at 225th Astronomical Society Meeting, in prep for publication in the *Journal of College Science Teaching.*

2.3.1. Sample

The same activity and pre-/post-test as used with the teachers was used with a total of 77 participants, including 54 college ASTRO 101 students, in-service K-12 teachers, and science and science fiction writers (the latter two grouped together as 23 professionals). There were 46 men and 23 women.

2.3.2. Methods

As in Section 2.2.2, we calculated pre-/post-test means, gains, effect size (Cohen's d, Cohen 1988), P-tests and T-tests, and standard deviations. These were calculated for the group as a whole, and for the women and men separately, and for the teachers and professionals separately.

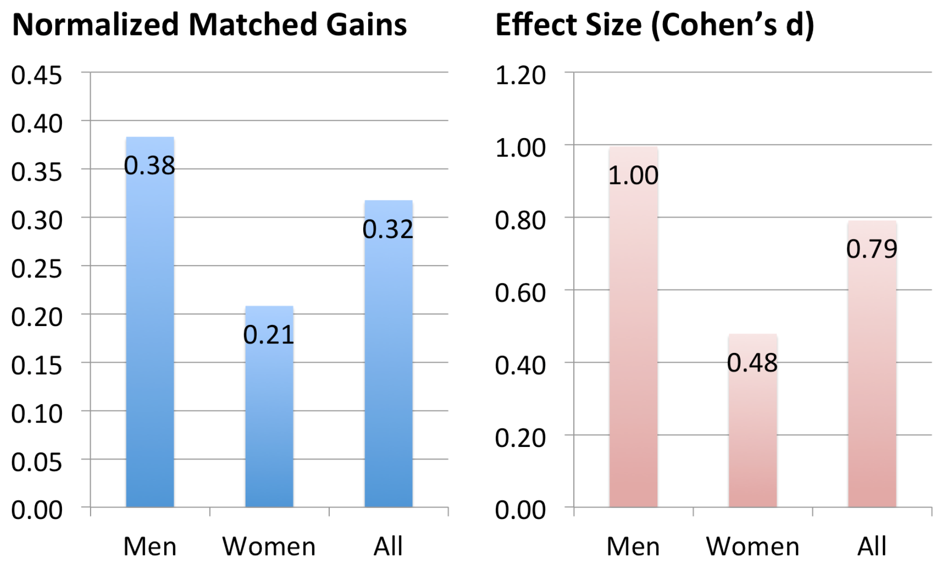

Fig. 7.— Left: Normalized matched gain scores (Hake 1998). Right: Effect size (Cohen's d, Cohen 1988).

2.3.3. Preliminary Results

All groups showed statistically significant differences between their pre- and post-tests gains, women's and men's gains (0.127 and 0.423, respectively, calculated as per Hake 1998) showed statistically significant differences, and while professionals had higher pre- and post-test scores than students, their gains were the same. Figure 8 displays the pre-/post-test scores, Figure 9 the gains, and Figure 10 the effect size.

2.3.4. Preliminary Conclusions and Implications

We conclude that both students and professionals, men and women, can learn how to work with astronomy databases through formal education. The difference between the men's and the women's learning needs to be explored further in the future. We observed during the group work on this project that the men often talked over the women, such as interrupting them, ignoring their comments, and being more likely to be the person controlling the computer. Looking at the qualitative data also collected in more depth will allow us to either confirm this first impression, or to dismiss it. Repeating the experiment with different group arrangements, such as assigning random mixed-gender groups, assigning same-gender groups, or having women participants work alone, will help us to explore the role of gender in this learning.

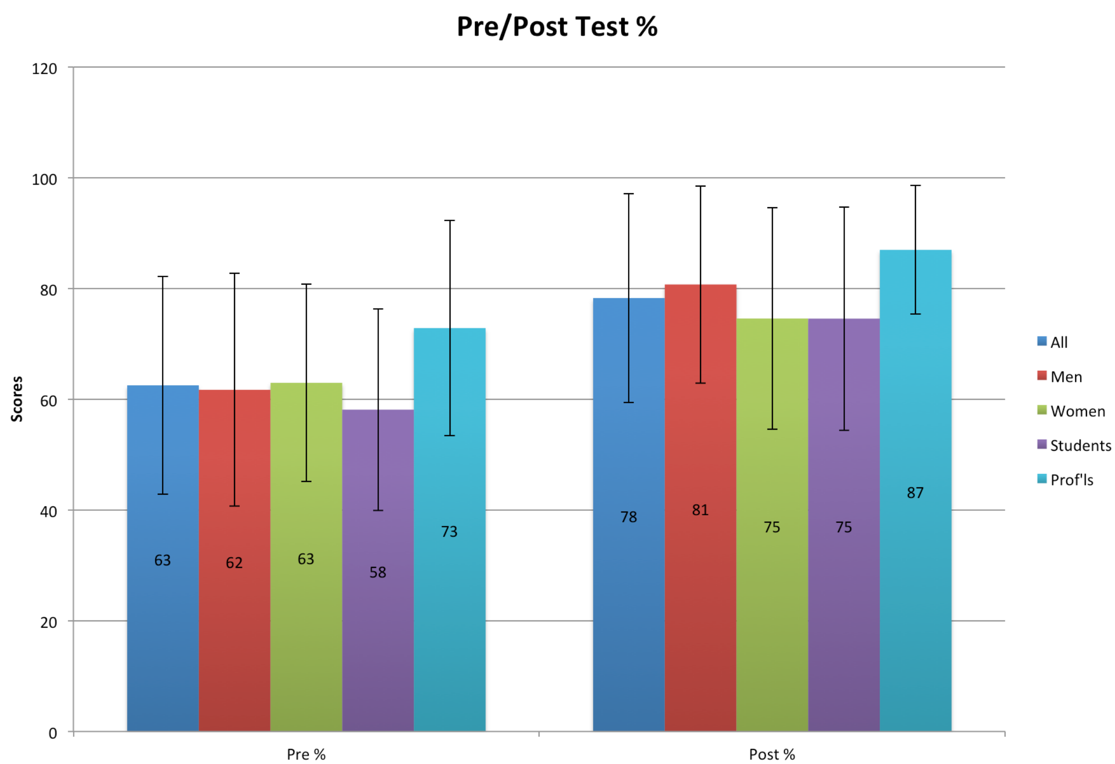

Fig. 8.— Pre- and post-test scores for all participants (N=77), and split by gender and student/professional status. Black bars indicate standard deviation.

2.4. Action Research in Studio Physics

In prep for *Educational Action Research*, with Sarah Katie Guffey (Ph.D. candidate in Secondary Education) as co-author. The philosophy of action research can stated as a researcher partnering with a community to solve a problem. In this project we used an action research approach to investigate the effects of partnering with college studio physics students via student/TA conferences.

2.4.1. Sample

I worked with a studio physics section of calculus-based Physics II. Twenty-nine individuals consented to participate in the study, 24 men and five women. Twenty-six individuals attended student/TA conferences.

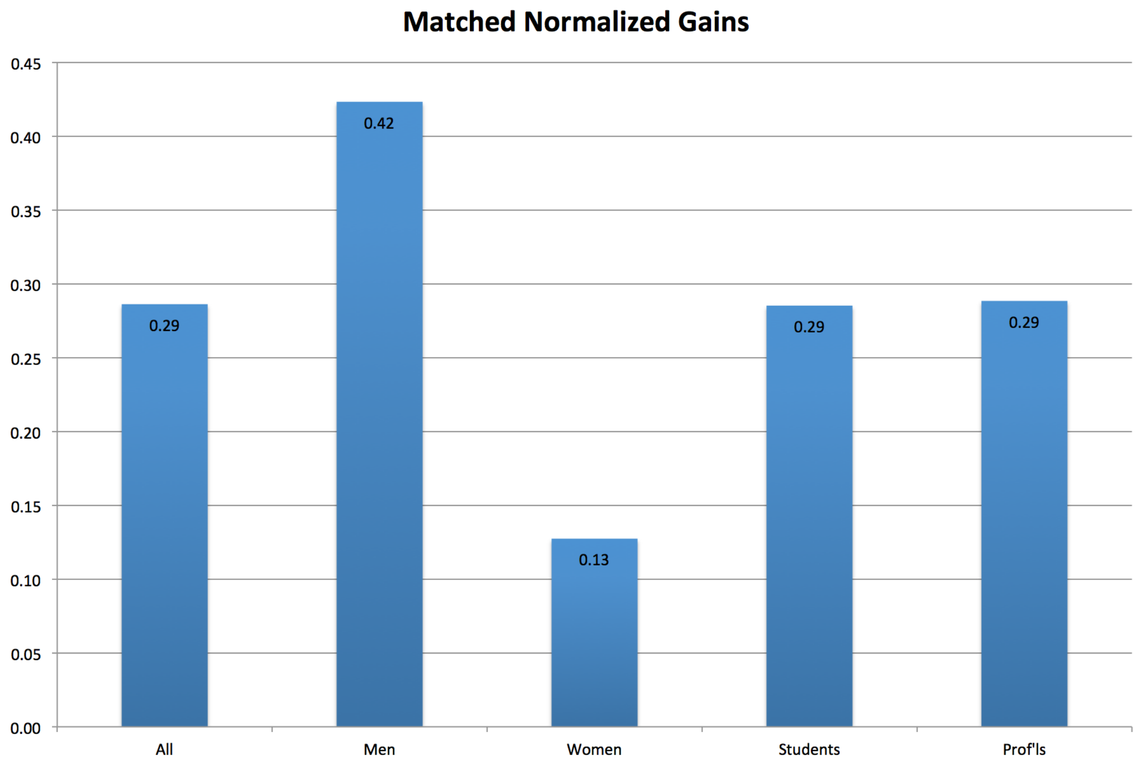

Fig. 9.— Gains for all participants (N=77), and split by gender and student/professional status. Gains for students and professionals are identical, while gains for men are more than three times that for women.

2.4.2. Methods

Data gathered included a pre-/post-survey with yes/no questions, Likert scale questions, and free-response questions. Additional data was collected after the conferences about how often the students interacted with both myself (the TA) and the faculty instructor, and assistants in non-studio sections also collected data on how often their students interacted with the TA, their instructor, and the SI (supplemental instructor, an undergraduate learning assistant). Quantitative analysis looked at responses to yes/no and Likert scale questions, and the number of interactions per student. Qualitative analysis looked at the survey's free-response questions and coded for themes.

Non-studio physics meeting times were explicitly divided into lecture, discussion, and lab sections. In the studio physics section, lecture-like was identified as teacher-centered instruction (following a mostly transmissionist model, with the instructor engaging in self-described "chalk-and-talk" style teaching, such as by worked examples), discussion-like was identified as student-centered sessions (more active learning with students working in small groups, for example using *Tutorials in Introductory Physics*, McDermott & Schaffer 2001), and lab-like was identified as when the students

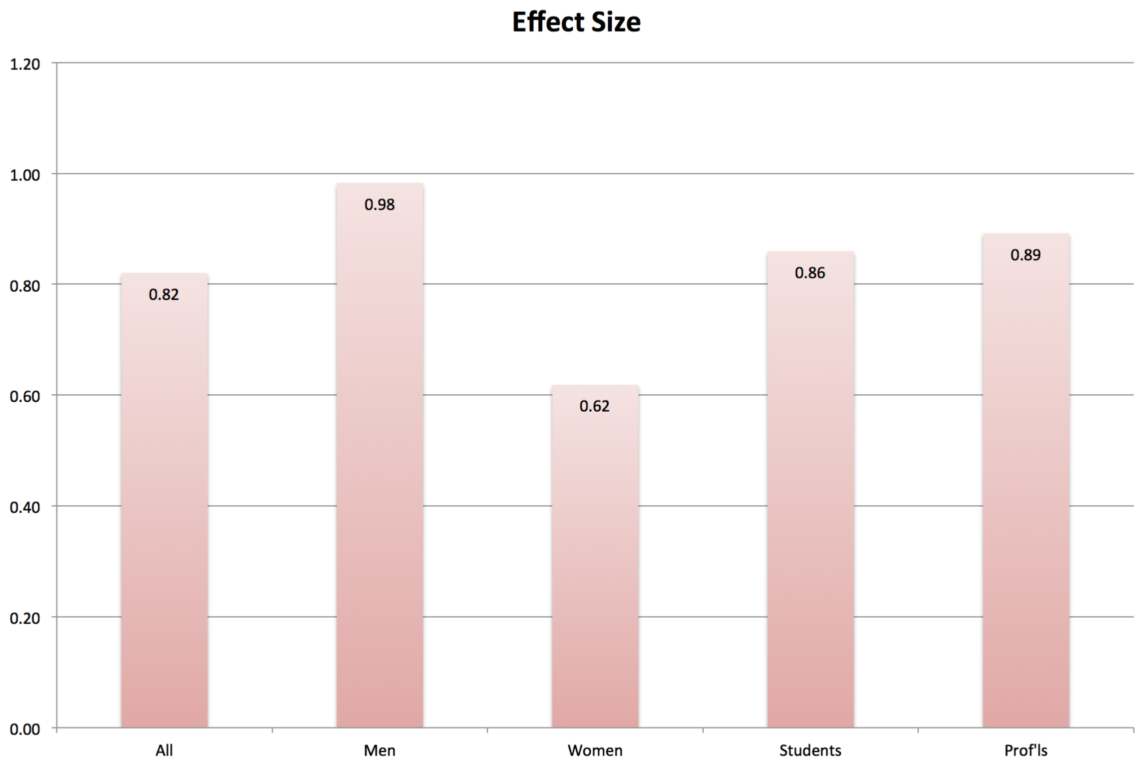

Fig. 10.— Effect size (Cohen's d) for all participants (N=77), and split by gender and student/professional status.

worked with physical equipment as per the course lab manual (Michalak 2012). In the interaction counting, the number of interactions per session per student were calculated for each of these three modalities. E.g., if one day 3 students out of 20 interacted with the instructor, and the next day 7 students out of 20 did, that would be $(3 + 7)/(20 \times 2) = 0.25$. All interactions were counted regardless of the originator of the interaction (e.g., student raising a hand, student approaching the TA during lab, instructor calling on a student randomly during lecture, instructor walking around to student groups in discussion).

2.4.3. Preliminary Results

My self-assessment that I improved my knowledge of student names conflicted with the students' impression that I already knew 80% of student names at the start of the semester. Students reported that I better knew them as individuals and their strengths and weaknesses as students at the end of the semester than at the start. As shown in Table 2, students in studio physics engaged in three times more interactions with instructors per lecture, but students in non-studio physics had almost twice as many interactions with their lab TA as compared with studio physics students during lab-like sessions.

	Studio Physics		Non-Studio Physics	
Modality	N	# interactions	N	# interactions
Lecture	36	0.128	63	0.0476
Discussion	36	0.286	35	0.214
Lab	36	0.333	26	0.538

Table 2: Number of interactions with instructor by modality. N for the non-studio sections is average per section. Studio physics data was taken after the student/TA conferences. Non-studio physics did not have student/TA conferences. Number of interactions are per student per session.

2.5. Next Steps

The next immediate steps are to complete the drafts for publication. After that, additional analysis can be done, for example the qualitative work currently only includes to the sample of teachers, and can easily be extended to the sample of ASTRO 101 students. Additional data will also be collected during the Spring semester, such as one-on-one interviews with the ASTRO 101 students.

3. Timeline and Funding

3.1. Timeline

My proposed timeline is in Table 3. This schedule puts me on track to defend in April and walk in commencement May 16, 2015. Should the timeline slip, I would defend by the end of July 2015, allowing me to graduate by summer 2015.

3.2. Funding

My graduate assistantship for Spring 2015 is provided jointly by the Physics & Astronomy department through a TA position, and by the Secondary Education department through a grant coordinator graduate assistant position (Launching Astronomy: Standards and STEM Integration or LASSI, a federal grant administered by the Wyoming Department of Education, #WY140202). Should my work continue through Summer 2015, funding may be available through LASSI, another Secondary Education grant, or through serving as an adjunct faculty member.

Date	Goal
February	Submit Paper 1 (mixed methods teachers)
	Submit Paper 2 (quantitative) to *Journal of College Science Teaching*
	Submit Paper 3 (action research) to *Educational Action Research*
March	Revise Papers 1-3 as necessary
April	Submit Paper 4 (quasar clustering) to *Monthly Notices of the Royal Astronomical Society*
	Submit Dissertation Paper
	Final Exam / Oral Dissertation Defense
May	Revise Paper 4 as necessary
	Further revision of Papers 1-3 as necessary

Table 3: Proposed timeline.

REFERENCES

Abazajian, K. N., Adelman-McCarthy, J. K., Agüeros, M. A., et al. 2009, ApJS, 182, 543

Antonucci, R. 1993, ARA&A, 31, 473

Begelman, M. C., Blandford, R. D., & Rees, M. J. 1984, Reviews of Modern Physics, 56, 255

Blandford, R. D., & Payne, D. G. 1982, MNRAS, 199, 883

Bransford, J. D., Brown, A. L., & Cocking, R. R. 2000, How People Learn: Mind, Brain, Experience, School (National Academies Press), 385

Chiu, H.-Y. 1964, Physics Today, 17, 21

Cohen, J. 1988, Statistical Power Analysis for the Behavioral Sciences, 2nd edn. (Lawrence Erlbaum Associates), jacob Cohen Cohen?s d

Elvis, M. 2000, ApJ, 545, 63

Hake, R. R. 1998, American Journal of Physics, 66, 64

Landy, S. D., & Szalay, A. S. 1993, ApJ, 412, 64

Larkin, J., McDermott, J., Simon, D. P., & Simon, H. A. 1980, Expert and Novice Performance in Solving Physics Problem, gives a bunch of examples in math and physics - looks like all ?simple? problem-solving cases

McDermott, L. C., & Schaffer, P. S. 2001, Tutorials in Introductory Physics (Prentice Hall), 445

Michalak, R. 2012, Calculus Based University Physics II (Kendall Hunt), 129

Richards, G. T., Strauss, M. A., Fan, X., et al. 2006, AJ, 131, 2766

Richards, G. T., Kruczek, N. E., Gallagher, S. C., et al. 2011, AJ, 141, 167

Schmidt, M. 1963, Nature, 197, 1040

—. 1968, ApJ, 151, 393

Schneider, D. P., Hall, P. B., Richards, G. T., et al. 2007, AJ, 134, 102

Schneider, D. P., Richards, G. T., Hall, P. B., et al. 2010, AJ, 139, 2360

Shen, Y., Strauss, M. A., Ross, N. P., et al. 2009, The Astrophysical Journal, 697, 16561673

Shen, Y., Richards, G. T., Strauss, M. A., et al. 2011, ApJS, 194, 45

Sheth, R. K., Mo, H. J., & Tormen, G. 2001, MNRAS, 323, 1

Smith, R. E., Peacock, J. A., Jenkins, A., et al. 2003, MNRAS, 341, 1311

York, D. G., Adelman, J., Anderson, Jr., J. E., et al. 2000, AJ, 120, 1579

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