THE USE OF AN AUTHENTIC RESEARCH EXPERIENCE IN ASTRONOMY TO TEACH THE PROCESS OF SCIENCE

T.A. Rector, Puckett, A.W. & Wooten, M. (University of Alaska Anchorage), Howell, S.B. (National Optical Astronomy Observatory) and Coble, K. (Chicago State University)

ABSTRACT

"Research-Based Science Education" (RBSE) is an established instructional model that integrates scientific research with education by giving introductory-level undergraduate astronomy students an opportunity to do authentic research with real data. Its goals are threefold: (1) to teach that science is a process of discovery, not just a body of knowledge, (2) to improve attitudes towards science and STEM careers, and (3) to develop critical thinking, teamwork and goal-driven work skills that are important in any career path.

The RBSE curriculum currently consists of five authentic research projects in astronomy: recovering asteroids, searching for classical novae in M31, studying semi-regular variable stars, identifying active galactic nuclei (AGN) in the Faint Images of the Radio Sky at Twenty centimeters (FIRST) survey, and measuring the photometric redshift of distant galaxies in the NOAO Deep Wide Field Survey (NDWFS). Each project uses real astronomical data from professional observatories to investigate authentic research questions for which the answers are not known. The curriculum has been designed to teach students the skills necessary to measure physical quantities from the data and perform meaningful analysis. The projects were chosen and designed so that the students can understand and contribute in a way that improves the body of scientific knowledge. The research questions are authentic, in that their answers are not yet well known by the scientific community. In other words, in order to learn science, students are given the opportunity to actually *do* science. Similar efforts have been done in other fields, including geology (Barnett, Kafka & Pfitzner-Gatling 2005; Bhattacharyya 2009) and biology (Campbell et al. 2012).

From 2003 to 2014, the RBSE curriculum has been developed and tested at six partner institutions, forming a "RBSE University" (RBSE-U) network. In this paper, we explain the philosophy behind the RBSE program, describe the research projects, and outline the scientific and educational outcomes that have resulted from their participation.

INTRODUCTION

The RBSE method of instruction models the processes of scientific inquiry and exploration used by scientists. It is "research-based," integrating *scientific* research with education. It brings the excitement of discovery to classrooms by giving students the opportunity to do science, not just study it through lectures removed from the actual research process. Students participate in research projects, utilizing research-class telescope observations, analyzing data and interpreting their results. They personally explore and work together as collaborators in a cooperative environment.

RBSE is an integration of research and education, teaching science as it is done by scientists. The RBSE curriculum incorporates teaching strategies that model scientific reasoning. These include focusing on an in-depth project, engaging in self-organization and reflection, using computers as a tool for data analysis, and using student logs and concept maps for assessment. RBSE is used in college introductory science courses because, for many students, it represents their last formal exposure to science. It enables students to experience the rewards of research early enough to pursue science as a career – most scientists chose their career because of a passion for research. But the opportunity to participate in research usually comes only to STEM majors, and not before the junior year. Even if students do not pursue STEM degrees, RBSE develops skills that are helpful in any career, such as teamwork and interpretation of information and data to draw a conclusion. And for those who become teachers, it leverages the concept of scientific discovery to a broader audience of learners. The importance of an undergraduate research experience in career selection is well established (e.g., Hathaway 2002; Russell 2007). Ninety percent of the students who intend to pursue graduate studies in physics participate first in a research project, as compared to 65% of those who plan graduate studies in other fields and 68% of the students who plan to enter directly into the workforce (Mulvey & Nicholson 2002).

Over the last twelve years we have developed and tested the effectiveness of RBSE at six partner institutions. This group included two large "research one" universities (Indiana University-Bloomington (IUB) and U. Washington in Seattle), two medium-size, teaching universities (U. Alaska Anchorage and Chicago State U.) and two community colleges (Pima Community College in Tucson, AZ, and Truckee Meadows Community College in Reno, NV). A "RBSE-U" network of instructors from the partner institutions was developed to foster collaboration and to share innovation. Student gains in understanding the process of science, changes in attitudes towards science and STEM careers, and gains in critical thinking were assessed with various tools, the results of which will be given in a separate paper. The curricula were also improved based upon student and faculty feedback.

THE RBSE CURRICULUM

The RBSE curriculum consists of five authentic research projects developed for "Astro 101" students. Each project contains: (1) real scientific data, (2) curricula to teach the necessary data-analysis skills and the relevant science content, and (3) introductory exercises that model the research pedagogy. Each focuses on a topic accessible to students to which they can make a valuable scientific contribution. Most can be extended, so that students can build upon the work of prior cohorts. It is emphasized that the RBSE research projects are based upon authentic scientific questions, not static activities. In each case "answers" are not known, and address outstanding problems in astronomical research.

Each project has introductory exercises that teach important research skills, i.e., how to approach a problem like a scientist. These exercises also cover the topical material necessary for the project. For example, to do the Nova Search project students do several structured activities to learn how to search for novae, to measure their locations, and to precisely determine their brightness using aperture photometry with in-field standard stars. We call these "toolbox" activities (instead of "cookbook") because students learn the techniques they will use to complete the project in a manner similar to that advocated by Brown, Collins, and Duguid (1989). Students also learn skills that are valuable in other contexts, e.g., to visually display and interpret data in the form of a graph or chart. Students performing authentic activities are more likely to develop their inquiry and communication skills and become better lifelong learners (Edelson 1998).

The research projects currently require software to be installed on users' computers. Image-based projects use the *ImageJ* freeware program, a generic image-processing program developed by the National Institute of Health. Our *Polaris* plugin adds to *ImageJ* the necessary functions of aperture photometry, astrometry and timing for a range of FITS datafiles, including the pixel-specific timing of images from the Sloan Digital Sky Survey (SDSS). For spectroscopic projects, we use a commercial program from Vernier, Inc. called *Graphical Analysis 3* (GA3). It is a generic graphing program that allows a spectrum to be plotted linearly.

Each project has been designed to match areas in content and pedagogy commonly taught in introductory college astronomy courses. For example, the skills and science content for a "Variability of Solar-Type Stars" project include:

The Nature of Light:
- The EM Spectrum
- Optics and Telescopes
- Cameras and CCDs
- Motion of the Sky
- Celestial Coordinates

The Nature of Stars:
- Properties of the Sun
- Solar Variability
- The Sun as a Star
- Stellar Evolution
- Types of Variable Stars

Tools of Astronomy:
- Image Processing
- Data Analysis
- Astrometry
- Aperture Photometry
- H-R Diagram

Thus, students learn scientific content knowledge in the context of the research project. They are more likely to retain this knowledge because they are using it as part of the project. It therefore becomes relevant to the students, rather than merely a set of abstract information they were told to learn.

THE PROJECTS

Currently the RBSE curriculum consists of five research projects:

1. "Recovery" Observations of Asteroids

Students analyze images from the WIYN 0.9m, SkyNet or SDSS telescopes to search for known asteroids at risk of becoming "lost." Roughly one-fifth of all discovered asteroids are lost when, over time, orbit uncertainties increase to the point that finding them again near their predicted locations becomes unlikely. Students "recover" asteroids and refine their orbits by analyzing images of predicted locations and searching for objects that have moved from one image to the next. If an object's orbit suggests a possible impact with a planet, students have the tools to calculate these odds as well. An important aspect of the project is that students participate in an iterative approach to refining an asteroid's orbital parameters. This helps them understand that much of scientific enterprise is devoted to improving the accuracy of knowledge.

Once found, the asteroid's location is measured using the *ImageJ+Polaris* software. A separate program called *Find_Orb* is then used to determine consistency with past observations, and to generate a new best-fit orbit along with hundreds of alternate possible orbits. Students confirm that they have improved knowledge of the orbit by showing that the range of possibilities has been reduced. They then submit their astrometric observations to the IAU Minor Planet Center (MPC) database, resulting in publication in the *Minor Planet Circulars* (e.g., Holmes et al. 2010).

The current version of this project requires three separate programs, one of which only runs on a PC (*Find_Orb*), meaning this project can currently only be done on PC computers**.** However, recent progress toward platform-independence has been made through development of our online "OrbitMaster" visualization tool, based on the previous "OrbitViewer" tool developed by AstroArts Inc and NASA/JPL.[1] Hundreds of possible orbits can now be visualized and compared from both before and after the students' contributions, as in the following figure. "OrbitMaster"

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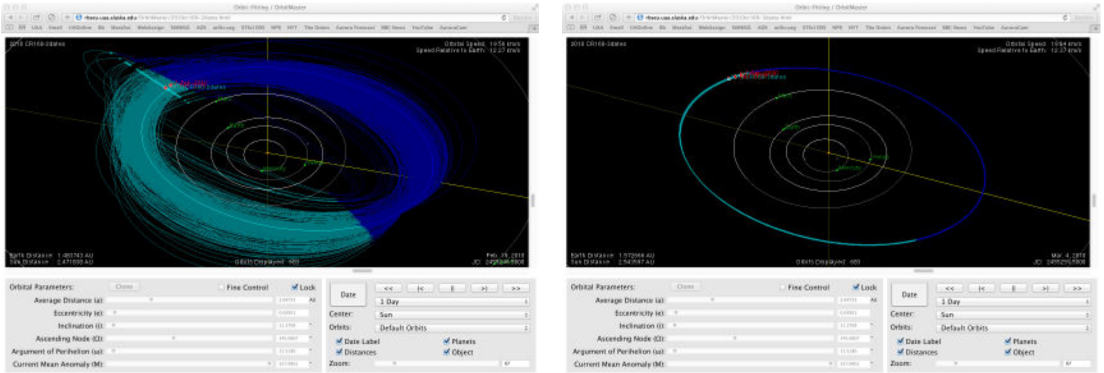
[1] http://www.astroarts.co.jp/products/orbitviewer/index.html This program is free software; you can redistribute and/or modify it under the terms of the GNU General Public License as published by the Free Software Foundation.

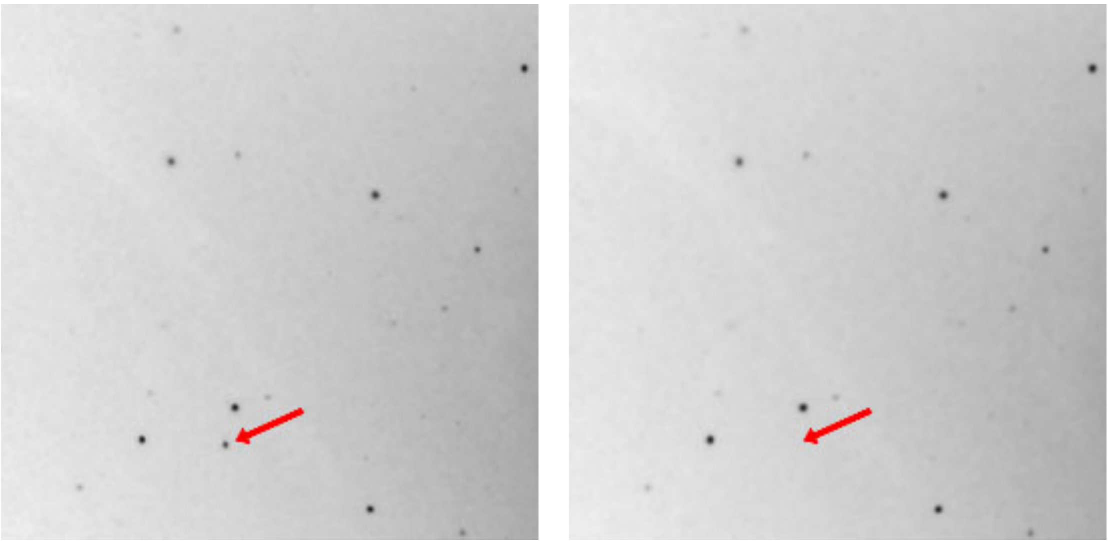
now also enables hands-on investigation of Kepler's laws, automatic detection of Earth impacts and close approaches, and updated relative speeds due to Earth's gravity.



Caption: "OrbitMaster" visualizations of over 600 potential orbits of asteroid 2010 CR$_{160}$, showing reduced uncertainties based on our students' work. The left panel shows orbits based on initial observations by La Sagra Observatory, along with data taken 12 days later by the Astronomical Research Observatory on Skynet. The right panel shows orbits refined using serendipitous Spacewatch observations from 13 days later still. The La Sagra and Spacewatch observations were not known to be of the same object until after our students "linked" them by submitting to the MPC their measurements of the intervening ARO images a few weeks later (Holmes et al. 2010).

2. *Nova Search*

Images of the Andromeda Galaxy (M31) are obtained regularly (monthly to weekly) with the WIYN 0.9-meter telescope. Students are looking for a "nova," a flaring that is caused by a thermonuclear reaction on the surface of a white dwarf star due to mass exchange with a gravitationally bound partner. Students find the novae by "blinking," or rapidly comparing, images taken of the same location on different dates. Stars in the short-lived novae phase will thus flare and be detectable for a few months to over a year.

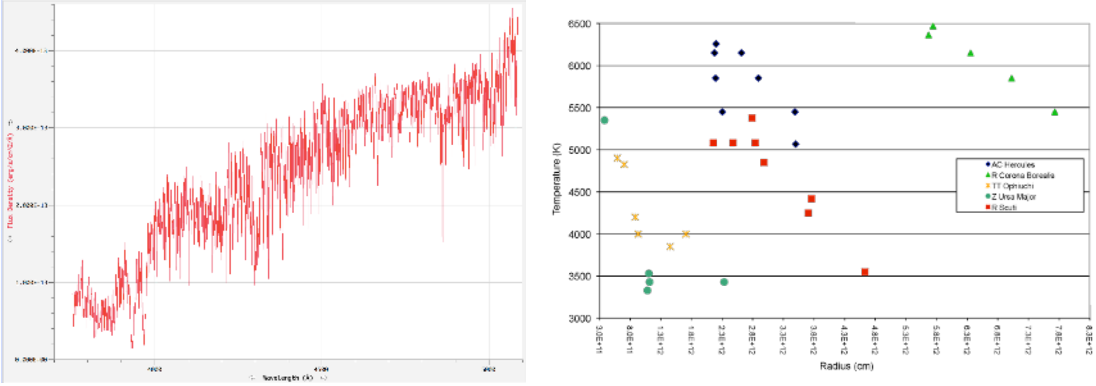


Caption: Two images of near the center of the Andromeda Galaxy taken in August 1995 (left) and July 1997 (right). The images are inverted so the stars look black and the night sky is white. If you look closely, you can see a nova was erupting in August 1995 in the lower-left corner of the left image. By July 1997 that nova had faded from view.

Students examine the novae they discover with *ImageJ+Polaris*. If a nova is seen in more than one image, students generate a light curve by plotting the brightness of each nova over time. Students have investigated a range of questions, such as: Is there a relationship between the distance of a nova from the galactic center and its rate of decay? Do the locations of novae correlate with *Chandra* X-ray sources? And is there a correlation between peak brightness and rate of decay? There is debate in the literature on these and other questions (e.g., Ciardullo et al. 1990 and Yungelson *et al*. 1997).

3. Spectroscopy of Semi-Regular Variable Stars

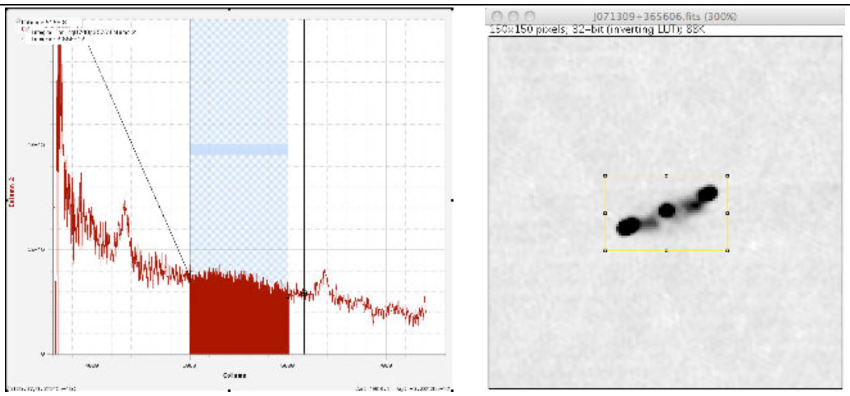
An unconventional class of stars, known as semi-regular variables, or "RV Tauri stars," exhibits complex changes in brightness as well as dramatic spectral changes over time scales of years. Students analyze spectra taken 1-2 times a year with the Kitt Peak Coudé Spectrograph to determine each star's current spectral class and surface temperature. Using photometry from the American Association of Variable Star Observers (AAVSO) database and astrometry from the Hipparcos catalog, students determine brightness and distance, and therefore calculate luminosity and size. Determining what correlations exist between varying stellar temperature, luminosity and radius will improve our understanding of the RV Tauri stars, including their physical state and why they change, and how they are related to other types of stars (e.g., Bjorkman et al. 2000). Student work has let to several published papers (e.g., Howell et al. 2009). The latest undergraduate research results were presented in Hernandez et al. (2013), Pugh et al. (2013) and Kurgatt et al. (2013). The plots below show five example stars.



Caption: Students analyze a spectrum (left) to determine a star's spectral class during a particular epoch. Multiple epochs for five sample variable stars are plotted on a temperature versus radius graph (right) to illustrate their complex behavior.

4. Active Galactic Nuclei (AGN) Spectroscopy

The Kitt Peak 2.1m and other telescopes have been used to obtain spectra of over 2000 optical counterparts to FIRST radio sources (White et al. 1997) and in X-ray surveys. These objects are believed to be active galactic nuclei (AGN) because of their luminous radio and X-ray emission. The primary goal is to determine the nature of each object: is it a quasar, a radio galaxy, or something altogether unexpected? Students also analyze each optical spectrum to determine a redshift, and thus distance, for each object. FIRST radio images are then downloaded to measure radio flux density and angular size. Once a distance is determined, students may calculate intrinsic luminosity at optical, radio and X-ray wavelengths, as well as physical size.


J071309+365606.fits (300%)

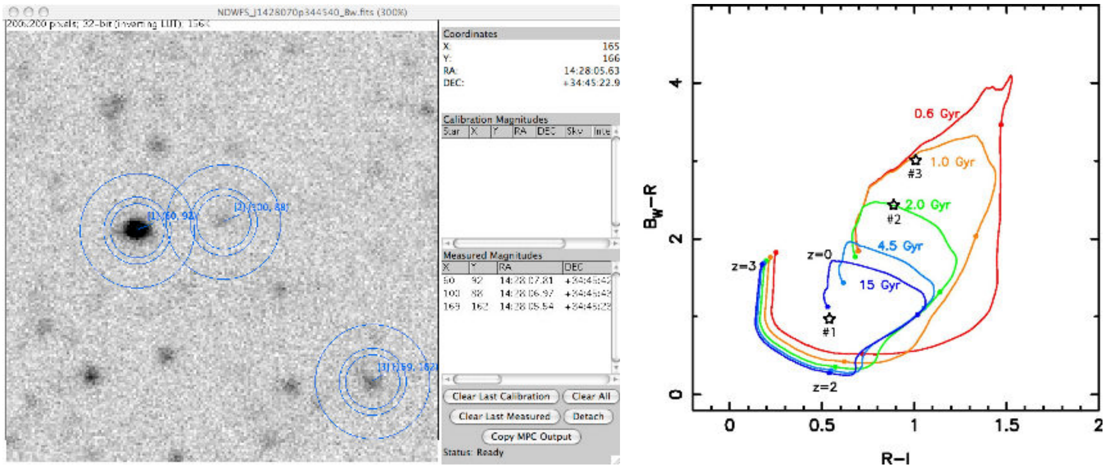
150x150 pixels; 32-bit (inverting LUT); 88K

Caption: Quasar optical emission lines are identified, a redshift is measured, and optical flux density and luminosity are calculated (left). FIRST maps provide a radio luminosity and physical size (right).

The survey nature of this project allows students to investigate many different research questions; e.g., are quasars more numerous than radio galaxies? Is there a relationship between an object's physical size and its luminosity? For each class of object, students can also generate a "luminosity function," a histogram of the number of objects as a function of luminosity.

5. *Photo Z (Photometric Redshifts and Stellar Evolution)*

This project is intended for students with a good understanding of photometry and spectroscopy drawn from the other RBSE projects. Students search for distant galaxies in the NOAO Deep Wide Field Survey (NDWFS), using aperture photometry for red galaxies in three filters. Galaxy "colors" (the difference in brightness between filters) are plotted on a color-color plot (see below). Each "track" shown represents a theoretical model for a galaxy in which star formation occurs for a different amount of time (with redder tracks representing galaxies for which star formation has long since ended). A galaxy's position on each track depends on its redshift. Thus, the redshift (distance) *and* star-formation history of a galaxy can be estimated by its location. The long-term goal of the project is to identify distant galaxies by searching regions near quasars in the survey area.


NDWFS_J1428070p344540_Bw.fits (300%)

200x200 pixels; 32-bit (inverting LUT); 156K

Coordinates

X: 165

Y: 166

RA: 14:28:05.63

DEC: +34:45:22.9

Calibration Magnitudes

Star	X	Y	RA	DEC	Sky	Inte

Measured Magnitudes

X	Y	RA	DEC
50	92	14:28:07.81	+34:45:42
100	88	14:28:06.97	+34:45:43
169	162	14:28:05.54	+34:45:23

Status: Ready

Caption: Aperture photometry in three filters of three galaxies discovered in the NDWFS (left) allows them to be plotted on a color-color diagram (right). Each "track" shows a galaxy with a different star-formation history. A galaxy's position on a track depends on its redshift and history.

STUDENT GAINS AND DISCOVERIES

Students participating in the RBSE curriculum have also made several important scientific discoveries. One of the RBSE research projects is to search for classical novae in the Andromeda Galaxy (M31). Because of the complex environment of M31, identifying novae is more reliably done by eye. Students search for novae within the central 20' region of the galaxy. “Double blind” searches were completed by students from different classes. Over a thousand students have searched 169 images over the last 12 years. Currently 103 confirmed novae have been identified in M31, with an additional 86 candidate novae, more than any other single effort (e.g., Shafter & Irby 2001). The latest student results from this project are presented in Shafter et al. (2015).

As part of the variable star RBSE research project, a group of students has been spectroscopically monitoring semiregular variable stars (e.g., RV Tauri-class stars). The periodicity of RV Tauri and semiregular types is not as well-behaved as other variables such as Cepheids, and a single cycle takes between months and years. These constraints make the study of these objects difficult. While they lie between the Cepheids and the Miras on the Hertzsprung-Russell Diagram and are believed to be in transition from the Asymptotic Giant Branch to white dwarf phase, their evolution is not well understood. Long-term monitoring of these objects with the KPNO Coudé Feed spectrograph has revealed considerable new insights into their behavior. Three posters on results from this project were presented by students at the 221st meeting of the American Astronomical Society (AAS) in Long Beach, CA.

Finally, students participating in the recovery observations of asteroids have, in the last four years, generated 504 astrometric measurements, recovering 96 asteroids and Kuiper Belt objects. Students have determined that none of these objects are a threat to the Earth or other planets.

As part of the program, we also assessed students’ conceptions of the scientific process and what it was like to participate in an authentic scientific research project. The results of those analyses will be presented separately from this paper.

CONCLUSIONS

The learning objectives invoked by many science educators often focus on gains in student content knowledge regarding science concepts. But authentic science is a process of discovery, not just a body of knowledge. In recent years there have been several calls for teaching to better reflect how science is done (e.g., Handelsman et al. 2004). To this end, the RBSE curriculum seeks to engage students in the process of scientific research in an astronomy content-rich context, emphasizing the discovery-oriented work of a scientist. The outcomes examined in this paper reveal that introductory science students, majors and non-majors alike, have the potential to do the work of scientists and contribute their results to science. The extent to which students exhibit learning about the process and practice of science as a result of participating in the curriculum will be presented in a separate analysis.

The RBSE curriculum is free to use by anyone and we welcome instructors who are interested in incorporating the projects in their teaching. Documentation and datasets for each of the five projects can be found at the project websites:

http://rbseu.uaa.alaska.edu/	(UAA website)
http://www.astro.indiana.edu/catyp/rbseu/	(IUB website)

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