Fundamental Astronomy: Direct Measurement of Masses for O Stars

Motivation

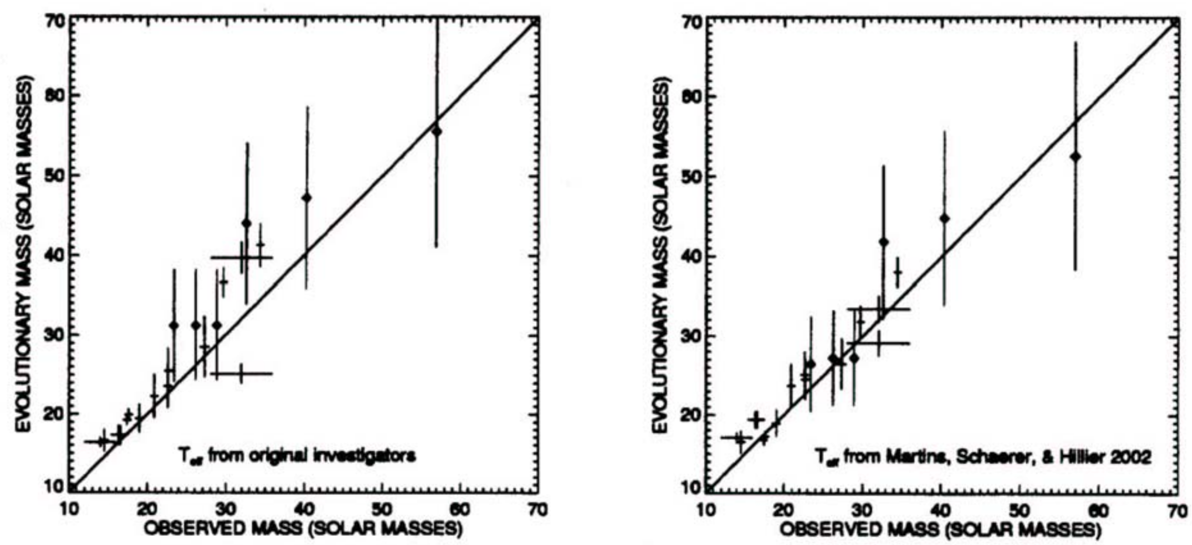
Although very rare, the most massive stars wield an influence far greater than their numbers would imply. Throughout their entire life cycle, these stars interact with their surroundings radiatively, dynamically, and chemically, and hence have a direct effect on the evolution of their host galaxies. When observing distant galaxies, it is also these most luminous stars that dominate the integrated light at most wavelengths. Star formation rates in galaxies are routinely calculated by measuring the integrated emission from HII regions, and then working backwards to calculate the number of ionizing (massive) stars with an assumed Initial Mass Function (e.g. DeGioia-Eastwood et al. 1984). And it now seems likely that the first generations of these most massive stars are at least partially responsible for the "cosmic reionization" of the universe at $z \approx 6$ (Sokasian et al. 2003).

Given the number of investigations in astronomy that depend on understanding these most massive stars and their evolution, one might assume that the stars were well understood theoretically. However, due to the complexity of these stars, this is not yet the case. Their high masses and low surface gravities lead to extensive and ongoing mass loss, making both evolutionary and stellar atmosphere models difficult to pin down. It is only in the last two decades that the massive star community has agreed that Wolf-Rayet stars are simply O stars in stages of advanced evolution: the WN stars are believed to be what is left of an O star after extensive mass loss has revealed the core after main-sequence hydrogen burning has been completed, and the WC stars are thought to be the revealed helium-burning core (see recent review by Massey, 2003.)

In 1992, Herrero et al. first documented what they called the "mass discrepancy" for O stars. This discrepancy was a systematic difference between masses derived purely spectroscopically by comparing the stellar spectra with model atmospheres, and those derived by placing the star in the H-R diagram and interpolating between evolutionary tracks. This discrepancy was found for only a few individual cases for main sequence stars, but found to be systematic for the supergiants, which are plagued with excessive stellar winds as the stars evolve off the main sequence. At the most recent international meeting on massive stars, IAU Symposium 212 in June 2002, most participants agreed that this "mass discrepancy" has been lessened with the introduction of a new generation of stellar atmosphere models that include not only mass loss but sphericity and metal-line opacities. The new models basically suggest a new, lower, scale for the effective temperature at a given spectral type (see Martins, Schaerer, and Hillier 2002, and others).

This "mass discrepancy" was also discussed at that meeting by Doug Gies (2003) in a review on the masses of O stars derived from binaries. Gies discussed the only two direct methods for determining stellar masses, i.e. spectroscopic and photometric observations of a double-lined spectroscopic binary system which is also eclipsing, and the measurement of an astrometric orbit through high angular resolution techniques. So far only one massive binary system has been discovered that falls into the period range suitable for the astrometric technique. Thus most of the masses that have been directly determined for massive stars have been measured through the first technique, which is generally possible only for short period binaries since the probability of observing an eclipse decreases with increasing separation between the stars. As Gies points out, however, the masses of close binaries may be altered by mass transfer between the two stars, and thus when comparing measured masses to evolutionary models it is necessary to restrict the sample to unevolved binaries.

In the figure below we reproduce Gies' (2003) Figure 1, where he has plotted masses obtained from the only twelve binary systems for which masses for unevolved O stars have been determined. On the vertical axis he plots "evolutionary mass" which he obtained by interpolating in the (log T_{eff}, log L/L_O) plane of evolutionary models (Schaller et al. 1992, Schaerer et al. 1993), and on the horizontal axis he plots the directly determined mass. In the left-hand panel he uses the "old" temperature scale, and in the right-hand panel he uses the "new" temperature scale of Martins, Schaerer, and Hillier (2002). The better agreement between theoretical and observed masses in the right-hand panel lends even more credence to the new, lower, temperature scale.



However, what struck me is the paucity of datapoints above 30 M_O. Gies declares the "record holder" of "the most massive star ever measured" to be R 136-38 in the LMC, recently measured by Massey, Penny and Vukovich (2002, hereafter referred to as MPV) to be 56.9 $\pm$ 0.6 M_O. In a theoretical world where evolutionary tracks are routinely calculated for stars of 120 solar masses (c.f. Maeder and Meynet 2000), *only two stars with masses greater than 35 M_O have been measured directly, and the most massive star to be measured directly has a mass of only 60 M_O.* This is a very weak observational underpinning for theoretical work that is fundamental to so many lines of inquiry.

The primary reasons for this paucity are the fundamental scarcity of O stars and, correspondingly, their large distances. Spectroscopic binaries are generally discovered, well, spectroscopically, and most of the nearest O stars are sufficiently distant such that only one spectrum (if any) has ever been obtained. Add to this the relatively small fraction of the double-lined spectroscopic binaries that will also be eclipsing systems, and one begins to understand why so few O star masses have been measured directly.

We propose to remedy this situation by undertaking a photometric search for eclipsing binary systems containing at least one O star. Follow-up spectroscopy will then allow us to determine the masses directly. The existing number of directly-measured masses is so small that discovering even a few viable systems will make a huge improvement.

Proposed Work

In order to identify O stars that are part of eclipsing binary systems, we will perform differential photometry in OB associations, where the surface densities of O stars are the highest. As discussed below, our first target will be Cygnus OB2. Following MPV, who similarly adapted an observing scheme developed by Abi Saha for observing Cepheid variables with the HST, we will develop an observing scheme with the temporal spacing optimized for catching eclipses in binaries with periods between one and thirty days.

The Lowell Observatory 31-inch telescope, equipped with the National Undergraduate Research Observatory (NURO) CCD camera and available to us for relatively large blocks of observing time, is well suited for this project. The most luminous stars in Cyg OB2 have V magnitudes between 10.0 and 12.5 (Massey and Thompson, 1991). This telescope/camera combination can obtain photometry with a signal to noise ratio greater than 100 in only a minute or two at these magnitudes. The camera field of view is only 4 arcmin on a side; admittedly, a larger field of view would be preferable to increase the number of available comparison stars on each frame, but the stellar density in Cyg OB2 is high enough to make proposed scheme feasible. A camera with a larger field of view is in the works at Lowell Observatory, but the proposed work does not depend on that camera.

Rather than using just two or three stars as comparisons, we will use the average of all available stars on the frame as a comparison. Care will be taken to exclude known variables, and to exclude stars that are so faint that adding them in would actually decrease the signal to noise of the comparison magnitude. Data reduction will be in IRAF, using DAOPHOT. Part of the project will involve writing IRAF scripts to make the process as automated as possible.

The OB association Cyg OB2, also known in the Simbad world as VI Cyg, is the obvious place to start in the northern hemisphere. First noted as an OB association by personages no less illustrious than Harold Johnson and W.W. Morgan in 1954 (the year I was born!), this heavily and unevenly reddened association has recently been characterized as the prototype of a young globular cluster within our own Galaxy (Knodlseder 2003, Comeron et al. 2002). From multi-wavelength studies, Knodlseder estimates 120 ± 20 O stars in Cyg OB2. Massey and Thompson (1991) list 72 “brightest and bluest” stars in their study of Cyg OB2, which was not 100% complete.

Cyg OB2 subtends about 40 arcmin by 50 arcmin on the sky. Even with our 16 square arcminute field of view, we will be able to cycle through the entire field in about a half a night. Thus we should be able to revisit each sub-field for a second time on most nights, allowing us to catch periods somewhat shorter than one day. At RA ≈ $+20^h\ 30^m$, D ≈ $+41^d$, the peak observing season will be July and August, with reasonably good coverage from mid-May through October. July and August are unfortunately the rainiest months in Flagstaff, but it is correspondingly a time when observing time is easy to get. It is also a time when both students and faculty are less burdened with coursework, making it an ideal time for the training of students. May, June, and October tend to have excellent weather. Fortunately, differential photometry does not require photometric conditions; it is possible to work through thin cloud cover that is stable over time scales of a few minutes. Additionally, as discussed below, this observing project will be made available as a NURO Key Project, and thus occasional data points will be contributed by other observers at various times.

What makes us think that we will be lucky enough to discover new eclipsing systems? In their recent determination of "the most massive star ever measured" in R136 in the LMC, MPV (2002) did follow-up photometry (and spectroscopy) with HST after the discovery of four double-lined spectroscopy binaries by Massey and Hunter (1998). Their photometric monitoring included 59 stars in their field. In addition to the four known binaries, they discovered five additional light variables, four of which show signatures of what might be eclipses. If our survey comes even close to eight of 59 O stars (13%) showing eclipses, our study will be more than worthwhile.

Once an eclipsing system has been discovered, we will apply for observing time at an appropriate public facility to obtain the necessary spectra; unfortunately Lowell Observatory does not have a suitable spectrograph. The PI has access to Steward Observatory telescopes as well as national facilities. The PI has sufficient experience to obtain and reduce the spectra, but not the experience necessary for the model atmosphere fitting necessary to obtain the orbital elements. Professor Laura Penny at the College of Charleston, a predominantly undergraduate institution, has agreed to collaborate and perform this part of the analysis as she did for MPV (2002).

Broader Impact

The impact of the proposed work will be considerable. The primary purpose of this proposal is to fund a master's student at Northern Arizona University (NAU). This terminal master's program in Applied Physics is still in its infancy; the current academic year is only its third year of existence. Funding is crucial to obtaining good students, and good students are crucial to establishing a quality program. We should point out here that, unlike a Ph.D. student who has passed qualifying exams, this student will be taking a full nine-hour course load at the same time he or she is working on this project, and thus will not make progress as fast as a Ph.D. student. It is also true that the teaching load in the NAU Physics and Astronomy Department, for a professor with funded research, is six hours per semester rather than the one course per semester typically found at large research universities.

We have also included funds in the budget to fund an NAU undergraduate student at about ten hours per week each semester. This project is observing-intensive, and we do not like to send anyone observing alone. We envision an observing team of one graduate student and one undergraduate student. We always have a large number of undergraduates wishing to participate in research programs. This experience is important for them, and it is part of my job expectation to provide experiences for them. However, many of our students are putting themselves through school, and they cannot afford to do research unless they are paid. This is particularly true for our large population of Hispanic and Native American students. I certainly cannot guarantee that I will be able to hire a minority student – they tend to major in engineering rather than in physics – but I consider this to be an important part of my mission, and will certainly attempt to do so.

The secondary purpose of this proposal is to provide an appropriate key project for the NURO. NURO is a consortium of primarily undergraduate institutions that use the Lowell 31-inch telescope to train undergraduate students, both science and non-science majors. Each member school pays an annual fee to NAU, and NAU in turn pays Lowell for a percentage of the telescope maintenance, and provides technical support to the observers. The current NURO members are Alma College, Ball State University, Benedictine College, Central Michigan University, Denison University, Dickinson College, Franklin and Marshall College, Gettysburg College, Louisiana Tech, Maria Mitchell Observatory, McMurry University, University of Nevada Las Vegas, Northern Arizona University, University of Puerto Rico Humacao, Western Connecticut University, and Widener University. See www.nuro.nau.edu for more information. NURO has now been operating for over a decade, and has worked well for some member schools but not so well for other members. The faculty at some of the schools do not have their own scientific programs, and need group projects in which to be involved. These participatory "key projects" need a scientific leader to supervise data acquisition and actually do the science.

The proposed project is *ideally suited* as a NURO key project. The data are easy to obtain since no absolute calibration is required. Extra data points at odd times can only help. Thus we propose to designate this work as a key project. The only differences between doing it on our own and as a key project are: (1) NURO observers will be invited to contribute data points for the light curves, and (2) detailed instructions on targets and data acquisition will be posted for the observers. NURO students and professors will probably not be listed as co-authors on any publications, but will be acknowledged in the text. Funds are included in the budget for an undergraduate web programmer to post the necessary information on the NURO website and keep it up to date.

Not only has NURO been lacking in scientifically relevant key projects, but they have not had a single key project keyed to the scientific interests of Lowell astronomers. The proposed work is of interest to Phil Massey, a Lowell staff astronomer and my frequent collaborator. It is hoped that providing a project of mutual interest will help smooth the sometimes rocky relationship between Lowell and NURO.

Another non-negligible impact of this work will be the involvement of at least two summer undergraduate students who are participants in NAU's NSF-funded REU program. Many of these students are looking for an observational program, and are often disappointed when they arrive and find that they are working on a project for which the data have already been obtained. This work will provide projects in which they can participate in all the aspects of the scientific process – planning, data acquisition, reduction, and analysis. There will probably be other, less interesting variable stars that may provide projects that an undergraduate can handle basically on their own and publish the results.

One last point is that the REU students in the NAU program are of the highest caliber; typically they have gone on to the best graduate schools. The involvement of these undergraduate students in the proposed project should stimulate their interest in stellar astronomy, which has suffered somewhat recently due to the popularity of extragalactic astronomy and cosmology.

Timeline

Obviously we cannot guarantee that we find even one eclipsing O binary. However, with as much data as we will have, it seems highly likely that we will find *something* interesting in terms of variable stars. The timeline below represents a best-case scenario in which we discover at least one eclipsing O star during the first observing season. The items listed in italics will happen only if such stars are found; all the other activities will take place regardless. In the worst-case scenario that we find only more "ordinary" variable stars, we will perform the appropriate analysis and publish the data.

Summer '04	First observing season with summer REU student. Finalize observing procedures. Develop reduction scripts in IRAF.
Fall '04	Start training new master's student in reductions. Finish reduction of summer's data. Hire undergraduate student to put observing info on web for NURO key project.
Winter/Spring '05	*Apply for spectroscopic observing time.* Start training master's student in observing, as well as a new NAU undergraduate to help the master's student with observing.
Summer '05	Second observing season. Obtain any additional photometric data needed on possible eclipsing systems; possibly start on new OB association. Train second REU student in observing and reductions. *Travel to KPNO or Steward for spectroscopic observations.*
Fall '05	*Reduce spectroscopic data*; analyze new photometric data. *Send reduced data to Laura Penny for derivation of orbit.*
Winter/Spring '06	Master's student will start writing manuscript. *Apply for spectroscopic observing time*
Summer '06	Third observing season if justified. Master's student to finish writing of thesis. *Travel to KPNO or Steward for spectroscopic observations.*
Fall '06	Master's student finishes writing manuscript and submits for publication; works on turning it into a thesis.
Winter/Spring '07	Revision and publication of manuscript; finishing of thesis.

Results from Prior NSF Support

AST-9988007 $305,121 5/15/2000 to 5/15/2005
Research Experiences for Undergraduates in Astronomy in Flagstaff, Arizona

This award represents continued funding for my Research Experiences for Undergraduates site at Northern Arizona University, established in 1992. We support eight undergraduate students each summer, recruited nationally. The students come to NAU for the ten-week summer school session and are placed with mentors at all the scientific institutions in Flagstaff; these institutions are NAU, the Lowell Observatory, the U.S. Naval Observatory, and the astrogeology branch of the U.S.G.S. Since the only graduate program in physics and astronomy in Flagstaff is the fledgling master's program, these undergraduate researchers are placed squarely in the middle of their research projects, and typically do the work one might expect from a graduate student.

In addition to their research projects, the students receive university credit for attending a twice-weekly seminar series showcasing the different kinds of research being done in astronomy. The students are all housed together in an NAU dormitory, and are also invited to various social events. At the end of the summer, each student produces a short paper on their research, and gives a talk on their work at a student mini-symposium. Students with results appropriate for presentation at a AAS or DPS meeting are supported for that travel during the following year.

Our alumni have done very well at getting into graduate schools; in the last several years they have been very well represented in the top astronomy programs in the country. Many of our first students are now postdocs (Kelsey Johnson, Erika Gibb, DJ Pisano, Henry Throop) or assistant professors (Laura Woodney, Cornelia Lang). We have also been particularly successful at mentoring young women; over half of all our summer students have been female.

Participants to date for current award:
2000
Matt Bavender, Indiana University
Lindsay DeRemer, Wellesley College
Alaine Duffy, Gettysburg College
Clara Eberhardy, University of Washington
Jeff Fehring, Pacific Lutheran University
Andrea Gelatt, Grinnell College
Brian Keeney, University of Virginia
Alyssa Reiffel, Yale University
Kathryn Zylstra, Western Washington University

2001
Olivia Billett, Yale University
Ryan Greer, Wittenberg University
Thomas Grimstad, McMurry University
David Law, University of Virginia
Brandon Preblich, University of Michigan
Colette Salyk, MIT
Sarah Stokes, University of Wyoming
Jes Therkelsen, Amherst College
Julia Vukovich, Wichita State University

2002
Kristina Barkume, Reed College
Shane Bussman, University of California, Berkeley
Josh Bury, University of Oregon

Trent Dupuy, University of Texas Austin
Eric Furst, Bucknell University
Andrew Morrison, University of Puget Sound
Jennifer Palguta, University of Wisconsin-Madison

2003
Nicole Baugh, Augusta State University
Emily Bowsher, Wellesley College
Selby Cull, Hampshire College
Christopher Jackolski, Appalachian State U.
Katie Kern, University of Wisconsin-Madison
Justin Pryzby, Gettysburg College
Brandon Swift, University of California, Berkeley
Wayne Schlngman, University of New Mexico

Publications to date for current award; asterisks indicate undergraduate authors.

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WATCH THIS SPACE; not done yet

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