THE SCIENCE OF SCIENCE WRITING

A Senior Honors Project

by

Lydia M. Welker

May 2014

THE SCIENCE OF SCIENCE WRITING

by

Lydia M. Welker

May 2014

A Senior Honors Project

Submitted to the English Department and the Honors College

Missouri State University

In Partial Fulfillment of the Requirements for

Departmental Distinction in Professional Writing

Approved:

____

Ms. Tracy Dalton, Project Director

____

Dr. W.D. Blackmon, English Department Head

____

Dr. John Chuchiak, Dean of the Honors College

THE SCIENCE OF SCIENCE WRITING

by

Lydia M. Welker

May 2014

A Senior Honors Project

Submitted to the English Department and the Honors College

Missouri State University

In Partial Fulfillment of the Requirements for

Departmental Distinction in Professional Writing

THE SCIENCE OF SCIENCE WRITING

English Department

Missouri State University, May 2014

Lydia M. Welker

ABSTRACT

By informing the general public about science through writing that is interesting to read and easy to understand, science writers can create avenues for a better-informed public. Science writing has been used to present complex information as early as 60 BCE. Science writing is both a craft and an art. Science writers have the opportunity to work in many different fields of study and constantly learn new things. If scientists or writers are interested in entering the science writing field, they should be prepared to provide proof of education in either writing or science fields. Just as science itself is ever-varied and ever-changing, science writing shifts and moves with it. Science literacy is hugely important; without it, it is difficult for people to make informed decisions about everyday interrelated issues concerning the environment, health issues, or scientific movements. The most important avenue for improving science literacy is clear and accessible writing. It is the duty of science writers to provide the public with correct views on modern science. Elements of good science writing should include audience analysis research, a logical structure, and the traditional elements of technical communication. To demonstrate the science writing process and provide examples of popular science literature, I worked with two peer-reviewed articles in the scientific fields of economics and astrophysics: *Female Autonomy in Rural North India: Impact of Economic, Social and Political Factors* by Sharmistha Self and Richard Grabowski and *Three ways to solve the orbit of KIC 11 558 725: a 10-day beaming sdB+WD binary with a pulsating subdwarf* by J. H. Telting et al. If scientists and writers have a passion for providing avenues for a better-informed public and simplifying complex scientific information for a general audience, they should consider making the transition to popular science writing.

Keywords: science writing, popular science, scientific literacy, science

Table of Contents

Introduction

In the fields of both science and writing, members have a common goal: to share information. Scientists conduct research, make advancements, and build upon the experiments of others before publishing their work for fellow scientists to attempt and refine. Writers use words to carry ideas across pages and continents that are read by, commented on, and critiqued by other people. These two cycles of information may at first seem unrelated, but there is a powerful overlap that needs attention. With a society shaped by scientific advancements or discoveries such as genetic engineering, antimatter, and cloning, the demand for science writing that is understandable and interesting is strong. Scientific writing—peer-reviewed articles in scientific journals or laboratory reports, for example—is one method to inform readers about modern science. However, for the general population, such writing can be confusing, boring, and inaccessible. Unless individuals have an educational or professional background in a particular scientific field of study, it could be a struggle for them to understand any scientific literature in that field. Science writing for a popular audience is another option—an option that is not only available for both writers and scientists but also requires skills from both. It is the duty of science writers to explain complex scientific material in words that people want to read. By informing the general public about science through writing that is interesting to read and easy to understand, science writers can create avenues for a better-informed public.

Defining Science Writing

From *The Immortal Life of Henrietta Lacks* to the annual editions of *Best American Science Writing*, popular science writing is everywhere. However, even though science writing is easy to find, it is not easy to define. Throughout history, and especially in BCE, science writing was disguised by fables and epic poems. In as early as 60 BCE, Titus Lucretius Carus wrote an epic poem called *The Persistence of Atoms* presenting the atomic theory of Epicurus. In his concluding lines, Lucretius described a doctrine of classical physics that was held to be true until the 1900s—the idea that matter can be neither created nor destroyed:

> For everything of mortal mass long since
> has been used up as boundless time passed by.
> But if the stuff of which this sum of things
> is built has lasted down through empty ages,
> surely it is endowed with deathless nature;
> no thing, therefore, can be reduced to nothing. (Bolles 423)

In 1905, when Einstein indicated that matter could be destroyed, the doctrine was reworked. Even though the physics behind *The Persistence of Atoms* is no longer held as valid, the epic poem is still one of the oldest and most beautiful examples of science writing.

Similarly, in his essay *On Science Writing*, science writer Timothy Ferris speculated that scientific literature was first introduced not in written form but through fables. In the eighth century BCE fable *Works and Days*, Hesiod described the movement of constellations as indicators for when to plant and harvest certain crops. It was so widespread to incorporate astronomical information into fables that Quintilian claimed in the first century CE "no man can understand poets if he is ignorant of astronomy" (Ferris 4). Ferris concluded that "writing from its very beginnings may be identified dualistically as both a craft (the recording of information) and an art, which makes information and sentiment memorable," as exemplified by Lucretius and Hesiod. Science writing is neither an art nor a craft—it is an intermingling of both (Ferris 4–6).

If what Ferris concluded is true, and science writing is both a craft and an art, it is equally as important to understand what science writing is not. The Massachusetts Institute of Technology used this approach to help clarify the definition of science writing: "What science writing is not is a technical report aimed at other specialists. Or a lab paper, or a how-to manual, or a peer-reviewed research article in even the most prestigious scientific journal" ("What is Science Writing?"). Writer George Gopen explained further, arguing that "the fundamental purpose of scientific discourse is not the mere presentation of information and thought, but rather its actual communication." No matter how pleased authors may be with their writing, the importance of the work lies in the ability of its audience to accurately perceive the material (Gopen and Swan).

Usually, that audience is the general public. Through avenues such as newspapers, radio/podcast programs, books, and technology, a science writer "communicates information about science (and/or medicine, math, engineering, technology) in terms intended to be understandable and relevant to a broad audience" (Stein and Baccouche 119). In the article *Popular Science Writing: Communicating Science to Peers and Public*, Khoon Koh Aik described popular science books as "the bridges between science and society" (144). Aik argued that people who have the ability to write highly technical information for the public are rare—that they make the complicated look simple, but not simplistic (143–144). It is an ambitious, difficult, and compelling goal ("What is Science Writing?"). Although science writing can be overshadowed by the enormous amount of scientific disciplines, technical articles, and specialized works that exist, Ferris argues that it challenges readers to change their viewpoints and open their minds (11). Therefore, it has an irreplaceable spot in the worlds of both writing and science.

Careers in Science Writing

Science writers have the opportunity to work in many different fields of study and constantly learn new things. Ben P. Stein, a science writer at the American Institute of Physics, and Aziza Baccouche, an accomplished science television producer, described science writing as a fulfilling career because they have the opportunity to learn something new every day: "Science writing is a fulfilling, mind-expanding, and enjoyable pursuit. It provides the twofold joy of learning about interesting research and explaining it in understandable terms to the general public. They argued that there is a desperate need for more communicators in science (Stein and Baccouche 119).

The work environment of science writers varies greatly. They can work at university news offices, national newspapers, or science departments. Stein and Baccouche claimed that "the setting in which most science writers work is in media relations/public information offices. These include the news offices of universities, national laboratories, corporations, nonprofit organizations, and museums" (Stein and Baccouche 119). Another popular avenue is freelance science writing or journalism ("A Guide to Careers in Science Writing"), through which science writers have the advantage of working from a place of their choosing and the freedom of flexibility.

If scientists or writers are interested in entering the science writing field, they should be prepared to provide proof of education in either writing or science fields. According to Stein and Baccouche, "many perspective employers of science writers look for applicants who have at least bachelor's degrees in either English/journalism/communications or in a branch of science, engineering, technology, or mathematics." However, many prospective employers of science writers also prefer experience in both fields (Stein and Baccouche 120).

Since science writers span from senior-level positions in national laboratories to entry-level assignments at small newspapers, the salary range is wide. The Council for the Advancement of Science Writing defined average salaries for several possible science writing careers. According to their salary guide, freelance science journalists are the most poorly paid science writers, averaging between $1.00 and $2.00 per word for magazine articles. On the other hand, authors of science books who actively market their work and establish their reputation can earn a healthy living ("A Guide to Careers in Science Writing").

Writers in the field of science writing do not necessarily emerge from writing-intensive backgrounds; there are often transitions between science and writing careers. One example of such a transition is Jenny Morber, who worked as an engineer for several years before deciding to write popular science. Although aspects of her transition were difficult, she found several opportunities to make a move to a science writing career:

> I found that opportunities are plentiful for scientists and engineers who want to write. Science journals need good writers to dissect, edit, and summarize clunky articles. Consumer organizations need people to translate research into newsletters that people can understand. Science bloggers and journalists keep the public up-to-date with scientific breakthroughs. (Morber 48)

Morber was drawn to popular science writing because it allowed her to explore a variety of interesting topics and the freedom to enter different scientific disciplines. From her journey, it is clear that popular science writing is a good choice for scientists or writers who are interested in communication, simplification, and modern science.

Trends in Science Writing

Just as science itself is ever-varied and ever-changing, science writing shifts and moves with it. The major movement from exclusively printed materials to a combination of online and paper is one change that affects the field of science writing. To meet audience needs and expectations, it is important to provide both options for science writing: if one of popular science writing's many goals is to be accessible, it makes sense that it should be physically accessible, as well. There are drawbacks, though, that are not necessarily obvious. Declan Butler, a senior reporter at *Nature* magazine, argues that electronic media may have the ability to be stored and accessed digitally, but paper has one major advantage: paper lasts. In a world of technology that constantly changes formats and digital objects, paper can survive for thousands of years, regardless of hardware and software obsolescence (Butler 198). Although traditional channels such as newspapers and science television are still popular, there has been a significant shift to online sources (Nisbet and Scheufele 1774). Butler summed up what may be the only realistic web strategy for some time: "Experiment as much as possible, and be as fast on our feet as we can" (Butler 200). To keep pace with changes in technology, science writers must pay attention to those changes. In her article *Responsible Writing in Science*, Lidija Bilic-Zulle described another trend in writing that is even more important to adhere to in science writing: responsible writing. She argues that there are two distinct ways in which science writers must uphold responsibility—the content of their writing and the quality of their research/experimentation. Bilic-Zulle further claimes that scientific misconduct, plagiarism, and self-plagiarism may be harmful to the reputations of science writers, but that such acts are also harmful to science itself (Bilic-Zulle 279–280). Although writers and scientists should avoid irresponsible writing regardless of the topic or genre, it is even more important to be aware while in the field of science writing. In addition to her thoughts on responsible writing, Bilic-Zulle commented on the importance of English in the scientific community. She argued that, since the "vast majority of scientific publications are in English and it is highly requested to write and publish in English to be recognized in broader scientific community," authors and scientists without experience in English will have further obstacles to overcome than their English-speaking counterparts (Bilic-Zulie 280). Although popular science writers cater to different audience needs, it is important to note that most of the scientific material they will be translating or simplifying will be written in English. Other than working with potential language barriers in an already complex field of writing, science writers must be aware of the flaws in scientific writing and take them into account when working with peer-reviewed articles or laboratory reports. In *Doing Science, Writing Science*, Jutta Schickore explained that "there is a mismatch between what scientists do and the presentation of results in scientific publications" (324). One of the main reasons for this mismatch can be attributed to the scientific journals in which scientists publish their research. Due to high page charges and severe space restrictions, scientists remove any information or steps that they feel are not absolutely essential to their argument. Therefore, some of the pieces that science writers need to work with an article or research may be missing. While a few obstacles exist in the field of poplar science writing, the field changes with science and technology, so problems may decrease and new issues may arise. Even so, the need for science writing is so great that science writers must move forward.

Science Literacy

Modern culture is heavily based in science and technology, so a population of scientifically literate global citizens is necessary. In *Reading and Writing to Learn Science: Achieving Scientific Literacy*, Shawn Glynn and Denise Muth based their definition of scientific literacy off of the American Association for the Advancement of Science and concluded that the scientifically literate person is "one who is aware that science, mathematics, and technology are interdependent human enterprises with strengths and limitations; understands key concepts and principles of science; is familiar with the natural world and recognizes both its diversity and unity; and uses scientific knowledge and scientific ways of thinking for individual and social purposes" (qtd. in *Science for All Americans*). Unfortunately, accepting this definition as true, many people are not scientifically literate (Glynn and Muth 1057). Science literacy is hugely important—without it, it is difficult for people to make informed decisions about everyday interrelated issues concerning the environment, health issues, or scientific movements. To further the lack of science literacy, academic texts in no way invite the general public to read them. Anne Osbourn, founder of SAW (Science, Art and Writing), argued that "the tendency of academics to 'tell' people things, often in inaccessible language and with an air of arrogance, is disrespectful . . . It is not the way we would like to be taught" (Osbourn 1547). One of the biggest barriers to science literacy is the typical research report and "its lack of clarity, intelligibility, and relevance except to a very limited audience" (Sandelowsk 375). In general, academic texts focus on methods and theories while popular articles focus on people (Parkinson and Adendorff 10). The distinction is important, especially concerning the science classroom.

Barbara Austin tested the effects of popular science literature on science literacy in her classroom. In her tenth grade summer physical science course, students read selections from a popular nonfiction science book, and the results were significant:

> Because the selections were interesting and accessible, there was no hint of the 'Why do I have to learn this?' attitude from students—in fact, the reaction was quite the opposite. The human story that framed the science concepts truly engaged students in learning science—they even requested more readings from the book because it helped them understand course concepts. (Austin 27)

To further showcase the success of popular science writing in her classroom, Austin added that a majority of her students had informal conversations with teachers and their peers about the readings and the science concepts within those readings (Austin 32).

Especially within classrooms, the effectiveness of popular science writings has been noticed. Some educators are frustrated with the arguably "dry, voiceless, and positivistic" traditional forms of scientific writing and actively pursuing science writing that cannot be "blamed for 'turning off' interest in science" (Keys 118). The importance of having science concepts explained in clear language is now seen as crucial to the growth of science literacy (Glynn and Muth 1058).

Jean Parkinson, a linguistics and applied language professor, outlined reasons why science literacy through popular science writing is so important. She first argued that, since popular science writers report on scientific findings before they are validated or endorsed, popular science writing allows students to see inside the social construction of scientific knowledge. Additionally, popular science texts challenge the idea that science is authoritative and introduce the idea that science is open for debate. Parkinson further claimed the accessibility of popular science texts "represent science as the activity of many unknown scientists rather than a few well-known people like Einstein," which challenges the idea that science is limited to a select group of people. While all of her points defend popular science writing as a tool to improve science literacy, her concluding remarks go back to the idea that popular science writing is "conceptually simpler than academic texts, and thus can help students understand the science" (Parkinson 18) Therefore, the most important avenue for improving science literacy is clear and accessible writing.

Global Demand

Science is powerful, and while it affects our daily lives, millions neither understand nor care about it (Ferris 7). There exist feelings of confusion and distrust, and it is more difficult and important than ever for scientists and researchers to be able to explain and justify their findings and research to a broader audience ("How to be Popular"). Yet, since universities and laboratories have not recognized the academic position of popular science writing (Huiyun 307), few scientists have received formal training in the genre ("How to be Popular"). In *Views on Popular Science Publishing*, Shen Huiyun argued that creating works of popular science benefits nations and the people who live in them and that science writers "bear the responsibility for propagating scientific knowledge, the scientific method, and scientific thought. If popular science writing is accurate and high-quality, it can help improve national development and educate the general population (Huiyun 307–308). It is the duty of science writers to provide the public with correct views on modern science.

Elements of Good Science Writing

Good science writing falls under the categories of both good science and good writing, and the combination of the two disciplines creates high expectations for science writers to meet. Factors such as audience analysis, voice, use of metaphor, presentation of research, and the elements of technical communication apply to well-written and well-researched popular science writing. In *Readings for Technical Communication*, Jennifer MacLennan argued that prose without passion, in the passive voice, and without analogies is also devoid of humanity. Such prose perpetrates that "science is not what human beings make, but something human being merely report as having been made or discovered" (MacLennan 47). Science writers should aim for writing that is clear, interesting, and accessible to all of its readers.

Similar to any significant writing project, a piece of popular science writing should be founded on the expectations and needs of its audience. From the structure of the entire piece to sentence-level choices, every part of the writing process must adhere to what the audience expects. In general, the piece "needs a beginning, a middle, and an end—and, unless you are Quentin Tarantino, it needs to be presented in this order" ("How to be Popular"). Each individual sentence needs to maintain the interest of the audience and encourage them to read until the conclusion.

In *The Science of Scientific Writing*, Gopen and Swan provided an example of meeting audience expectations. Suppose a table of data was included in the piece that tracked the temperature of some substance in three-minute intervals. This data could be represented in several ways, but consider the following option:

Temperature (°C)	**Time (minutes)**	**Time (minutes)**	**Temperature (°C)**
25	0	0	25
27	3	3	27
29	6	6	29
31	9	9	31
32	12	12	32
32	15	15	32

Table 1 (Gopen and Swan)

Even though the same data is represented on both sides of the table, most readers find the right side easier to understand for several reasons. Since we read left-to-right, the audience prefers familiar context on the left and more interesting information on the right; similarly, information is most efficiently and easily understood when it placed where the audience expects (Gopen and Swan).

Another important technique—an aspect of science writing that clearly differentiates it from scientific writing—is voice. Qualitative and scientific research is usually written in a detached, third-person voice. Jane Gilgun, professor of social work and author of *Grab and Good Science: Writing Up the Results of Qualitative Research*, stated that "qualitative researchers who write in distanced, third-person voices and who give short shrift to informants believe that this kind of writing is scientific and that lively, first-person writing is not" (Gilgun 260), and she vehemently disagreed with that claim. On the contrary, she argued that readers should be hooked by the material as well as find it both memorable and interesting (Gilgun 261).

Metaphors are another powerful literary tool that science writers can use to liven up their work. However, there is a danger to using weak comparisons in science writing. When science writers do not take metaphors seriously enough, the meaning behind the comparison can be easily misunderstood and therefore affect the audience's understanding of the scientific concepts behind that metaphor (Sandelowski 378). The line between metaphor and theory is thin (Low 145), and it is the duty of the science writer to make a compromise between accuracy and simplification—there is a balance between simplifying ideas and communicating accurately that must be maintained (Low 129).

Although qualitative data is not as prevalent in science writing as it is in scientific texts, there are occasions during which it will have to be relayed to a general audience. In *Writing a Good Read: Strategies for Re-Presenting Qualitative Data*, Margarete Sandelowski emphasized the story behind qualitative data in popular science writing. In each set of data, there are a multitude of stories to tell—the popular science writer just has to choose. She argued that, usually, "researchers will summarize as much as they can of their data, in the hopes of getting it all in, and of achieving the much-touted 'thick description' without getting to the point of what any of these data mean." In her opinion, the best way to work with data is to illustrate or exemplify parts of the story that the science writer wants emphasized.

The traditional elements of technical communication—accuracy, clarity, simplicity, and readability—perfectly apply to popular science writing. In the case of science-based writing, it could be argued that accuracy of the data, concepts, and evaluation is the most important factor. Even so, as MacLennan argued, "regardless of how accurate his material may be, however, it becomes worthless if it is communicated inaccurately" (MacLennan 144). Clarity, on the other hand, should be "our constant aim." From the organization of the piece as a whole to the paragraphs and individual sentences to individual words, clarity is a prerequisite to audience understanding. (MacLennan 145–146). Hand-in-hand with clarity is simplicity: the goal of communicating an idea as quickly and easily as possible, whether that is by choosing familiar words instead of technical terms or defining complicated terms (McLennan 148). To improve readability, science writers should vary sentence structure and length, exercise versatility, and write with style (MacLennan 150–151). Language should be accessible, without convoluted sentences or jargon (Glasper and Peate 965). By employing the elements of technical communication, science writers can make their work more accessible and interesting to their audience.

Carl Zimmer, the author of eight popular science books on topics from parasites and *Escherichia coli* to evolution, is already familiar with the field of science writing. In his interview with Nicola Jones, he stressed that scientists do not need a long paper trail to become a writer and, even though many scientists think that science writing is easy because it is not scientific research, good science writing is difficult to produce. In his interview, he concluded with solid advice for new science writers: "Find a subject you love so much that you could spend two years writing about it—even if nobody bought the book when you were done. That way, if people do buy the book, it's a bonus. Love for your topic is very important" (Jones 737). Passion for the scientific topic is crucial; without it, the writing will reflect that impassion.

Application

To demonstrate the science writing process and provide examples of popular science literature, I worked with peer-reviewed articles in the scientific fields of economics and astrophysics. Throughout the project, I met with the professors at Missouri State University, interviewed them to understand the technical information in the articles, and wrote popular science pieces inspired by their work.

Dr. Sharmistha Self's article *Female Autonomy in Rural North India: Impact of Economic, Social and Political Factors* was published in the *Journal of Economic Development* in 2013 (*see Appendix A*). She was excited to introduce me to her research and explained to me that she was a development economist, and any issue that pertained to developing countries interested her. Although she presented me with several choices, I decided to work with *Female Autonomy in Rural North India* because it combined research in economics, sociology, and political science. Dr. Mike Reed worked with eighteen other scientists around the world to write *Three ways to solve the orbit of KIC 11 558 725: a 10-day beaming sdB+WD binary with a pulsating subdwarf* in *Astronomy & Physics* (*see Appendix B*). Among other things, the article contained research based in seismology, Dr. Reed's specialty.

Working with subject-matter experts was daunting at first, because it was the first time I had ever done so. To make the process easier and take up as little time as possible from both professors, I compiled a short list of specific questions. Most of my questions were unrelated to the information directly in the article—I asked them about their inspirations for research and for any interesting stories concerning the articles. The two most helpful questions I raised during our discussion were "What inspired you to research this topic?" and "Do you have any interesting stories about researching this topic or working with your coauthors?" I wanted to get a hook or personable story that I could include in my version to make it interesting for my audience, and Dr. Self and Dr. Reed were willing to share stories with me. They were also happy to explain the more complicated economics and astrophysics concepts.

Midway through writing the popular science pieces inspired by the articles, I realized that simplifying the articles was tricky. I have absolutely no background in economics, politics, sociology, astronomy, and physics—sometimes, even the most basic concepts throughout the articles confused me. If popular science writing is meant for an audience that does not have an educational or professional background in those fields of study, then I was a member of that audience. After that realization, working with the articles became an entirely new and interesting experience. I also noticed that my pieces were significantly shorter than the peer-reviewed science articles because I was working with concepts instead of specific methodology.

While working with the peer-reviewed articles and deciding what information was important for my audience to know, I implemented several elements of science writing. To showcase the difference between scientific and science writing, I will present several examples from both sets of articles.

My overall goal with my economics piece was to describe the methodology and research in terms that a general audience could understand and would want to read. In Dr. Self's article and in my popular science piece *Female Independence and How to Achieve It* (*see Appendix C*), the language has several terms unfamiliar to anyone in the audience who has not studied or practiced economics. To clarify some of the terms, like "autonomy," I used synonyms such a "independence" and "self-governance." There were several spaces where I tightened the language and significantly lowered the word count:

> The main focus of the paper will be to determine those variables which influence the extent of female autonomy in the Indian state of Uttar Pradesh. This state was chosen for two reasons. First, this state represents an environment in which

> traditionally women have faced significant barriers which have created large gender gaps in terms of employment, health care, and physical mobility. Thus it will be very useful to determine whether within such an environment there are useful policies which could have been used to enhance female autonomy. Secondly, the data set utilized for Uttar Pradesh contains information on a variety of household and individual variables unavailable in other publicly available data sets. (60–61)

In my popular science piece *Female Independence and How to Achieve It* (*see Appendix C*), I derived the intention behind the paragraph and used simpler language. It appears as follows:

> Self decided to center her research in the rural state because there are large gaps in gender equality in areas such as employment and the data covers a variety of individuals and households.

At a later point in her article, Dr. Self used several tables and graphs and then used statistics to derive information from the graphs:

> A preliminary look at the data shows wide variability in terms of both measures of female autonomy being used in this paper. In terms of leaving the house without permission, these proportions range from 0% of the women needing permission (three villages) to 76% of the women needing permission to leave the house. On average about 35% of women needed the permission of a male member of the family. In terms of whether or not a woman has the freedom to visit the doctor without a male escort, the values range from 0% of the women needing a male escort to 69% needing male escort. On average, about 33% of women overall need a male escort. Given this variability in a woman's freedom of movement outside the home, a natural question arises regarding what factors might be able to explain or influence

> the variation in female autonomy within any particular village, as well as across villages. (66)

I was concerned that so much statistical data would unnecessarily confuse the audience, so I wrote the following alternative:

> Slightly more than a third of all women from the Uttar Pradesh data set need the permission of a male family member to visit the doctor. Similarly, a more than a third need a male escort.

One section in Dr. Self's article listed the parameters of her study within a paragraph:

> Most papers relating to female autonomy concentrate on her autonomy within the household. This paper begins by taking a different view by measuring female autonomy outside the household. Specifically, it looks at two measures: a woman being able to leave the house to see a doctor without the permission of a male member of the family and a woman being able to go to a doctor's office unescorted by a male member. Thus, here we are not focusing on mobility for its own sake, which is important in itself, but we are looking at mobility that is associated with a definite purpose and thus even more important. A woman may need to visit the doctor for her own health or for her children or any other member of the family. Both of the variables being utilized as the dependent variables measure whether females enjoy freedom or autonomy of mobility outside the home. (64)

Instead of using a paragraph, I decided to implement a bulleted list:

> In her research, Self chose one situation as a measurement of female independence: mobility, the freedom of a woman to move about. Instead of looking at overall female mobility, she further focused her view on two scenarios:

- the ability of a woman to visit a doctor without permission from a male family member
- the ability of a woman to visit a doctor without a male escort

The scenarios include a definite purpose and a destination outside the home. By working with general concepts, simplifying statistical data, and implementing lists, *Female Independence and How to Achieve It* is more accessible to a general audience than a peer-reviewed article.

Astronomy and astrophysics are incredibly difficult subjects. To further my restrictions, I attempted to use portions of the article to which Dr. Reed personally contributed and not directly work with sections headed by other scientists. Instead of describing the methodology and research, as opposed to how I approached the economics article, I focused on the results of the research. To non-scientists, describing more than fifteen months of recording data from wavelengths of light and radiation from a single star and its orbit is not interesting. However, the thought of an invisible star is fascinating, and so in *Invisible Dwarf* (*see Appendix D*), I focused my popular science piece on the conclusion as opposed to the methods. For example, the main portion of the conclusion is as follows:

> From our new low-resolution spectroscopy we discovered that KIC 11 558 725 is a binary consisting of a B subdwarf and an unseen companion. We found a circular orbit with P_{orb} = 10.05 d, and a radial-velocity amplitude of 58 km s^{-1}. From the high signal-to-noise average spectrum we redetermined the atmospheric parameters of the subdwarf: T_{eff} = 27 910K and log g =5.41 dex. (10)

The information presented in that paragraph would be overwhelming and complicated for a general audience. To describe the same information and relay the same message in my popular science piece *Invisible Dwarf* (*see Appendix D*),I focused on the overall meaning:

> There is an invisible star circling its companion, and Dr. Mike Reed, in cooperation with astronomers from around the world, used measurements and observations to prove its existence.

Similarly, there were complex portions of the conclusion involving methodology that was important to the overall meaning of the research:

> One may wonder if it is still necessary to use spectroscopy to solve orbits for targets in the *Kepler* field. For the case of KIC11 558 725 the phasing of the spectroscopic results with respect to the *Kepler* light curve proved essential in order to establish that the light-curve modulation is due to Doppler beaming, and not due to reflected light from the companion or to a contaminating object in the course *Kepler* pixel aperture. In general, the Doppler beaming amplitude may not reflect the radial-velocity amplitude in case the companion significantly contributes to the observed combined beaming amplitude. However, the phase and amplitude of the light-travel delay as determined by using the pulsations as clocks provide the same orbital constraints as derived from spectroscopy. (11)

I summarized the research and methods to highlight the important points:

> When collecting data on light wavelengths from the subdwarf B star, there was always the chance that the subdwarf's invisible companion could eclipse the other and skew the data. It was *Kepler* that saved the day—it applies algorithms to give accurate light curve data regardless of contamination from other influences.

Since Dr. Reed's article contained so much mathematics, physics, and astronomy, it was very confusing for a non-professional. To alleviate misunderstanding, I included definitions and metaphors. For example, I defined a pulsating subdwarf B star as "a type of subdwarf star with spectral type B. Subdwarf B stars are much brighter and hotter than typical subdwarf stars, and KIC

11 558 725 is no different." To further explain the pulsating aspect of subdwarf B stars, I included a comparison: "It pulsates, and the changes in its brightness make it look like the twinkling star from the childhood song." Although the resulting popular science article was short, I pulled the meaning out from behind the scientific jargon in Dr. Reed's article and clearly displayed it for my audience.

My pieces, while not intended for a specialized audience, simplify the content of the original peer-reviewed articles and make them accessible for a general audience. By using literary and rhetorical techniques and following the standards of technical communication, *Female Independence and How to Achieve It* and *Invisible Dwarf* exemplify popular science writing.

Conclusion

Science writing is powerful and difficult, but it is also rewarding. Popular science writers are in demand everywhere—in newsrooms, at universities, and in national laboratories---and for good reason, because the genre contributes positively to science literacy in and out of the classroom.

While there are techniques of good writing and technical communication that are applicable to all writing, including science writing, the most important aspect is passion. Science writers must want to learn new things each day and spend time familiarizing themselves with one research topic at a time. They must love what they do, because working with subject-matter experts, scientists and academics who do not accept science writing as legitimate or scholarly, and unfamiliar scientific concepts must be exhausting. However, if scientists or writers have that passion for providing avenues for a better-informed public and simplifying complex scientific information for a general audience, they should consider making the transition to popular science writing.

Works Cited

Austin, Barbara, Jackie Menasco, and Trenda Vannette. "The Nature of Science in Popular Nonfiction." *Science Teacher* 75.5 (2008): 27–32. *Academic Search Complete*. Web. 26 Jan. 2014.

Bilic-Zulle, Lidija. "Responsible Writing In Science." *Biochemia Medica* 20.3 (2010): 279–281. *Academic Search Complete*. Web. 24 Nov. 2013.

Bolles, Edmund Blair, ed. *Galileo's Commandment: 2,500 Years of Great Science Writing*. New York: Henry Holt and Company, 1999. Print.

Butler, Declan. "The Writing Is On The Web For Science Journals in Print." *Nature* 397.6716 (1999): 195. *Academic Search Elite*. Web. 16 Jan. 2014.

Ferris, Timothy. "On Science Writing." *Physics in Perspective* 4.1 (2002): 3. *Academic Search Complete*. Web. 24 Nov. 2013.

Gilgun, Jane F. "Grab and Good Science: Writing Up the Results of Qualitative Research." *Qualitative Health Research*15.1 (2004): 256–262. Web. 15 Jan. 2014.

Glasper, Edward Alan and Ian Peate. "Writing For Publication: Science and Healthcare Journals." *British Journal of Nursing* 22.16 (2013): 964–968. *Academic Search Complete*. Web. 24 Nov. 2013.

Glynn, Shawn M. and K. Denise Muth. "Reading and Writing to Learn Science: Achieving Scientific Literacy." *Journal of Research in Science Teaching* 31.9)1994): 1057–1073. Web. 13 Dec. 2013.

Gopen, George and Judith Swan. "The Science of Scientific Writing." *American Scientist*. 2 Jan. 2011. Web. 15 Nov. 2013.

"A Guide to Careers in Science Writing." *Council for the Advancement of Science Writing*. Council for the Advancement of Science Writing, 2013. Web. 16 Jan. 2014.

"How to be Popular." *Nature Physics* 7.1 (2011): 827. *Academic Search Complete*. Web. 16 Jan. 2014.

Huiyn, Shen, Maode Lai, and Jufang Shao. "Views on Popular-Science Publishing." *Journal of Scholarly Publishing* 37.4 (2006): 307–312. *Academic Search Complete*. Web. 8 Jan. 2014.

Jones, Nicola. "Q&A: Carl Zimmer on Writing Popular-Science Books." *Nature* 463.1 (2010): 737. *Academic Search Complete*. Web. 8 Jan. 2014.

Keys, Carolyn W. "Revitalizing Instruction in Scientific Genres: Connecting Knowledge Production with Writing to Learn in Science." *Science Education* 83.2 (1999): 115–130. Web. 15 Jan. 2014.

Koh Aik, Khoon, et al. "Popular Science Writing: Communicating Science to Peers and Public." *Reading Improvement* 46.3 (2009): 143–146. *Academic Search Complete*. Web. 24 Nov. 2013.

Low, Graham. "Explaining evolution: the use of animacy in an example of semi-formal science writing." *Language and Literature* 14.2 (2005): 129–148. Web. 13 Dec. 2014.

MacLennan, Jennifer. "Readings for Technical Communication." Ontario: Oxford University Press, 2008. Print.

Morber, Jenny Ruth. "From Engineer to Science Writer." *Advanced Materials & Processes* 171.2 (2013): 48. *Academic Search Complete*. Web. 24 Nov. 2013.

Nisbet, Matthew C. and Dietram A. Scheufele. "What's Next For Science Communication? Promising Directions and Lingering Distractions." *American Journal of Botany* 96.10 (2009): 1767–1778. *Academic Search Complete*. Web. 16 Jan. 2014.

Osbourne, Anne. "A Meeting Place: The Science, Art and Writing Initiative." *Current Science* 97.11 (2009): 1547–1554. *Academic Search Complete*. Web. 24 Nov. 2014.

Parkinson, Jean and Ralph Adendorff. "The use of popular science articles in teaching scientific literacy." *English for Specific Purposes* 23.4 (2004): 379–396. Web. 20 Jan. 2014.

Sandelowski, Margarete. "Writing a Good Read: Strategies for Re-Presenting Qualitative Data." *Research in Nursing and Health* 21.1 (1998): 375–382. Web. 14 Dec. 2013.

Schickore, Jutta. "Doing Science, Writing Science." *Philosophy of Science* 75.3 (2008): 323–343. *Academic Search Complete*. Web. 24 Nov. 2013.

Self, Sharmistha and Richard Grabowski. “Female Autonomy in Rural North India: Impact of Economic, Social, and Political Factors.” *Journal of Economic Development* 38.1 (2013): 59–82. Print.

Stein, Ben P. and Aziza Baccouche. “Careers in Science Writing.” *AIP Conference Proceedings* 991.1 (2008): 119–121. *Academic Search Complete*. Web. 24 Nov. 2013.

Telting, J. H., et al. “Three ways to solve the orbit of KIC 11 558 725: a 10-day beaming sdB+WD binary with a pulsating subdwarf.” *Astronomy & Astrophysics* 544.1 (2012): 1–16. Print.

“What is Science Writing?” *MIT Graduate Program in Science Writing*. Massachusetts Institute of Technology, 2014. Web. 16 Jan. 2014.

Appendix A: *Female Autonomy in Rural North India: Impact of Economic, Social and Political Factors*

Printed with permission from Sharmistha Self

Self, Sharmistha and Richard Grabowski. "Female Autonomy in Rural North India: Impact of Economic, Social, and Political Factors." *Journal of Economic Development* 38.1 (2013): 59–82. Print.

JOURNAL OF ECONOMIC DEVELOPMENT 59
Volume 38, Number 1, March 2013

FEMALE AUTONOMY IN RURAL NORTH INDIA: IMPACT OF ECONOMIC, SOCIAL, AND POLITICAL FACTORS

SHARMISTHA SELF[a] AND RICHARD GRABOWSKI[b*]

[a]*Missouri State University, USA*
[b]*Southern Illinois University, USA*

This paper attempts to answer a number of questions concerning factors which influence female autonomy as measured by mobility in rural north India (Uttar Pradesh). It is hypothesized that a female autonomy outside the home is influenced by social, economic, and political factors. The results of the empirical analysis indicate that the availability of certain types of infrastructure along with off-farm employment opportunities at the village level have a positive influence on female autonomy. In terms of the political structure of local government, there is no evidence to support the notion that having a female Pradhan will result in greater female autonomy. However, female autonomy is enhanced if the Pradhan is from a scheduled caste and/or the Pradhan has significant political experience. Data for the 2000s shows improvements in female autonomy and female participation in local government in Uttar Pradesh. However, significant challenges continue to remain. The results have important policy implications.

Keywords: Female Autonomy, Female Mobility, Village Governance, Rural North India, Female Village Pradhan, Schedule Caste Village Pradhan
JEL classification: J16, O10, O17

1. INTRODUCTION

What does the term female autonomy mean? Dyson and Moore (1982) define female autonomy as “the capacity to manipulate one’s personal environment. Autonomy indicates the ability-technical, social, and psychological - to obtain information and to use it as a basis for making decisions about one’s private concerns and those of one’s intimates” (p. 45). Kabeer (1999) defines female autonomy or agency as “processes by which those who have been denied the ability to make strategic life choices acquire such

[*] We are most grateful to an anonymous referee for valuable suggestions.

an ability" (p. 437). More specifically, female autonomy is defined as "the ability of women to make choices/decisions within the household relative to their husband's" (Anderson and Eswaran, 2009, p. 179).

Recently, empowering women or increasing a woman's autonomy has been shown to be important in a variety of different ways. It is thought to lead to long-term reductions in fertility, higher child survival rates, and allocations of resources within the household which benefit the children within the household (Anderson and Eswaran, 2009). Thus improvements in women's autonomy have positive, indirect spillover effects.

However, increases in female autonomy also have very direct and important positive effects on females. Specifically, violence against females by males within the family is prevalent in many parts of the world. It is argued by many that increases in a woman's autonomy serves as a very powerful instrument for limiting such violence. Thus factors increasing female autonomy are important in terms of the direct effect of reducing violence against females and the indirect, positive spillover effects.

What factors influence the extent to which females have autonomy? In economics the literature is quite limited. However, outside economics the literature is more abundant. Specifically, the sociological literature tends to focus on those societal factors which tend to create and enforce situations in which female autonomy is greatly reduced. Specifically, the customs and norms of patriarchal societies are thought to be important causal factors in determining female autonomy. They operate both directly and indirectly. "In the direct sense they may limit women's ability and willingness to bargain. In this case issues are not uncontested and natural, but established practices and expectations make success in bargaining extremely difficult. In the indirect sense, norms may influence the access women have to means of improving their bargaining power" (Kantor, 2003, p. 428). From this perspective, policy is viewed as being quite limited in the impact that it can have in terms of enhancing women's autonomy. Instead, cultural and social change are critical (See Narayan, 2005).

The difficulty with the above is that social scientists have little knowledge, wisdom, nor special skills in terms of engineering social change in order to achieve greater autonomy for women. As a result, this paper will focus on policies that can be manipulated so as to bring about changes at the margins of tradition based societies. Thus the focus will not be on engineering dramatic social change which would be transformational in nature, but instead promoting policies that can be manipulated so as to bring about small changes in social relationships which enhance female autonomy. The literature concerning marginal, incremental change and policy is centered in economics.

The main focus of the paper will be to determine those variables which influence the extent of female autonomy in the Indian state of Uttar Pradesh. This state is chosen for two reasons. First, this state represents an environment in which traditionally women have faced significant barriers which have created large gender gaps in terms of employment, health care, and physical mobility. Thus it will be very useful to determine whether within such an environment there are useful policies which could have been used to enhance female autonomy. Secondly, the data set utilized for Uttar Pradesh contains information on a variety of household and individual variables unavailable in other publicly available data sets.

Section 2 will review the literature while section 3 will present the empirical model that will be estimated as well as discuss the data drawn from the household survey carried out in Uttar Pradesh. Various problems arising with the estimation will also be discussed in some detail. Section 4 will present the results and utilize them to try and determine what variables likely enhance female autonomy. Section 5 will update the results by looking at recent experience in Uttar Pradesh. Finally, Section 6 will summarize the results and present conclusions.

2. SOME LITERATURE AND THEORETICAL MODELS

The empirical literature focused on female autonomy is very limited. Kantor (2003) sought to analyze the extent to which home based production in the garment sector in Ahmedabad, India empowers females who participate in such activity. Her reading of the economic and sociological literature indicates that both tend to emphasize a women's access to resources as being a key variable. However, she argues that greater access to resources may not be enough. This is the result of the fact that women's decision making may be constrained and filtered by existing social norms.

The work of Rahman and Rao (2004) also seeks to analyze those factors influencing the extent of female autonomy. The paper actually focuses on Dyson and Moore's explanation as to why South Indian women are generally more autonomous than North Indian women. Dyson and Moore's explanation focused on the North's (North India) bias towards favoring exogamous marriage, the wife marrying outside the community and family, with the South (South India) favoring endogamous marriage, within the community and extended family. The latter assures that the wife maintains her kinship network as a support mechanism whereas the former isolates the wife from this network of relationships. The ability of women in the south to depend upon her kinship network allows her greater autonomy whereas in the north the lack of such a network reduces autonomy. Rahman and Rao seek to empirically test this proposition.

In the process of analyzing the above issue the Rahman and Rao paper develops into an analysis of factors influencing female autonomy. They measure female autonomy by looking at two types of measures. The first category measures the extent of female mobility and represents the extent to which a woman can move around without the permission of her husband. A second category of measures seek to quantify the extent to which women participate in various household decision making processes. Right hand side variables include cultural factors such as the extent of village exogamy and consanguity, as well as various female exclusion practices. Village level data on male and female wage rates were used to measure economic opportunity. Finally, measures of the availability of public infrastructure are also included.

The results indicate that with respect to economic variables, higher female wages enhance a woman's mobility and her influence in household decision making. Higher male wages have the reverse effect. Also, infrastructure at the village level tends to be strongly associated with improvements in female mobility and enhancement of female involvement in decision making.

Anderson and Eswaran (2009) develop a model of household behavior in order to draw conclusions about factors which increase female autonomy. They then empirically test the hypotheses using data from Bangladesh. The model is very interesting. The household is not viewed as a monolithic unit with a single decision-maker, instead a better approach is to view decision making within the household as being conflictual in nature. Typically, this has resulted in the development of bargaining models in which the influence of the woman is a function of her threat options, measured by the level of well being the woman could obtain if the marriage dissolves (outside threat option). An improvement in the outside threat option enhances the autonomy of the woman within the marriage. This is the model upon which the previously discussed work implicitly depends.

However, Anderson and Eswaran (2009) are really interested in determining whether it is work within the household or work outside the household that is more important in raising the autonomy of women. Also, their data is drawn from Bangladesh where divorce, as a threat option, is not possible. Thus the outside threat of divorce is not relevant. In this case, a breakdown in bargaining by spouses implies that the threat option within the marriage is the critical factor and this threat option will depend on the non-cooperative solution between spouses within the marriage (household). Their model presumes that men can work outside the home or take leisure and the former allows him to consume private goods and contribute income (not labor) to the production of a household public good (not income). The wife can take leisure, devote labor to the production of the household public good, or work outside the home for income. It is assumed in this model that working inside the household by the female does not increase her threat option, it does not increase her ability to work outside the household. So, for example, working on the family farm does not provide her with skills that could be used to earn income outside the household.

So in this model the bargaining position of the wife depends on external earnings possibilities through outside (of the family) work. The greater these opportunities are (increase in wage for external work), the stronger the position of the wife (autonomy). She can significantly harm the position of the husband by choosing to devote more time to external work and reduce how much time she devotes to household work (public good) and leisure. The husband will have to devote greater income to the production of the public good, his consumption of private goods declines, and he works more and consumes less leisure. This is what will happen if cooperation between the wife and husband breaks down. Thus the wife's threat is greater and this allows her more autonomy within the marriage. Using data from Bangladesh they do indeed find that external work opportunities are the key to enhancing a woman's autonomy, not work within the household. The measures of autonomy used include measures of the female's say in decisions concerning the purchases of various items.

Over and above the factors mentioned so far, one must also consider another important external factor, the local governance institutions. As mentioned earlier, given the low level of political participation of women in the deliberative bodies of India, in 1992 the Constitution of India was amended such that a third of the seats in the Panchayats (local governments), including the chairperson (Pradhan), must be set aside for women. One might think that this should influence political decision making leading to increases in female autonomy (Chhibber, 2002).

Chattopadhyay and Duflo (2003) empirically examined the impact of this amendment by utilizing data from two districts in India: Birbhum, in West Bengal, and Udaipur, in Rajasthan. They found that having women and scheduled castes Pradhans in the Panchayat made a difference. Specifically, women and scheduled caste Pradhans tend to engage in policies which favor women and thus tend to increase their autonomy. Thus the composition of local government may be a critical factor influencing the threat utility levels of women.

Ban and Rao (2008) use data from south India to further investigate these issues. They do not find any evidence to support the idea that female Pradhans are mere tokens. They find evidence that most women leaders are drawn from "the upper end of the quality distribution of women" (p. 501). They also do not find any evidence that female political leaders are likely to make decisions that favor women's concerns. A similar sort of conclusion is reached in Raabe *et al.* (2009) who look to see how political reservations for women affect local governance and rural services in Karnataka, in south India. Their results indicate that women's reservation policies are by themselves ineffective in making provisions for rural services and local governance more inclusive and gender equitable. Similar conclusions are reached in Krishnan (2007) who finds no evidence that lower caste (scheduled tribe) legislators perform any differently than legislators elected from unreserved constituencies. However, this paper finds that scheduled caste legislators perform better at providing greater access to educational facilities, in particular, primary schools, within their districts and constituencies. Rajaram and Gupta (2009) conclude that economic fundamentals trump gender of the village head in policy choices.

Thus a number of specific research questions concerning female autonomy are apparent. Does the opportunity of women to work, whether on the family farm or off-farm, increase the woman's autonomy? Are women in poor relative to non-poor families more likely to be autonomous? Do infrastructural factors have a significant impact on female autonomy? Finally, does a change in the structure of local government (reservations for women Pradhans) herald an increase in female autonomy?

3. DISCUSSION OF DATA AND EMPIRICAL MODEL

The data being utilized for the purpose of this paper comes from the World Bank's Living Standard Measurement Survey of households conducted for the State of Uttar Pradesh in India for the years 1997-98. The survey was conducted for two states, but due to unavailability of relevant data for the state of Bihar, this paper concentrates only on the state of Uttar Pradesh.

The data from Uttar Pradesh is utilized for three important reasons. Although the data is approximately fourteen years old, it is the only publicly available data set that has information on governance in the state. Specifically, information is provided on the sex caste, and length of time in office for village Pradhans. This enables a synthesis of the household level information with the village specific information. In addition, Uttar Pradesh at this period of time was characterized by significant barriers to women's economic, social, and political activities. However, the central government had in 1992 passed amendments to require that a third of the seats in Panchayats (local governments), including the chairperson (Pradhan), be set aside for women. Given that the survey being utilized here took place in 1997-98, it provides an opportunity to determine whether the amendment significantly improved women's autonomy. Last, but not least, to our knowledge there are no other studies which address the question/s addressed in this paper for Uttar Pradesh. This may be because the LSMS data utilized for this paper is the only data set of its kind. Most other studies on this topic use NFHS data (which is state or household level data, not village level) or other data collected by the author/s relating to different states within India. The importance of Uttar Pradesh concerning questions related to female autonomy is discussed in detail in Section 5.

Most papers relating to female autonomy concentrate on her autonomy within the household. This paper begins by taking a different view by measuring female autonomy outside the household. Specifically, it looks at two measures: a woman being able to leave the house to see a doctor without the permission of a male member of the family and a woman being able to go to a doctor's office unescorted by a male member. Thus, here we are not focusing on mobility for its own sake, which is important in itself, but we are looking at mobility that is associated with a definite purpose and thus even more important. A woman may need to visit the doctor for her own health or for her children or any other member of the family. Both of the variables being utilized as the dependent variables measure whether females enjoy freedom or autonomy of mobility outside the home.

The survey being utilized for this paper uses data based on interviewing 2000 women spread over 64 villages and 11 *tolas* (districts) within the state of Uttar Pradesh. The respondents are chosen as the (female) spokesperson for the family. Thus each respondent represents one family. Upon closer inspection of the data it appears that even though these respondents were supposed to be a representative female from each family, some respondents were male. These respondents are dropped from the sample. This leaves us with 1963 responses by females and this constitutes our sample. The summary statistics with a brief definition of the variables are provided in Table 1.

Table 1. Summary Statistics

Variable	Description	Obs	Mean	Std Dev	Min	Max
Indiv/Household Variables						
Age	Age of respondent	1013	36.91017	12.60036	13	90
Age of Household Head	Age of respondent's husband	1011	46.81405	14.36018	17	95
Education	Educational attainment: 1 if illiterate, 2 if literate but no schooling, 3 if less than primary, 4 primary, 5 middle, 6 matriculate (10th grade), 7 intermediate (12th grade), 8 bachelors degree, 9 masters degree, 10 professional degree, 11 diploma	1013	1.673248	1.663026	1	11
Hindu	1 if household head is Hindu, 0 otherwise	1013	0.9296029	0.2559306	0	1
Caste	1 if high caste, 0 Otherwise	1013	0.1569507	0.3639175	0	1
Average Child Age	Average age of children in household	1013	15.35039	10.46729	0	50
Poor	1 if family below poverty line	1013	0.3043088	0.4603207	0	1
Femalehead	1 if household head is female, 0 otherwise	1013	0.032287	0.1768406	0	1
Working for Wage	1 if respondent is employed for wage income, 0 otherwise	1004	0.3525896	0.4409816	0	1
Average Land Holding	Total agricultural land owned in acres.	1013	3.342029	2.669647	0.5440869	12.48908
Village Level Variables						
Female Pradhan	1 if pradhan (leader of village governance) is female, 0 otherwise	63	0.2857143	0.4553826	0	1

PradhnSC	1 if pradhan (leader of village governance) is from the lowest caste known as Scheduled Caste, 0 otherwise	64	0.25	0.4364358	0	1
Pradhanlength	Number of years the current pradhan (leader of village governance) has been in office	64	4.186094	3.370063	0	15
School	1 if village has access to a school, 0 otherwise	64	0.6875	0.4671766	0	1
Telephone	1 if village has access to a telephone	64	0.171875	0.3802542	0	1
Off-farm Income	Share of houeholds which have significant off-farm source of income	62	41.37097	28.66782	2	95
Roadaccess	1 if part if at least some part of the village is accessible by trail only, 2 if temporaary road, 3 if paved road, 4 if permanent road	64	2.671875	0.9767892	0	4

A preliminary look at the data shows wide variability in terms of both measures of female autonomy being used in this paper. In terms of leaving the house without permission, these proportions range from 0% of the women needing permission (three villages) to 76% of the women needing permission to leave the house. On average about 35% of women needed the permission of a male member of the family. In terms of whether or not a woman has the freedom to visit the doctor without a male escort, the values range from 0% of the women needing a male escort to 69% needing male escort. On average, about 33% of women overall need a male escort. Given this variability in a woman's freedom of movement outside the home, a natural question arises regarding what factors might be able to explain or influence the variation in female autonomy within any particular village, as well as across villages.

It is hypothesized that a woman's autonomy outside the home is influenced by social, economic, and political factors. For ease of analysis these characteristics have been bundled under individual, household and village characteristics. Individual characteristics can be both economic and/or social in nature, as are household characteristics. Village characteristics measure the infrastructural support, degree of economic development, and political factors that are hypothesized to have an impact on female autonomy of movement. Over and above the variables of interest, the explanatory variables also include control variables.

In terms of some overall social/cultural characteristics of the sample a majority of the women in the sample are Hindu with only about 7% being Muslim. Additionally, about 85% of the women belong to the low caste. Caste is seen as a symbol of social status in India, especially in rural areas. According to Deshpande (2002), an assessment of the contemporary state of the gender-caste overlap suggests that the economic condition of women continues to be defined and constrained by their caste status.

Some additional characteristics relating to education and employment, we find that about 79% of the women in the sample are illiterate. Additionally, for women in the working age group the average age of the respondent is thirty-seven, with her husband typically about ten years older. This age difference between the spouses is not uncommon for Asia, especially South Asia. About 54% of the women in the sample report being employed (with 85% in the agricultural sector) but only 35% earn a wage income.

In terms of household characteristics, a majority of households earn income above the poverty line. However, a third of the households are very poor, that is, their household income is below the poverty line (this is discussed in more detail below). Over and above being poor, most families are large with an average household consisting of seven members and at least one child and more than 20% of the families having children six years of age or under. Additionally, as expected, men head most households in the sample with only about 3% of households being headed by women.

In terms of access to resources, this paper looks at various different facilities accessible to the villages where the respondents live. These include access to an urban area, access to people outside the home and outside the village, access to education, and access to employment opportunities outside the agricultural sector. Empirical evidence shows that infrastructure is an important measure of economic well-being of a community (Rioja, 2001). These resources are expected to increase a woman's autonomy outside the home. For example, access to roadways would increase her ease of transportation and opportunities for employment outside the village. Access to a telephone would increase her ability to contact people if necessary, while access to a school is expected to increase her chances of being educated. Additionally, having a large percentage of the villagers reporting some non-agricultural source of income is seen as a sign of a reduced dependence of the community on agriculture.

The data show that on average villages are accessible by semi-permanent or paved roadways. Additionally, even though about 61% of the villages claim to be electrified, on average only 21% of each village has access to electricity. Moreover, only 17% of the villages have access to a telephone. In terms of access to education, about 69% of the villages have access to a school. On average, villages report that a majority of households are dependent primarily on agriculture. Only about 41% report income from a non-agricultural source.

At the village level we also consider the governance process at the local level. The choice of a leader in village governance (Pradhan) is expected to influence the social and political environment of the community. As mentioned earlier, Chattopadhyay and Duflo (2003) find that women benefit when the village Panchayat is led by a woman or people from a scheduled caste. According to the data, on average 28% of the villages in the sample have female Pradhans and about 25% of the villages have a Pradhan who belongs to a scheduled caste, which is the lowest caste. One of the hypotheses that will be tested concerns whether or not those villages having a female or someone from the scheduled caste as a Pradhan will be characterized by greater autonomy for its females. Also the length of time a Pradhan is in office may also be important. In the sample utilized here the average length of time a Pradhan has been in power is a little over four years. However, there is variation in the distribution of this variable.

Next, we construct an empirical model that will enable us to analyze the data and answer the research questions raised above. A binomial logit model is utilized for the analysis. There are two different dependent variables being utilized for this analysis since we are looking at female autonomy measured by two different measures of mobility outside the house. In one instance the dependent variable takes the value 1 if the respondent can visit a doctor without the permission from a male member of the family and 0 otherwise (*Docpermission*). In the second instance, the dependent variable takes the value 1 if the respondent can visit a doctor without a male escort and 0 otherwise (*Docescort*).

The regression model that is estimated is given by

$$W_{ijk} = \alpha + \beta_1 Individual + \beta_2 Household + \beta_3 Village + \varepsilon_i, \tag{1}$$

where W_{ijk} is a zero - one variable representing whether a woman i in household j and village k has the freedom of movement outside her home, measured the two ways discussed in the previous paragraph. *Individual*, *Household*, and *Village* are vectors of individual, household, and village characteristics. The β 's are the parameters to be estimated.

Several different specifications of the above model are utilized to test for robustness of the empirical results. In addition, we also carried out the analysis utilizing the Heckman two-stage procedure to see whether the logit results were biased due to selection bias. The logit analysis relates to responses of women who acted as the spokeswoman for their respective families. In contrast, the first stage of the Heckman estimations, which is the selection estimation, tested to see what factors influence a woman being selected to be the respondent to the survey questionnaire. The second stage of the estimation, the outcome equation, tested to see what factors affect the autonomy of women in the family being represented by the spokeswoman. The Heckman results (available upon request) which pertain to all women in the sample are almost identical to the logit results in terms of signs and statistical significance.

The selection of explanatory variables is influenced by existing literature, theory and the hypotheses being tested in this paper. In terms of individual characteristics, first we consider the respondent's age (*Age*). The literature shows that older women are more experienced and have a better understanding of how to get what they need. Additionally, they are seen to enjoy a closer relationship with the husband (and his family), having fulfilled particular social obligations such as bearing children (Mason and Smith, 2003).

The second variable we look at is the respondent's husband's age (*Age of household head*). It is believed that the older the husband or the wider the age gap between the husband and the wife, the lower is the level of a woman's autonomy. The literature on female empowerment finds support for this hypothesis (Cain, 1993; Presser, 1975).

The third individual level variable is the respondent's level of educational attainment (*Education*). This is a continuous variable and Table 1 gives a detailed description of this variable. There is a wealth of empirical literature in support of the importance of education in general and for women in particular. For example, Maitra (2002) shows that the sex of the household head, the education attainment of the household head, ethnicity and region of residence have significant effects on both the poverty status and standard of living of the household in South Africa. It is expected that if a woman is educated she will have a higher probability of being gainfully employed which would increase her autonomy.

The fourth variable relates to the respondent's economic status by measuring not just her employment, but whether or not she works for wages (*Work for wages*). This is a binary variable which takes the value 1 if the woman is employed and earns a wage income, regardless of whether she is employed in the agricultural or non-agricultural sector, and 0 otherwise. A woman is expected to be more mobile and therefore enjoy greater autonomy if she makes a financial contribution to the family. This is expected to increase her bargaining power within the family while at the same time increasing her access to resources.

The fifth and sixth individual variables have to do with a woman's social status. These are her religion (*Hindu*) and her caste (*Caste*). Religion is measured by a binary variable which takes the value 1 is the respondent in Hindu and 0 otherwise. The only other religion that is found in the sample is Muslim. The majority of the women in the sample are Hindu. Religion has been found to have profound influence on social institutions which in turn have an impact on women. For example, Mason *et al.* (2003) find differences between Muslim and non-Muslim women that live in the same geographical area.

The *Caste* variable is also a binary variable taking the value 1 if the respondent belongs to the high caste and 0 otherwise. Given that India is a caste based society, caste plays an important role in determining social status. This is particularly relevant for the state of Uttar Pradesh. Jejeebhoy and Sathar (2001) find that for Uttar Pradesh female autonomy measured in a variety of ways is influenced by social status along with education and economic activity. Thus caste is expected to play a role in determining female autonomy.

The household level variables being considered are whether or not the family's income level lies below the poverty line (*Poor*), average size of land holding (*Average land holding*) which is expected to reflect the family's wealth status, whether or not he family is headed by a female (*Femalehead*), and the average age of children in the household (*Average child age*). Both *Average land holding* and *Poor* are used to measure the economic condition of the family, while *Femalehead* and *Average child age* are used to measure the freedom the woman has in terms of making decisions and in terms of mobility. The assumption is that if a woman has infant children or children who are not going to school, she will have less mobility and freedom of movement outside the house. *Femalehead* is a binary variable which takes the value 1 if the household is headed by a female and 0 otherwise. It is assumed that a family that is headed by a woman will be more enabling for women than a household headed by a man.

Poor is used as a proxy for the family's income. A household below the poverty line "qualifies for the Below Poverty Line (BPL) subsidy for food grains offered through the revamped Public Distribution System (PDS)" (Sakamoto, 2006). This is measured by a binary variable, which takes the value 1 if the family's income is below the poverty line and 0 otherwise.

Finally, the village level political variables include whether or not the village has a female Pradhan as the leader of the village Panchayat (*Female Pradhan*), whether or not the Pradhan belongs to the scheduled caste (*PradhanSC*), and how long the Pradhan has been in power (*Pradhanlength*). The first two are binary variables which take the value 1 if the Pradhan is a female (for *Female Pradhan*) or from the scheduled caste (for *PradhanSC*) or 0 otherwise. The third is a continuous variable and measures the number of years the current Pradhan has been in power.

The other village level variables measure the village's access to resources such as access by road (*Roadaccess*), access to a school (*School*), access to a telephone (*Telephone*). All three are binary variables. All three variables are expected to proxy for the extent of infrastructure in the village the respondent lives in. There is one additional village level variable. This measures the general economic environment of the village. This is a measure of the proportion of people in the village that earn a significant portion of their income from non-agricultural or off-farm sources (*Off-farm income*). This last variable is a continuous variable.

4. RESULTS

Results are reported for the *Docpermission* (freedom to go to a doctor without the permission of a male member of the family) variable as the dependent variable. Results relating to *Docescort* (freedom to go to the doctor without a male escort) are not reported since they are very similar to those relating to *Docpermission* (available upon request). Before discussing regression results, we try to gain some intuition about the relationship between the variables being considered in this analysis. Thus, to begin with, we look at pair-wise correlations between the different variables. These correlations shed light on the fact that the relation between the dependent variable and the independent variables are endogenous and complex. One needs to be aware that the relation between the variables might introduce bias in the regression results. Thus, before we begin any discussion about the regression results, the correlations are expected to set the stage in terms of how the variables are related. All correlations are presented in Tables 2A and 2B. Over and above presenting the correlations, the table also identifies those correlations which are statistically significant at 95% or above.

Table 2A. Correlations

	Docper-mission	Age	Hindu	Caste	Age of HH Head	Average Land Holding	Tele-phone	Female HH Head
Docpermission	1							
Age	0.072*	1						
Hindu	0.027	0.007	1.000					
Caste	-0.041	0.014	-0.294*	1.000				
Age of HH Head	-0.032	0.504*	0.016	0.059*	1.000			
Average Child Age	-0.033	0.335*	0.046	0.089*	0.85*	1.000		
Average Land Holding	-0.143*	-0.078*	0.108*	0.022	-0.052*	-0.022	1.000	
Telephone	0.022	-0.048*	-0.095*	0.056*	-0.037	-0.030	0.014	1.000
Female HH Head	0.189*	0.139*	-0.05*	0.027	-0.023	-0.011	-0.043	0.103*
Education	-0.017	-0.072*	-0.001	0.282*	0.082*	0.096*	0.024	0.075*
Poor	0.132*	-0.026	0.076*	-0.126*	-0.116*	-0.096*	-0.062*	-0.040
Female Pradhan	-0.030	0.048*	-0.225*	0.084*	0.031	-0.004	-0.233*	0.095*
Pradhan SC	0.077*	-0.069*	0.036	-0.11*	-0.054*	-0.058*	-0.079*	0.245*
Pradhan Length	0.044*	-0.015	0.061*	0.021	-0.012	-0.007	0.021	0.115*
Off-Farm Income	0.079*	0.079*	0.08*	-0.007	0.061*	0.046	0.1277*	-0.091*
Road Access	0.132*	0.034	-0.079*	-0.005	0.016	-0.028	-0.341*	0.19*
School	0.051*	-0.036	0.032	0.027	0.008	-0.026	0.115*	0.034
Work for Pay	0.107*	0.062*	0.043	-0.109*	-0.074*	-0.089*	-0.096*	-0.084*

Note: * statistically significant at 5%.

Table 2B. Correlations Continued

	Female HH Head	Education	Poor	Female Pradhan	Pradhan SC	Pradhan Length	Off-Farm Income	Road Access	School	Work for Pay
Female HH Head	1.000									
Education	-0.023	1.000								
Poor	0.056*	-0.109*	1.000							
Female Pradhan	0.014	0.018	-0.01	1.000						
Pradhan SC	-0.007	-0.052*	0.13*	-0.089*	1.000					
Pradhan Length	0.054*	0.041	0.028	-0.217*	-0.269*	1.000				
Off-Farm Income	-0.067*	0.009	0.06*	-0.012	0.134*	0.049*	1.000			
Road Access	0.019	-0.019	0.008	-0.04	0.272*	0.048*	-0.085*	1.000		
School	-0.011	-0.042	0.104*	-0.063*	0.164*	0.085*	0.032	-0.022	1.000	
Work for Pay	0.117*	-0.117*	0.17*	-0.06*	-0.032	0.011	-0.015	0.036	0.015	1.000

Note: * statistically significant at 5%.

The first column in Table 2A presents correlations between the dependent variable and all other explanatory variables. These show that at the individual level, the dependent variable is positively and statistically significantly correlated with age of the respondent and if the respondent works for wages. At the household level the dependent variable is positively and statistically significantly correlated with poverty and if the household has a female household head and negatively with the average size of land holding or wealth of the family. At the village level, the dependent variable is positively related to the proportion of villagers earning income from some non-agricultural/farm source and if the village has access to the nearest town via roads. Additionally, at the political level, the dependent variable is positively and statistically significantly correlated with the caste of the village Pradhan and political stability as measured by the length of time a Pradhan has been in office. The other columns show the direction of correlation between the explanatory variables.

What is important to note from the correlations is that the correlation between the dependent variable and whether or not the Pradhan is a female is negative and not statistically significant. However, a woman's autonomy appears to be positively correlated with whether the village has a Pradhan from a scheduled caste/tribe and the length he/she stays in office. This seems to imply that having a female for a village Pradhan is not strongly related to the degree of autonomy a woman enjoys in terms of freedom of movement outside the house. However if the Pradhan belongs to a low caste it seems to imply that females in that village enjoy greater freedom of movement.

The *Female Pradhan* variable itself is negatively and statistically significantly correlated with a Pradhan belonging to the scheduled caste/tribe (*PradhanSC*) or the length of time (*Pradhanlength*) and, surprisingly, to the presence of a school (*School*) in the village. The negative correlation between Female Pradhan and PradhanSC seems to support Ban and Rao (2008) that female Pradhans are selected from the "upper end of the quality distribution of women" (p. 501). Thus they are perhaps less likely to belong to the scheduled caste or tribe. Additionally the negative correlation between having a female Pradhan in local governance and the existence of a school in the village appears to echo Raabe *et al*. (2009) who did not find a link between political reservations for women and rural services for the state of Karnataka.

Unlike the *Female Pradhan* variable, the *PradhanSC* variable and the *Pradhanlength* variables are both positively and statistically significantly correlated with the proportion of villagers earning income from a source alternative to farming (*Off-farm income*), better access to other towns via roads (*Road access*) and to the presence of a school in the village. These seem to suggest a strong link between the caste of the Pradhan of the village (who perhaps continues to be in that position for any length of time) and better provision for rural services. Since women, more than men, are affected by the provision for different services, this may explain the strong positive correlation between these two political variables and the dependent variable. This may also be a reflection of Anderson's (2011) paper based on rural villages in India. This paper finds income to be substantially higher for low-caste households residing in villages dominated by a lower castes. Since a majority of our sample belongs to the lower caste, this may be a reflection of a woman's ability to earn a higher income (and thus enjoy greater freedom) if she resides in a village governed by a lower caste Pradhan. One should also take note that the election of a scheduled caste person as the leader of the village panchayat may itself be a reflection of a majority of the populace belonging to the lower caste or of being accepting of being led by someone from the lower caste (unless this is a result of reservation of the position for a scheduled caste member).

Next we turn our attention to the regression results. An important issue that needs to be addressed before discussing and analyzing regression results is the issue of endogeneity. Endogeneity refers to the fact that an independent variable included in the model is potentially a choice variable and thus correlated with unobservables relegated to the error term. For example, in our sample, a woman who wishes to enjoy freedom of mobility outside the home may choose to settle in a village which is being governed by a female Pradhan. Similarly a woman belonging to a low caste, but wanting to work outside the home may choose to settle in a village with a Pradhan from a low caste. Another case can be made concerning female headed households and a woman's freedom of mobility or a woman's employment and her mobility and/or her level of education and her mobility outside the home. These may be simultaneously influenced by a third factor such as the family's economic status or the general social environment in the village. The gender and caste of the village Pradhan itself could be considered to be endogenous unless we can control for the reservation status of the Pradhan seat. Failure to control for this will likely under-estimate the effect of having a female Pradhan or a low caste Pradhan on women's freedom of movement outside the home.

Needless to say, an endogenous relation is potential for almost all of the explanatory variables (with the exception of the respondent's age, her religion, and her caste) in this analysis. If the variables mentioned above are indeed endogenous a regular logit estimation would possibly generate biased and inconsistent estimates of the impact of the explanatory variable/s on the outcome. A common strategy for dealing with this endogeneity is to use instrumental variables (IV) estimation, where "instruments" are variables assumed to have no direct association with the outcome. However, the available data limits the ability to find or construct appropriate instruments for all the explanatory variables. Thus, we control for the three truly exogenous variables (*Age, Hindu*, and *Caste*) and then add the other explanatory variables. The results remain robust to inclusion of the independent variables. Additionally, they reflect the intuitive relations we find using correlation analysis. Thus one can assume that the results have not been biased due to potential endogeneity and/or multicollinearity issues. However, one needs to interpret the results with caution and understand that, given these possible limitations, the explanatory variables are possibly going to under-estimate the true impact of these variables on the dependent variable.

Logit results pertaining to the overall sample are presented in Table 2. The results include the elasticities (*dy/dx*) obtained from marginal probability analysis. All standard errors are robust and heteroscedastically consistent. The regression analysis does not find support for female Pradhans (*Female Pradhan)* having any statistically significant impact on female autonomy. However, the impact of Pradhans from scheduled castes (*PrahdanSC)* and the length of time a Pradhan has served in office (*Pradhanlength*) are statistically significant in all but the very last estimation. The very last estimation finds these two variables to lose statistical significance, but this may be due their high correlation with the access to better roads (*Roadaccess*) which is included in the last estimation.

Similar to the correlation analysis, the regression analysis seems to indicate that both low caste Pradhans and the time spent in office increase a woman's freedom of mobility outside the home. Thus, while we do not see support for female Pradhan's increasing the likelihood of women in the village enjoying greater freedom of movement, having a low caste Pradhan (male or female) is found to be beneficial as is the possible political stability that comes with the leader being in office for some length of time. The apparent lack of impact of having a female as the village leader found in this paper is also reflected in Ban and Rao (2009) and Raabe *et al*. (2009). Rajaram and Krhsinan (2009) find that ultimately economic fundamentals are more important in determining policy outcomes rather than the gender of the governing body. The reason may possibly be one identified by Ban and Rao (2009) that most of the time female leaders are simply tokens and the real decision-making is still being done by men. Our results find support for the village Pradhan being from a lower caste to have a beneficial impact on female autonomy in the village. These results are somewhat reflected in Krishnan (2007) who finds that scheduled caste legislators perform better at providing greater access to educational facilities, in particular, primary schools, within their districts and constituencies. Since women are in general greater beneficiaries of such public goods, this possibly explains our results as well.

Table 3. Results (Elasticities) for Full Sample: Dependent Variable *Docpermission*

Variables	*dy/dx*	*dy/dx*	*dy/dx*	*dy/dx*	*dy/dx*
Age	0.0130***	0.0145***	0.0204***	0.0196***	0.0149**
	(0.00398)	(0.00404)	(0.00564)	(0.00565)	(0.00588)
Hindu	0.130	0.129	0.300	0.259	0.318
	(0.203)	(0.213)	(0.229)	(0.229)	(0.236)
Caste	-0.254	-0.190	-0.161	-0.121	-0.141
	(0.160)	(0.160)	(0.180)	(0.180)	(0.191)
Age of HH Head			-0.03***	-0.028***	-0.0322***
			(0.00785)	(0.00784)	(0.00819)
Average Child Age			0.0245**	0.0233**	0.0281***
			(0.0100)	(0.0101)	(0.0105)
Work for Wages			0.534***	0.453***	0.462***
			(0.116)	(0.119)	(0.120)
Education			0.0395	0.0484	0.0213
			(0.0423)	(0.0425)	(0.0463)
Female Headed HH			1.570***	1.537***	1.652***
			(0.281)	(0.275)	(0.295)
Poor				0.338***	0.348***
				(0.104)	(0.108)
Telephone					-0.0729
					(0.144)
School					0.152
					(0.135)
Off-Farm Income					0.00873***
					(0.00204)
Roadaccess					0.330***
					(0.0567)
Female Pradhan		-0.0151	0.0225	0.0160	0.0567
		(0.111)	(0.116)	(0.117)	(0.122)
PradhanSC		0.415***	0.379***	0.343***	0.0558
		(0.0992)	(0.106)	(0.108)	(0.126)
Pradhanlength		0.0526***	0.0504***	0.0480**	0.0254
		(0.0175)	(0.0189)	(0.0189)	(0.0205)
Observations	1001	997	997	996	996

Notes: All equations have a constant term not presented in the Table; *, **, *** stand for statistical significance at 10%, 5%, and 1% respectively; results presented with heteroscedacticity consistent standard errors in parentheses.

In terms of the impact of some of the other variables, results in Table 3 show that access to resources plays an important role in promoting female autonomy outside the home. Access to roadways (*Roadaccess*) and access to education (*School*) have statistically significant positive impacts on female autonomy. Additionally, villages with a greater proportion of people relying on some source of off-farm income (*Off-farm income*) are also found to increase the likelihood of a woman enjoying greater freedom of mobility. In terms of household characteristics, not having to care for young children (*Average child age*) at home increases a woman's mobility. In terms of individual characteristics, older women (Age) and an improved economic status which comes from being employed and earning a measurable monetary wage (*Work for wages*) also greatly enhances a woman's mobility. Families headed by female household heads (*Female head*) are found to increase a woman's mobility outside the home as well. Women in poorer families (*Poor*) are found to have greater freedom of mobility. This mobility could be due to their financial situation which probably requires the family members to leave home to look for work and/or food. Wealth as measured by the size of land holding (*Average land holding*) and husband's age (*Age of household head*) are both found to have a negative and statistically significant impact on a woman's freedom of movement outside the home.

This result relating to wealth (and conversely to poverty) having a negative (positive) impact on mobility is consistent with theory as long as the higher standard of living is a result of higher income for the husband. Unfortunately, it is not clear whether the families that are wealthy are so as a result of higher income for the husband or it is wealth that is inherited through marriage. However, given the patriarchal nature of the society under consideration one can assume that the husband has control over family's resources regardless of its source. If we presume that this is the case, then these results appear to be consistent Kantor's (2003) findings.

In summary, we find that families headed by females increase a woman's mobility outside the house. Additionally, women who earn a wage income are more likely to enjoy greater freedom of movement. Access to resources is found to play a very important role in increasing women's freedom of mobility. Political factors are also found to play an important role. Women who live in villages where the Pradhan belongs to the lower caste are more likely to enjoy greater freedom of movement. Having older spouses is found to reduce the likelihood of women enjoying greater freedom of mobility as is belonging to wealthier families with large land holdings.

5. WHERE THINGS STAND NOW

The data utilized in this paper was collected in 1997-1998, approximately thirteen years ago. One might argue that since that time dramatic changes in the status of women in Uttar Pradesh may have altered the relevance of the analysis or its policy implications. Therefore, this section will seek to update the situation in Uttar Pradesh.

The state of Uttar Pradesh has long been subject to a patriarchal structure which has greatly limited opportunities for women. Although the constitutional amendment that one third of the Panchayats membership and the Pradhans should be women, initially in the early 1990s in Uttar Pradesh only 25% had been reserved for women. Also during this time period the state had one of the lowest voter turnouts for women and a very small percentage of women in the state legislature. The local government was "almost nonexistent" (Chhibber, 2002). The female to male ratio was 879, the lowest among Indian states and female literacy rates showed a gender gap of 33% when comparing males to females. Further the infant mortality rates showed significant gender differences. Mean year of marriage for females was reported at 17.27 and the total fertility rate was at 5.60.

Since then there have been improvements in the status of women in this state. In terms of literacy rates, these have risen for both men and women. However, the gap between male and female literacy remains high at 27.25% (in 2001). Infant mortality rates for both sexes have declined from 99.9 per thousand in the early 1990s to 73 per thousand in the early 2000s as reflected in the National Health Surveys. However, significant gender differentials still remain. The infant mortality rate is 76 per thousand for males relative to 84 per thousand for females. This is significantly higher than the all India average. The age of marriage remains low with 53% of the respondent women (National Family Health Survey 3) between the ages of 20 to 24 being married by the age of 18 (Government of Uttar Pradesh, 2007). Finally, there has been improvement in the sex ratio in Uttar Pradesh, rising to 908 females per 1000 males in the early 2000s.

In terms of economic empowerment there have also been improvements, but significant gender bias remains. National Sample Surveys (61st round) indicate that in Uttar Pradesh work participation rates were 50.2% for men and 21.6% for females. As compared to males, more females are crowded into lower paid manual work. Additionally, according to this survey, 80 % of female workers are engaged in agricultural production relative to 53.4% of males. Women workers make up only one tenth of the organized formal sector workers in the state (Government of Uttar Pradesh, 2007).

In this paper we are utilizing a woman's freedom of movement as a measure of her autonomy. According to the last round (2005-2006) of the National Family Health Survey (NFHS-3), at the national (all India) level on average only one-third of women are allowed to go by themselves to the market, to a health facility, and to places outside their own community. Women are least likely to have freedom to travel outside their own village or community (38%) and most likely to be allowed to go to the market alone (51%). Urban women, older women, and women in nuclear households have more freedom of movement than other women. The numbers for Uttar Pradesh imply that about 62% of women have the freedom to visit a health facility alone, about 60% have the freedom to go to the market alone and about 45% have the freedom to visit places outside their village/community. Thus these numbers show that women in Uttar Pradesh have greater freedom of mobility outside the home compared to national averages. We cannot necessarily compare these values to the values discussed earlier using the LSMS data because the NFHS-3 values are at the state level, while the LSMS data are at the household level. Additionally, the question asked in the LSMS survey related to whether or not women needed permission to visit a health facility on their own. The NFHS-3 does not provide data relating to that particular question, but it does give us some insight about a woman's freedom of movement outside the home.

In terms of political participation, traditionally political participation by women in Uttar Pradesh has been limited. The first legislative assembly had 13 female members. This rose to 30 in 1985. Since then it has fluctuated such that by 2002 there were only 26 members. Recent studies by the government of Uttar Pradesh indicate that about 50% of families surveyed showed that females are heavily influenced by the men in the family when it comes to exercising their right to vote. This does, however, represent an improvement from the past (Government of Uttar Pradesh, 2007).

There does seem to be a significant increase in participation of women as elected representatives to the Panchayat system. As of 2005 there has been a significant increase in the number of females elected and females as leaders, beyond the reserved positions set aside for women by the constitution (1/3). Thus women have become active participants in this local level of government (Government of Uttar Pradesh, 2007).

The evidence cited above indicates that there have been improvements in the status of women in Uttar Pradesh and that while political participation of women at the state level is weak, there have been improvements at the local level. However, significant gender differentials remain in terms of literacy, infant mortality, etc. In addition, women still seem to marry at a very early age and although the total fertility rate has fallen to 3.8, this is still quite high. Gender differentials are also quite high in terms of employment opportunities for men relative to women. In terms of political influence, women at the state level seem to wield less influence if one uses number of representatives that are female. However, at the local level women's participation has increased.

The quantitative analysis results of this paper based on historical data indicate that female Pradhans at the local level of governance do not seem to enhance the autonomy of women. If this study was carried out using more recent data the result might have been different given the fact that women's influence at the local level in Uttar Pradesh has increased. Thus there may be a time element involved in the quantitative analysis. As women's participation has grown through time, perhaps this would allow greater female influence over issues that would enhance female autonomy.

Some doubt, however, is cast on this idea if one examines the analysis of the impact of female participation at the local level in other states in India. Of particular importance is the recent work of Raabe *et al*. (2009). They have examined the effects of political reservations for women on the provision of rural services. This study is enlightening for the fact that it is focused on the state of Karnataka. "Among the Indian states, Karnataka is one of the earliest to have brought legislation that incorporates the provision of the 73rd Constitutional Amendment Act and streamlined decentralized government structures and service provision by promoting major institutional, administrative, and fiscal change" (p. 8). Karnataka has a history of decentralizing governance structures. It started in 1983 with legislation that devolved government and mandated reservations for women and scheduled castes. Thus this state had begun the process of incorporating women and others into the local political system before the constitutional amendment was passed. This longer history with this issue implies a strong commitment to these policies by the state government.

The empirical analysis carried out by Raabe *et al*. (2009) finds little support for the idea that gender reservation policies resulted in local governance and rural service provision favorable to the interests of women. Local governance and the provision of services were primarily determined by "social, economic, and institutional factors that are unrelated to women's reservation requirements" (p. 7). Similar conclusions are reached by Ban and Rao (2009) and Rajaram and Gupta (2009).

This suggests possibilities for future research. Although the results of this paper's analysis of women's autonomy in Uttar Pradesh finds little support for the influence of reservation on policies aimed at women, this may be an artifact of the time period covered. A follow up study might be very useful.

6. SUMMARY AND CONCLUSION

This paper has attempted to answer a number of questions concerning factors which influence women's autonomy, as measured by mobility, in rural north India (Uttar Pradesh). The paper undertakes a detailed quantitative analysis using household level data for the late 1990s. Thereafter, it updates the information using latest available data for 2005-2006. The latter data is at the state level, but it provides intuition in terms of changes relating to female autonomy and village governance that have taken place Uttar Pradesh in recent years. The updated state-level data gives us reason to be cautiously optimistic about female autonomy for the future. One can see improvements have been made but much still needs to be accomplished.

The overall results relating to the household survey data from the late 1990s indicate that the availability of certain types of infrastructure have a positive influence. In addition, if a village offers many opportunities to earn off-farm income, this also has a positive impact. The implication then is that policies aimed at promoting infrastructure investment and the availability of off-farm employment opportunities would enhance women's autonomy. More recent evidence suggests marked improvement in female mobility outside the home in Uttar Pradesh.

In terms of the political structure of local government, there is no evidence to support the notion that having a female Pradhan will result in greater female autonomy. The results concerning the impact of female Pradhans is consistent with the work of Ban and Rao (2008), Raabe *et al*. (2009), and Rajaram and Gupta (2009). This may be a reflection of the dominance of a patriarchal-type society in Uttar Pradesh. More recent evidence suggests increases in female participation in village governance in Uttar

Pradesh. This may be a sign of changing status of females in society.

The results also suggest that female autonomy is enhanced if the village Pradhan is from a scheduled caste and/or the Pradhan has significant political experience (length of time in office). Thus political reform that increases access to political office of individuals from lower castes is likely to increase female autonomy. The results concerning lower caste Pradhans is also consistent with Ban and Rao's (2008) work. They found that women who live in villages less dominated by upper castes do relatively better. Our results indicate that in villages having a scheduled caste Pradhan, women are likely to have greater autonomy.

With respect to household characteristics, the age of the household head has a negative impact while being a female household head has a positive impact on autonomy. A surprising result is that education which is not found to have a significant impact on women's autonomy as measured by female mobility. This is likely due to the low educational attainment of most women in the sample. This result may not hold up in samples which include greater levels of education. The bulk of the sample women were illiterate or semi-literate.

In summary, several policies suggest themselves. The creation of additional off-farm employment opportunities involving wage payments for female will enhance their autonomy. In addition, infrastructure investment will also have similar effects. Finally, political reform which breaks down caste barriers will improve women's autonomy as measured by mobility.

REFERENCES

Anderson, S. (2011), "Caste as an Impediment to Trade," *Applied Economics*, 3(1), 239-263.

Anderson, S., and M. Eswaran (2009), "What Determines Female Autonomy? Evidence From Bangladesh," *Journal of Development Economics*, 90, 179-191.

Ban, R., and V. Rao (2008), "Tokenism of Agency? The Impact of Women's Reservations on Panchayats in South India," *Economic Development and Cultural Change*, 156, 501-530.

Cain, M. (1993), "Patriarchal Structure and Demographic Change," in N. Federici, K.O. Mason, and S. Sogner, eds., *Women's Position and Demographic Change*, Oxford: Clarendon Press.

Chattopadhyay, R., and E. Duflo (2003), "The Impact of Reservation in the Panchayati Raj: Evidence from a Nationwide Randomized Experiment," *Economic and Political Weekly*, 39(9), 979-986.

Chhibber, P. (2002), "Why Some Women Are Politically Active: The Household, Public Space, and Political Participation in India," *International Journal of Comparative*

Sociology, 43(3-5), 409-429.

Deshpande, A. (2002), "Assets versus Autonomy? The Changing Face of the Gender-Caste Overlap in India," *Feminist Economics*, 8(2), 19-35.

Dyson, T., and M. Moore (1982), "On Kinship Structure, Female Autonomy, and Demographic Behavior in India," *Population and Development Review*, 18(4), 35-60.

Government of Uttar Pradesh (2007), "Status of Women," *Uttar Pradesh Human Development Report*, Lucknow, India.

Jejeebhoy, S.J., and Z.A. Sathar (2001), "Women's Autonomy in India and Pakistan: The Influence of Religion and Region," *Population and Development Review*, 27(4), 687-712.

Kabeer, N. (1999), "Resources, Agency, Achievements: Reflections on the Measurement of Women's Empowerment," *Development and Change*, 30, 435-565.

Kantor, P. (2003), "Women's Empowerment Through Home-Based Work: Evidence from India," *Development and Change*, 34, 425-445.

Krishnan, N. (2007), "Political Reservations and Rural Public Goods Provision in India: Institute of Economic Development," *Discussion University Paper*, 175.

Maitra, P. (2002), "The Effect of Household Characteristics on Poverty and Living Standards in South Africa," *Journal of Economic Development*, 27(1), 75-96.

Mason, K.O., and H.L. Smith (2003), *Women's Empowerment and Social Context: Results from Five Asian Countries*, Washington, DC, Gender Development Group, World Bank.

Narayan, D. (2005), *Measuring Empowerment: Cross-Disciplinary Perspectives*, Washington, D.C., The World Bank.

Presser, H.B. (1975), "Age Differences between Spouses: Trends, Patterns, and Social Implications," *American Behavioral Scientist*, 19, 541-561.

Raabe, K., M. Sekher, and R. Birner (2009), "The Effects of Political Reservations for Women on Local Governance and Rural Service Provision: Survey Evidence from Karnataka," IFPRI Discussion Paper, 00878, International Food Policy Research Institute, Washington, D.C.

Rahman, L., and V. Rao (2004), "The Determinants of Gender Equity in India: Examining Dyson and Moore's Thesis with New Data," *Population and Development Review*, 30, 239-268.

Rajaraman, I., and M. Gupta (2009), "Further Evidence on the Policy Impact of Randomized Political Reservation," Presented at North American Summer meeting of the Econometric Society. Available at: https://editorialexpress.com/cgibin/conference/ download.cgi?db_name=NASM2009&paper_id=304.

Rioja, F.K. (2001), "Growth, Welfare, and Public Infrastructure: A General Equilibrium Analysis of Latin American Economies," *Journal of Economic Development*, 26(2), 119-130.

Sakamoto, S. (2006), "Parental Attitudes toward Children and Child Labor: Evidence From Rural India," Institute of Economic Research, Discussion Paper, 136,

Hitotsubashi University.

Mailing Address: Sharmistha Self, Department of Economics, Missouri State University, 901 S. National Avenue, Springfield, MO 65897, USA. Tel: 417 836 5740. E-mail: SSelf@MissouriState.edu.

Received April 16, 2012, Revised September 27, 2012, Accepted January 10, 2013.

Appendix B: *Three ways to solve the orbit of KIC 11 558 725: a 10-day beaming sdB+WD binary with a pulsating subdwarf*

Printed with permission from Mike Reed

Telting, J. H., et al. "Three ways to solve the orbit of KIC 11 558 725: a 10-day beaming sdB+WD binary with a pulsating subdwarf." *Astronomy & Astrophysics* 544.1 (2012): 1–16. Print.

A&A 544, A1 (2012)
DOI: 10.1051/0004-6361/201219458
© ESO 2012

Astronomy & Astrophysics

Three ways to solve the orbit of KIC 11 558 725: a 10-day beaming sdB+WD binary with a pulsating subdwarf⋆,⋆⋆

J. H. Telting[1], R. H. Østensen[2], A. S. Baran[3], S. Bloemen[2], M. D. Reed[3], R. Oreiro[4], L. Farris[3], T. A. Ottosen[5], C. Aerts[2,6], S. D. Kawaler[7], U. Heber[8], S. Prins[2], E. M. Green[9], B. Kalomeni[10], S. J. O'Toole[11], F. Mullally[12], D. T. Sanderfer[12], J. C. Smith[12], and H. Kjeldsen[5]

[1] Nordic Optical Telescope, Apartado 474, 38700 Santa Cruz de La Palma, Spain
e-mail: jht@not.iac.es
[2] Instituut voor Sterrenkunde, KU Leuven, Celestijnenlaan 200D, 3001 Leuven, Belgium
[3] Department of Physics, Astronomy, and Materials Science, Missouri State University, Springfield, MO 65804, USA
[4] Instituto de Astrofísica de Andalucía (CSIC), Glorieta de la Astronomía s/n, 18008 Granada, Spain
[5] Department of Physics and Astronomy, Aarhus University, 8000 Aarhus C, Denmark
[6] Department of Astrophysics, IMAPP, Radboud University Nijmegen, PO Box 9010, 6500 GL Nijmegen, The Netherlands
[7] Department of Physics and Astronomy, Iowa State University, Ames, IA 50011, USA
[8] Dr. Remeis Sternwarte Bamberg, Universität Erlangen-Nürnberg, Germany
[9] Steward Observatory, University of Arizona, 933 North Cherry Avenue, Tucson, AZ 85721, USA
[10] University of Ege, Department of Astronomy & Space Sciences, 35100 İzmir, Turkey
[11] Australian Astronomical Observatory, PO Box 296, Epping, NSW 1710, Australia
[12] SETI Institute/NASA Ames Research Center, Moffett Field, CA 94035, USA

Received 23 April 2012 / Accepted 16 June 2012

ABSTRACT

The recently discovered subdwarf B (sdB) pulsator KIC 11 558 725 is one of the 16 pulsating sdB stars detected in the *Kepler* field. It features a rich *g*-mode frequency spectrum, with a few low-amplitude *p*-modes at short periods. This makes it a promising target for a seismic study aiming to constrain the internal structure of this star, and of sdB stars in general. We have obtained ground-based spectroscopic radial-velocity measurements of KIC 11 558 725 based on low-resolution spectra in the Balmer-line region, spanning the 2010 and 2011 observing seasons. From these data we have discovered that KIC 11 558 725 is a binary with period $P = 10.05$ d, and that the radial-velocity amplitude of the sdB star is 58 km s^{-1}. Consequently the companion of the sdB star has a minimum mass of 0.63 $M_{\odot}$, and is therefore most likely an unseen white dwarf. We analyse the near-continuous 2010–2011 *Kepler* light curve to reveal the orbital Doppler-beaming effect, giving rise to light variations at the 238 ppm level, which is consistent with the observed spectroscopic orbital radial-velocity amplitude of the subdwarf. We use the strongest 70 pulsation frequencies in the *Kepler* light curve of the subdwarf as clocks to derive a third consistent measurement of the orbital radial-velocity amplitude, from the orbital light-travel delay. The orbital radius $a_{\rm sdB} \sin i = 11.5\,R_{\odot}$ gives rise to a light-travel time delay of 53.6 s, which causes aliasing and lowers the amplitudes of the shortest pulsation frequencies, unless the effect is corrected for. We use our high signal-to-noise average spectra to study the atmospheric parameters of the sdB star, deriving $T_{\rm eff} = 27\,910$ K and $\log g = 5.41$ dex, and find that carbon, nitrogen and oxygen are underabundant relative to the solar mixture. Furthermore, we analyse the *Kepler* light curve for its pulsational content and extract more than 160 significant frequencies. We investigate the pulsation frequencies for expected period spacings and rotational splittings. We find period-spacing sequences of spherical-harmonic degrees $\ell = 1$ and $\ell = 2$, and we associate a large fraction of the *g*-modes in KIC 11 558 725 with these sequences. From frequency splittings we conclude that the subdwarf is rotating subsynchronously with respect to the orbit.

Key words. stars: early-type – binaries: spectroscopic – subdwarfs – stars: oscillations – stars: individual: KIC11558725

1. Introduction

The hot subdwarf B (sdB) stars populate an extension of the horizontal branch where the hydrogen envelope is of too low a mass to sustain hydrogen burning. These core helium burning stars must have suffered extensive mass loss close to the tip of the red giant branch in order to reach this core/envelope configuration. Binary interactions, either through stable Roche lobe overflow or common envelope ejection, are likely to be responsible for the majority of the sdB population (see Heber 2009, for a detailed review).

Several extensive radial-velocity surveys have targeted the sdB stars, with the most recent large sample explored by Copperwheat et al. (2011). They find that ~50% of all sdB stars reside in short-period binary systems with the majority of companions being white dwarf (WD) stars. A recent compilation of such short-period systems can be found in Appendix A of Geier et al. (2011), which lists a total of 89 systems. Adding 18 new systems from Copperwheat et al. (2011) brings the total well above a hundred sdBs with periods ranging from 0.07 to 27.8 d. These systems are all characterised by being single-lined binaries, i.e. only the sdB stars contribute to the optical flux, which directly constrains the companion to be either an M-dwarf

⋆ Based on observations obtained by the *Kepler* spacecraft, the Kitt Peak Mayall Telescope, the Nordic Optical Telescope and the *William Herschel* Telescope.

⋆⋆ Tables 1, 4, and 5 are available in electronic form at http://www.aanda.org or a compact stellar-mass object. Binaries with companions of type earlier than M are double-lined and also readily identifiable from a combination of optical and infrared photometry. Reed & Stiening (2004) find that ~50% of all sdB stars have IR excess and must have a companion no later than M2. Radial velocity studies targeting these double-lined stars have had a hard time detecting orbital periods, indicating that they must be exceedingly long. A recent breakthrough was made by Østensen & Van Winckel (2012) using high-resolution spectroscopy of a sample of eight bright subdwarf + main-sequence (MS) binaries detecting orbital periods spanning a range from ~500 to 1200 d with velocity amplitudes between 2 and 8 km s^{-1}. The period distribution of these different types of binary systems are important in that they can be used to constrain a number of vaguely defined parameters used in binary population synthesis models, including the common envelope ejection efficiency, the mass and angular momentum loss during stable mass transfer, the minimum core mass for helium ignition, etc. The seminal binary population study of Han et al. (2002, 2003) successfully predicts many aspects of the sdB star population, but the key parameters have a wide range of possible values. A recent population synthesis study by Clausen et al. (2012) explores the possible populations of sdB+MS stars and demonstrates how the entire population can change with different parameter sets, but does not deal with sdB+WD binaries.

A theoretical prediction of the existence of pulsations in sdB stars, due to an opacity bump associated with iron ionisation in subphotospheric layers, was made by Charpinet et al. (1997). Since both *p* and *g*-mode pulsations were discovered in sdB stars (Kilkenny et al. 1997; Green et al. 2003), there has been a focus on the possibilities to derive the internal structure and to put constraints on the lesser known stages of the evolution by means of asteroseismology. Currently the immediate aims of asteroseismology of sdB stars are to derive the mass of the Helium-burning core and the mass of the thin Hydrogen envelope around the core (e.g. Randall et al. 2006), the rotational frequency and internal rotation profile (Charpinet et al. 2008), the radius, and the composition of the core (e.g. Van Grootel et al. 2010; Charpinet et al. 2011).

Recent observational success has been achieved from splendid light curves obtained by the CoRoT and *Kepler* spacecrafts, delivering largely uninterrupted time series with unprecedented accuracy for sdB stars. Overviews of the *Kepler* survey stage results for sdB stars were given by Østensen et al. (2010b, 2011), and case studies revealing dense pulsational frequency spectra are presented by Reed et al. (2010) and Baran et al. (2011). From *Kepler* data it has become clear that the *g*-modes in sdB stars can be identified from period spacings (Reed et al. 2011). Earth-size planets stripped from their outer layers have been found around the pulsating sdB star KIC 05807616 (KOI-55, KPD 1943+4058, Charpinet et al. 2011), the star being also the subject of the first seismic study of an sdB star in the *Kepler* field (Van Grootel et al. 2010).

Kepler sdB+dM binaries with pulsating subdwarf components have been presented by Kawaler et al. (2010), Østensen et al. (2010a), and by Pablo et al. (2011). White-dwarf companions in close *Kepler* binaries are presented by e.g. Bloemen et al. (2011, 2012) and Silvotti et al. (2012).

Our target, KIC 11 558 725 or J19265+4930, is one of the 16 pulsating sdB stars detected in the *Kepler* field. The *Kepler* magnitude of KIC 11 558 725 is 14.95, and the *B*-band magnitude is about 14.6, making it the third brightest in the sample. A first description of the spectroscopic properties, and the pulsational frequency spectrum as found from the 26 day *Kepler* survey dataset, was given by Østensen et al. (2011), with the source showing frequencies in the range of 78–391 μHz. Based on this relatively short data set already 36 frequencies were identified, showing the potential of this star for a seismic study. Subsequently, Baran et al. (2011) derived 53 frequencies in total from the *Kepler* survey data, and the frequencies were identified in terms of spherical-harmonic degrees by Reed et al. (2011). As a consequence, the star was observed by *Kepler* from Q6 onwards. At the time of writing, we have analysed data from the five quarters Q6 to Q10. We present the full frequency spectrum resulting from these 15 months of short-cadence *Kepler* observations.

In this paper we present our discovery of the binary nature of KIC 11 558 725 based on low-resolution spectroscopy. This object was sampled as part of a spectroscopic observing campaign to study the binary nature of the sdB population in the *Kepler* field, for which some preliminary results have already been presented by Telting et al. (2012). Part of the data from this campaign were presented in case studies on the close sdB+WD binary KIC 06614501 (Silvotti et al. 2012), and the *p*-mode pulsating sdB KIC 10139564 (Baran et al. 2012).

From our new spectra of KIC 11 558 725 we solve the orbital radial-velocity amplitude, and derive a lower limit of the companion of the sdB star, which is most likely an unseen white dwarf (Sect. 2). We use the average spectrum to study the atmospheric parameters in detail. We show that the orbital *Kepler* light curve reveals strong evidence for Doppler beaming that results in light variations at the 238 ppm level, consistent with theoretical predictions, again allowing us to make an independent measurement of the orbital radial-velocity amplitude (Sect. 3). We extract 166 pulsational frequencies from the *Kepler* light curve (Sect. 4), and show that the orbit has an appreciable effect through the light-travel time on the observed phases and frequencies of these pulsations, which in fact allows us to make a third independent measurement of the orbital-radial velocity amplitude (Sect. 5). In the final sections of this paper we discuss pulsational period spacings and frequency splittings, aiming to identify the spherical-harmonic degree of the modes and to disclose the rotation period of the subdwarf in KIC 11 558 725.

2. Spectroscopic observations

Over the 2010 and 2011 observing seasons of the *Kepler* field we obtained altogether 35 spectra of KIC 11 558 725.

Low-resolution spectra ($R \approx 2000$–2500) have been collected using the Kitt Peak 4-m Mayall telescope with RC-Spec/F3KB, the kpc-22b grating and a 1.5–2.0 arcsec slit, the 2.56-m Nordic Optical Telescope (NOT) with ALFOSC, grism #16 and a 0.5 arcsec slit, and the 4.2-m *William Herschel* Telescope (WHT) with ISIS, the R600B grating and 0.8–1.0 arcsec slit. Exposure times were 600 s at KP4m and WHT, and either 600 s or 300 s at the NOT. The resulting resolutions based on the width of arc lines is 1.7 Å for the KP4m and WHT setups, and 2.2 Å for the setup at the NOT. See Table 1 for an observing log.

The data were homogeneously reduced and analysed. Standard reduction steps within IRAF include bias subtraction, removal of pixel-to-pixel sensitivity variations, optimal spectral extraction, and wavelength calibration based on arc-lamp spectra. The target spectra and the mid-exposure times were shifted to the barycentric frame of the solar system. The spectra were normalised to place the continuum at unity by comparing with a model spectrum for a star with similar physical parameters as we find for the target (see Sect. 3.2). The mean spectra from each of the three telescopes are presented in Fig. 1.

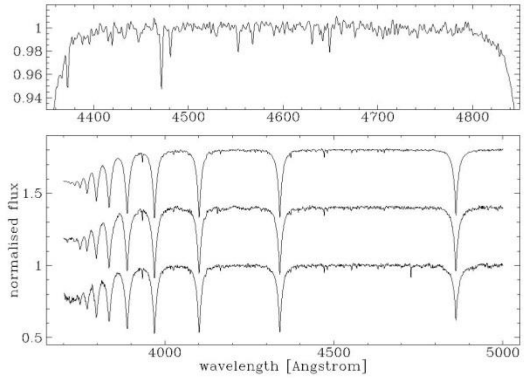

Fig. 1. Mean spectra from KP4m, NOT, WHT (*bottom to top*), offset in flux for clarity. The *top panel* is a zoom-in of the WHT spectrum, demonstrating some of the stronger lines of heavy elements, such as MgII 4481 Å and SiIII 4552, 4567 Å.

Table 2. Orbital solution of KIC 11 558 725.

System velocity [km s^{-1}]	−66.1	(1.4)
Radial-velocity amplitude K [km s^{-1}]	58.1	(1.7)
Period P [day]	10.0545	(0.0048)
Phase [BJD − 2 455 000]	421.682	(0.062)
χ^2	34.48	
Reduced χ^2	1.11	

2.1. Radial velocities and orbit solution

Radial velocities were derived with the FXCOR package in IRAF. We used the Hγ, Hδ, Hζ and Hη lines to determine the radial velocities (RVs), and used the spectral model fit (see next section) as a template. See Table 1 for the results, with errors in the radial velocities as reported by FXCOR. The errors reported by FXCOR are correct relative to each other, but may need scaling depending on, amongst other things, the parameter settings and the validity of the template as a model of the star. As our fit results in a χ^2-value close to unity (see Table 2) we trust that scaling of the FXCOR errors is not necessary and that the derived errors of the fit parameters are adequate.

Assuming a circular orbit we find an orbital period of 10.0545(48) d, with a radial-velocity amplitude of 58.1(1.7) km s^{-1} for the subdwarf. See Table 2 for the complete parameter listing. The radial velocities and the derived solution are shown in Fig. 2. When fitting an eccentric radial-velocity curve the amplitude goes down to 56.8 km s^{-1}, for eccentricity e = 0.063(33). Throughout this paper we regard the orbit as circular.

Given the solution presented in Table 2, the orbital radius of the sdB star can be approximated by $a_{\rm sdB}\sin i = 11.5\,R_\odot$, which corresponds to a light-travel time of 53.6(1.6) seconds between orbital phases corresponding to closest and furthest distance to the Sun.

The orbital solution combined with the mass function gives a lower limit for the mass of the companion of more than 0.63 $M_\odot$, if one assumes a canonical mass of 0.48 $M_\odot$ for the sdB star. As the spectrum does not reveal clear evidence for light contribution from a companion, it should be either an unseen compact object, or an unseen K star. As the 2MASS J = 15.38(5) and H = 15.35(9) magnitudes do not indicate a rising infrared flux that would reveal the presence of a K star in this system, we conclude that the unseen companion is most likely a white dwarf. If the inclination of the system is smaller than $i \lesssim 40$ degrees then the companion may be a neutron star or black hole ($i \lesssim 25$ degrees).

Assuming a radius for the sdB star of 0.2 $R_\odot$, and assuming a white dwarf companion, one may expect to see eclipses only if the inclination angle is higher than $i \gtrsim 88$ degrees. We did not detect eclipses (see Fig. 3).

Table 3. Atmospheric parameters of the subdwarf in KIC 11 558 725.

Telescope	$T_{\rm eff}$ K	$\log g$ cm s^{-2}	$\log (N_{\rm He}/N_{\rm H})$
KP4 m	27 950(110)	5.378(20)	−3.078(42)
NOT	27 410(110)	5.418(20)	−3.124(32)
WHT	28 010(50)	5.417(11)	−3.125(26)
adopted	27 910(210)	5.410(15)	−3.116(18)

2.2. Atmospheric parameters

The spectra were shifted to remove the orbital motion, before being co-added to obtain high-S/N spectra (KP4m S/N = 175; NOT S/N = 145; WHT S/N = 305) with minimal orbital line broadening, for all three observatories. We derive the atmospheric parameters of the star from each of these mean spectra, and produce a weighted mean using the formal fitting errors as variance weights, as listed in Table 3. Our final adopted values are $T_{\rm eff} = 27\,910(210)$ K, $\log g = 5.410(15)$ dex and $\log (N_{\rm He}/N_{\rm H}) = -3.116(18)$ dex, which are quite compatible with the parameters $T_{\rm eff} = 27\,400$ K, $\log g = 5.37$, $\log (N_{\rm He}/N_{\rm H}) = -2.8$ found from the initial survey spectrum in Østensen et al. (2011). The errors on the adopted values are the errors on the weighted means, and reflect the spread of the individual measurements rather than the formal errors. Systematic errors related to model physics typically are of the order 500 K, 0.05, and 0.05, for $T_{\rm eff}$, $\log g$, and $\log (N_{\rm He}/N_{\rm H})$, respectively.

Besides the lines of the hydrogen Balmer series and He I lines, clear lines of magnesium (4481 Å), and silicon (4552 Å, 4567 Å) are present. The high S/N mean WHT spectrum seen in the upper panel of Fig. 1 also allows the identification of a number of lines from O II, N II as well as the C II doublet at 4267 Å and the C III lines at 4647 and 4650 Å. By comparing the strength of these lines relative to LTE model spectra with explicit metal lines computed for the adopted parameters listed in Table 3, varying only the metallicity relative to solar, we find that oxygen is depleted to 4% of the solar abundance, nitrogen to 13%, and carbon to 1.6%. Such high depletion is normal in sdB stars due to gravitational settling, and large deviations from the solar mix for individual elements are also common (Heber et al. 2000).

3. The orbital light curve from *Kepler* photometry

We analysed the *Kepler* light curve of KIC 11 558 725 as obtained in quarters Q6–Q10, totalling roughly 15 months of data with 58.8 s sampling time (i.e. short-cadence data; see Gilliland et al. 2010). The photometric time series spans BJD 2 455 372 to 2 455 833, which is roughly the same range as our spectroscopic

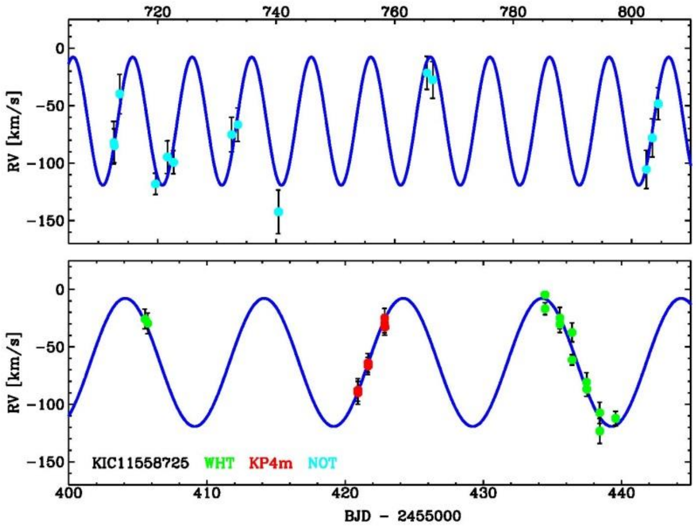

Fig. 2. Radial-velocity curve from observations with the KP4m Mayall, the NOT, and the WHT.

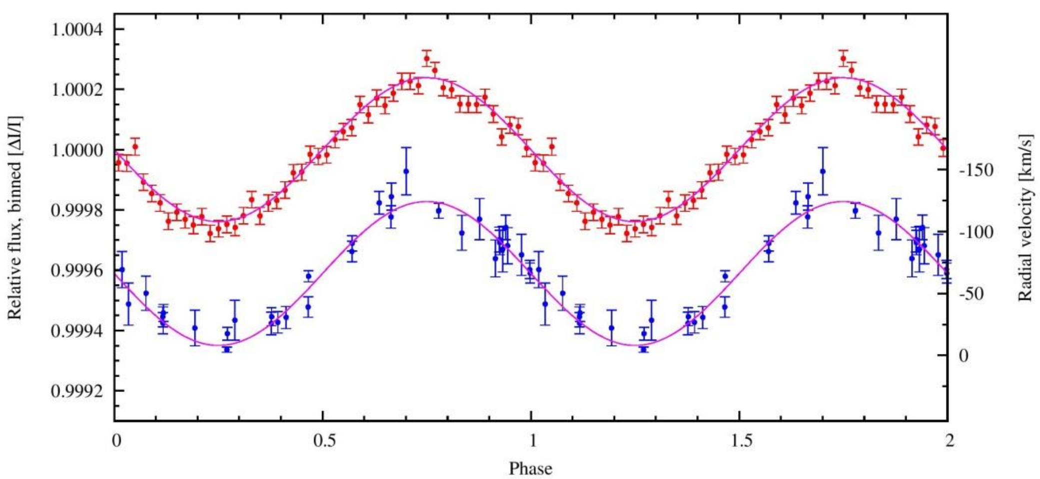

Fig. 3. *Top*: the 461 day long *Kepler* light curve from quarters Q6 through Q10, folded on the orbital period and binned into 50 bins. *Bottom*: phased radial velocities from the spectra.

dataset. We analyse the light curve as transformed to fractional intensities $\Delta I/I$.

At first we used the raw light curves produced by the *Kepler* data processing pipeline (SAP_FLUX; Jenkins et al. 2010). These light curves are extracted using a standard small pixel mask selected to minimise the noise in the output data. However, during the observations slight drifts were induced by guiding corrections and thermal effects in the focal plane, which implies that some light drifts in or out of the small pixel mask, causing trends that must be removed. For pulsations with much shorter timescales than the trends, this is not a problem, but with a 10 d orbital period in KIC 11 558 725, our concern was that the detrending could suppress the orbital beaming effect. We therefore analysed also the raw *Kepler* pixel data using a large custom pixel mask including all 20 to 23 pixels with target signal, as opposed to 4 to 6 pixels in the small pixel mask of the standard pipeline extraction. This recovers 36% more flux from the target and the monthly chunks can be detrended with simple linear trends. This approach gave a beaming amplitude that is 34% higher than our first estimate from the pipeline-reduced data. However, these large-aperture light curves are substantially more noisy and contain many more bad points. Hence we only use the raw, custom-mask pixel data to determine the amplitude of the Doppler beaming, but use the standard-mask pipeline-reduced raw data for our pulsation-frequency analysis in Sect. 4.

A Fourier analysis of the *Kepler* light curve reveals the orbital period to be 10.0516(27) d, in perfect agreement with the period found from spectroscopy. In Fig. 3 we show the *Kepler* light curve folded on the orbital period into 50 phase bins. A sine fit to the folded light curve, leaving only the amplitude as a free parameter, gives an amplitude of the orbital effects seen by *Kepler* of 238(6) ppm, and this amplitude is consistent with that derived from the Fourier analysis. The fit is shown as a solid line in the figure. We do not find orbital harmonics.

3.1. Doppler beaming

The high precision *Kepler* data permits us to accurately explore the low-amplitude Doppler beaming effect, something that is very hard to do with ground based data. This effect is induced by stellar motion in a binary orbit and causes brightness modulation (Rybicki & Lightman 1979). The Doppler beaming effect permits an estimate of the radial velocity without resorting to spectroscopic data. This effect was detected for the first time in *Kepler* data by van Kerkwijk et al. (2010) and for a planetary system in CoRoT data by Mazeh & Faigler (2010). A confirmation of the correspondence between Doppler beaming amplitudes and radial velocities was first established by Bloemen et al. (2011).

The light curve of KIC 11 558 725 displays a brightening of the sdB star at the orbital phases where the star is approaching us in its orbit (i.e. when its orbital radial velocities are negative, see Fig. 3), and this is exactly the effect expected by Doppler beaming. Note that unlike KPD 1946+4330 (Bloemen et al. 2011), KIC 11 558 725 does not show any sign of ellipsoidal deformation which in the closest sdB+WD binaries produces a strong harmonic signal at $P_{\rm orb}/2$ (see also e.g. Silvotti et al. 2012). This is consistent with the much longer orbital period of KIC 11 558 725 as opposed to the 0.4 d period of KPD 1946+4330.

In the case of Doppler beaming the observed flux from the target, F_λ, is related to the emitted spectrum and orbital velocity as

$$F_\lambda = F_{0,\lambda}\left(1 - B\frac{v_r}{c}\right) \quad (1)$$

and the beaming amplitude relates to the orbital radial-velocity amplitude K as

$$A_B\, D = B\frac{K}{c}, \quad (2)$$

where A_B is the amplitude of the beaming signal in the light curve (see Fig. 3), and D the decontamination factor discussed below.

The beaming factor B contains three terms. For an approaching source a contribution of +1 comes from the enhanced photon arrival rate, and another term of +2 from the geometrical aberration of the wavefronts. The last term comes from the Doppler shift of the spectrum, which for a hot sdB star produces a negative effect as the blue-dominated flux gets blue-shifted out of the observed *Kepler* bandpass when the star is approaching. We compute this last term using TMAP model spectra (Werner et al. 2003) that cover the entire *Kepler* bandpass, following the procedure described in Bloemen et al. (2011).

With the beaming factor $B = 1.403(5)$, and the spectroscopically derived orbital radial-velocity amplitude, we compute a predicted total beaming amplitude for the *Kepler* bandpass of 270 ppm. The observed beaming amplitude of $A_B = 238$ ppm is 88% of the predicted value.

The *Kepler* pixels onto which our target is imaged suffer from contamination from neighbouring objects, and from passing charge from brighter sources when clocking out the CCD. According to the *Kepler* Target catalogue[1], the contamination factors for KIC 11 558 725 are 0.098 (Q6,Q10), 0.110 (Q7), 0.079 (Q8) and 0.106 (Q9), or 0.0982 on average, implying that all periodic amplitudes derived from these *Kepler* fluxes should be multiplied by $D = 1/(1-0.0982) = 1.109$ to get the intrinsic amplitudes of KIC 11 558 725. When applying this decontamination factor we find that the photometric amplitude of the Doppler beaming as seen by *Kepler* is consistent with the spectroscopically derived radial-velocity amplitude within the errors of the data. Given the observed amplitude A_B, we use Eq. (2) to derive a value of $K = 56.5(1.4)\,{\rm km\,s^{-1}}$ for the orbital radial-velocity amplitude, from Doppler beaming.

The fact that this value is consistent with that of the spectroscopic value proves that the companion of the sdB does not significantly contribute to the observed Doppler beaming, consistent with a compact nature of the companion.

4. The pulsation spectrum

We are interested in the pulsation frequencies in KIC 11 558 725 for three reasons. Firstly, we intend to use the pulsations as clocks to derive the orbital light-travel time delay and consequently another independent determination of the orbital radial-velocity amplitude. Secondly, the pulsations may reveal the internal structure of the subdwarf through a detailed seismic study, for which we intend to derive mode identifications in Sect. 6. Furthermore, the frequency splittings may disclose the rotation period of the subdwarf.

To investigate the pulsational frequency spectrum we used the *Kepler* light curves as produced by the standard *Kepler* data processing pipeline. The fractional object intensities $\Delta I/I$ of quarters Q6–Q10 were first detrended, and subsequently outlying points were discarded leaving 625 617 data points with standard deviation $\sigma = 2600$ ppm. An iterative prewhitening process, involving a standard fast-fourier transform to find peaks and subsequent non-linear least-squares (NLLS) sine-curve fits to subtract the pulsational content mode by mode from the original data, was used to derive the frequency list of Table 4. In total we extracted 166 pulsational frequencies, in addition to the orbital frequency. The standard deviation of the data after removal of all significant periodic signals was $\sigma = 1900$ ppm.

The standard deviation in the Fourier amplitude spectrum of the original data amounts to $\sigma_{\rm FT} = 4.2$ ppm, and we adopt $4\sigma_{\rm FT} = 17$ ppm as the threshold of significance of the peaks in the Fourier amplitude spectrum.

We note that the observed amplitudes in Table 4 have not been corrected for the *Kepler* decontamination factor D (see above), nor for the amplitude smearing due to the effective exposure time of 58.8 s. Both effects cause the observed amplitudes to be smaller than the intrinsic amplitudes, and the latter affects mostly the shortest periods (p-modes). For the strongest pulsation, with a period of 3641.1 s, the exposure time leads to a decrease of the amplitude of 4.3%, while for the shortest extracted period of 197.9 s the amplitude decrease is 14%.

To illustrate the fact that all pulsational frequencies are present throughout the *Kepler* run, we show a section of the Fourier transform in a dynamic form in Fig. 4. There is clear beating among the stronger frequencies; in fact, these beatings show up as resolved frequencies in the Fourier transform of the full *Kepler* data set, and may be attributed to the rotation of the subdwarf (Sect. 7).

[1] http://archive.stsci.edu/kepler/kepler_fov/search.php

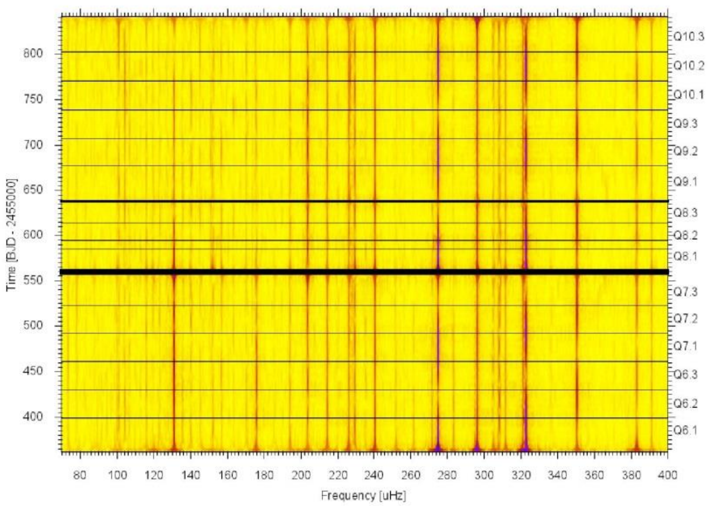

Fig. 4. A dynamic Fourier spectrum from quarters Q6 through Q10 computed for 20 day stretches of data. The pronounced beatings show up as resolved frequencies in the Fourier spectrum of the complete data set. The horizontal lines reflect data gaps.

4.1. Combination frequencies

We do not find evidence for harmonics of the pulsation frequencies. We do, however, find evidence for combination frequencies. When computing the residual frequency $\delta f = f_3 - f_2 - f_1$ for all combinations of 168 frequencies in Table 4, we find 13 combinations that are consistent with a residual $\delta f = 0$ within the errors of the frequencies. Thirty-five different frequencies are involved in these 13 combinations. One of the combinations is an orbital alias discussed in Sect. 5.1. See Table 5 for the list of frequency combinations.

To investigate the significance of this, we take our observed frequencies and perturb each of them by a random offset which is big enough to upset real combinations, but small enough such that the distribution of these randomised frequencies looks like that of the observed distribution. We perturb the frequencies by $\pm 1\,\mu$Hz. For each randomised frequency we adopt the frequency error of the original unperturbed peak. For 50 sets of such randomised frequencies, we find an average of 3.7 combinations that satisfy $\delta f = 0$ within the errors of the frequencies.

Hence, for the set of 13 combinations that we find in our 168 frequencies, we expect that about 4 are by-chance combinations. We assume that the combinations with the lowest-amplitude peaks are most likely to be by-chance combinations, as these peaks have the largest error on their frequency. These probable frequency combinations are marked in Table 4, and we take care when assigning these modes in period spacings and frequency multiplets.

5. Using the pulsations as clocks to derive the orbit

In analogy to the effect that the Earth's orbit has on arrival times of a variational signal, and on the apparent frequencies of that signal, the orbit of the sdB alters the phases and frequencies of its pulsations as perceived by a distant observer.

As we already established in Sect. 2, the light-travel time between conjunctions is 53.6 s, which amounts to a significant phase change for the 300 s p-mode pulsations in this star. Similarly, the Doppler frequency change of the pulsations at orbital quadratures amounts to $\Delta f = f * K/c$, which, with $K = 58\,\mathrm{km\,s^{-1}}$, even for g-modes gives frequency shifts of $0.02-0.2\,\mu$Hz. These are certainly measurable with our 460 day data set with frequency resolution of 0.025 μHz. If the orbit is known, one can simply correct for these effects by converting all observation timings to the centre-of-mass frame of the system, equivalent to the common approach of conversion of observation timings to the barycentric frame of the solar system.

If the orbit is not known, one can use the pulsations as clocks (see e.g. Hulse & Taylor 1975) to derive the light-travel time that corresponds to the radius of the orbit, which relates to the radial-velocity amplitude K that can be obtained from spectroscopy or the Doppler-beaming curve as

$$\Delta t_{\mathrm{R}} = \frac{a_{\mathrm{sdB}} \sin i}{c} = \frac{K}{c}\frac{P_{\mathrm{orb}}}{2\pi}\sqrt{1-e^2}, \tag{3}$$

where we introduce the Rømer delay, Δt_{R}, to represent the light-travel time.

For a circular orbit, the light-travel delay as a function of the subdwarf's position in its orbit can be written as

$$T_{\mathrm{delay}}(t) = \Delta t_{\mathrm{R}}\ \cos\left(\frac{2\pi}{P_{\mathrm{orb}}}(t - T_{\mathrm{orb}})\right), \tag{4}$$

where T_{orb} is the time at which the subdwarf is closest to the Sun in its orbit, corresponding to the orbital phase listed in Table 2.

We did not detect any second- or third-harmonic peaks, neither for the orbit nor for the pulsations. Hence, for sinusoidal signals the *Kepler* light curve of KIC 11 558 725 can be approximated by

$$\begin{aligned}\frac{\Delta I(t)}{I} &= A_B \sin\left(\frac{2\pi}{P_{\mathrm{orb}}}(t - T_{\mathrm{orb}})\right) \\ &\quad + \sum_i A_{\mathrm{i,puls}} \sin\left(2\pi F_{\mathrm{i,puls}}(t - T_{\mathrm{i,puls}} + T_{\mathrm{delay}}(t))\right), \end{aligned} \tag{5}$$

where the first term describes the orbital beaming effect, and where all individual pulsations are affected by the same orbital light-travel delay $T_{\mathrm{delay}}(t)$. Here, the phase of the individual pulsations, $T_{\mathrm{i,puls}}$, is expressed in the time domain rather than as an angle. Note that the above sum of sine curves is equivalent to the model that we fit as part of the prewhitening procedure described in Sect. 4, with the addition of a phase delay that introduces just one extra parameter, i.e. the amplitude Δt_R of the light-travel delay.

We apply the above Eq. (5) to derive a third independent measurement of the radial-velocity amplitude of the subdwarf in KIC 11 558 725. For this purpose, we included the above phase delay in our NLLS Levenberg-Marquardt routine, and fitted the above model (5) to the *Kepler* Q6–Q10 light curve. In the model we included the 70 strongest frequencies that are identified to be part of $\ell = 1$ and $\ell = 2$ sequences of the subdwarf (see next section), as to avoid possible pulsations from the unseen component in the binary.

Simultaneously fitting all 70 pulsational amplitudes, frequencies and phases, together with the Rømer delay and phase as free parameters, we find $\Delta t_R = 26.5(1.5)$ s and $T_{\rm orb} = 421.744(88)$ [BJD − 2 455 000], which is in perfect agreement with the spectroscopic parameters in Table 2, and the Doppler beaming amplitude. Given the observed Rømer delay Δt_R, we derive a value of $K = 57.5(3.2)\,{\rm km\,s^{-1}}$ for the orbital radial-velocity amplitude, from the light-travel time effect.

5.1. Orbital aliases in the Fourier domain

Above we have solved the orbit by directly fitting the light curve with a parameterised model of the pulsations that includes the orbital light-travel delay. A different approach was recently investigated by Shibahashi & Kurtz (2012), who demonstrated how one can derive the orbit from the ratio of the amplitude of the central peak to the orbital aliases that the Rømer delay introduces in the observed Fourier spectrum.

In the case of KIC 11 558 725 we find that, of our 166 extracted pulsation frequencies, only a few of the strongest g-modes and a few of the highest-frequency pulsation modes in the weak *p*-mode regime have orbital aliases strong enough to be close to the amplitude level of significance.

Around the strongest g-modes the orbital sidelobes appear in frequency regions populated by weak unresolved structure and prewhitening residuals. A more clear example of the orbital sidelobes is given by the two peaks at 3073.5 and 3075.0 μHz, shown in the top panel of Fig. 5a. The sidelobes of each of the two central peaks can just be discerned close to the 4.0-σ line at a separation of $F_{\rm orb} = 1.15\,\mu$Hz. Since the amplitudes of these aliases are hardly significant, direct application of the ratio method of Shibahashi & Kurtz (2012) leads to inaccurate results for this particular dataset.

The two central peaks, however, are at $\sim 16\sigma$, and their amplitudes can be measured with very high precision. We can therefore exploit the energy theorem in Fourier analysis that implies that the total power in the Fourier transform should not change due to the time-distorting orbital motion. All the power observed in the sidelobes will therefore be restored into the central peak if the light curve is corrected for the light-travel time. In the bottom half of Fig. 5a we show that this is indeed the case. When we perform a light-travel time correction on the observation timings of the light curve, in the same way as the barycentric correction is done to remove the spacecraft orbit, then the orbital aliases in the Fourier domain disappear and the power is transferred to the central peak. For comparison, Fig. 5c shows a simulation using noise-free, evenly-sampled data modelled with and without an imposed Rømer delay.

We can also use the amplitude of the central peak to measure the Rømer delay, and get another estimate of the radial-velocity amplitude. If we take our observed light curve and adjust the observation timings for various values of the Rømer delay, we find that the Fourier amplitudes of the pulsation peaks vary as shown in Fig. 5b. Clearly, all five modes reach maximum amplitude for roughly the same delay correction. The delays and peak amplitudes are given in Table 6, and if we take an average using the amplitudes as weights we find $\Delta t_R = 26.4(0.7)$ s. The gain in amplitude for these modes is about 6%, when the optimal Rømer delay is applied.

Table 6. Measured Rømer delay from high-frequency pulsations.

Frequency μHz	Δt_R s	A_0 ppm
3059.896	26.04(05)	62.2(1)
3073.467	25.45(05)	66.2(1)
3075.021	26.25(07)	53.6(1)
3102.271	29.35(15)	31.4(2)
3103.849	29.23(13)	29.9(1)

Notes. The amplitude A_0 is the recovered amplitude when applying the corresponding Rømer delay Δt_R.

A model of how the observed amplitude of a pulsation peak taken to reside at 3073.5 μHz drops with increasing Δt_R is shown in Fig. 5d. The corrected amplitude of the central peak is found to be 6.1% higher in a simulated light curve with no Rømer delay than in one with a 26 s delay, as observed. The predicted amplitude of the orbital alias is found to be 25.2%. Rearranging Eq. (27) in Shibahashi & Kurtz (2012) in terms of this ratio, we find

$$\frac{A_{+1} + A_{-1}}{2A_0} = \frac{\pi \Delta t_R}{P_{\rm osc}}, \qquad (6)$$

which corresponds to 24.2% for $\Delta t_R = 25$ s and $P_{\rm osc} = 325$ s, which demonstrates that our numerical modelling (Fig. 5d) is consistent with their analytical derivation.

In Fig. 5d we show that the total power contained in the central peak and its aliases is preserved while applying observation-timing corrections. The curve drops off for large delays as we have only accounted for the first pair of a full comb of orbital aliases.

6. Pulsational period spacings

Recently, Reed et al. (2011) have revealed that *g*-modes in sdB stars show sequences with almost fixed period spacings. This is contrary to what models predicted up to now, i.e. strongly variable period spacings caused by mode trapping due to a highly stratified internal structure. The observed regular period spacings indicate that internal mixing processes must be considerably stronger than presumed. As the period spacings follow the asymptotic relation for *g*-modes, they change with the value of the spherical-harmonic degree ℓ of the modes. Hence, the spacings allow us to determine the ℓ-value of the modes directly.

Reed et al. (2011) already identified ℓ values for the pulsations that could be resolved in the *Kepler* survey data of KIC 11 558 725. They identified an $\ell = 1$ sequence with period spacing $\Delta\Pi_{\ell=1} = 246.8$ s, and an $\ell = 2$ sequence with period spacing $\Delta\Pi_{\ell=2} = 142.6$ s.

Here we use the same methods of Reed et al. (2011) to derive the period spacings, using the much longer Q6–Q10 data set. First we defined the period spacing for $\ell = 1$, as marked in Table 4. This was achieved iteratively. As $\ell = 1$ modes suffer the least geometric cancellation (see e.g. Reed et al. 2005), and hence should have highest amplitudes if all modes are driven at

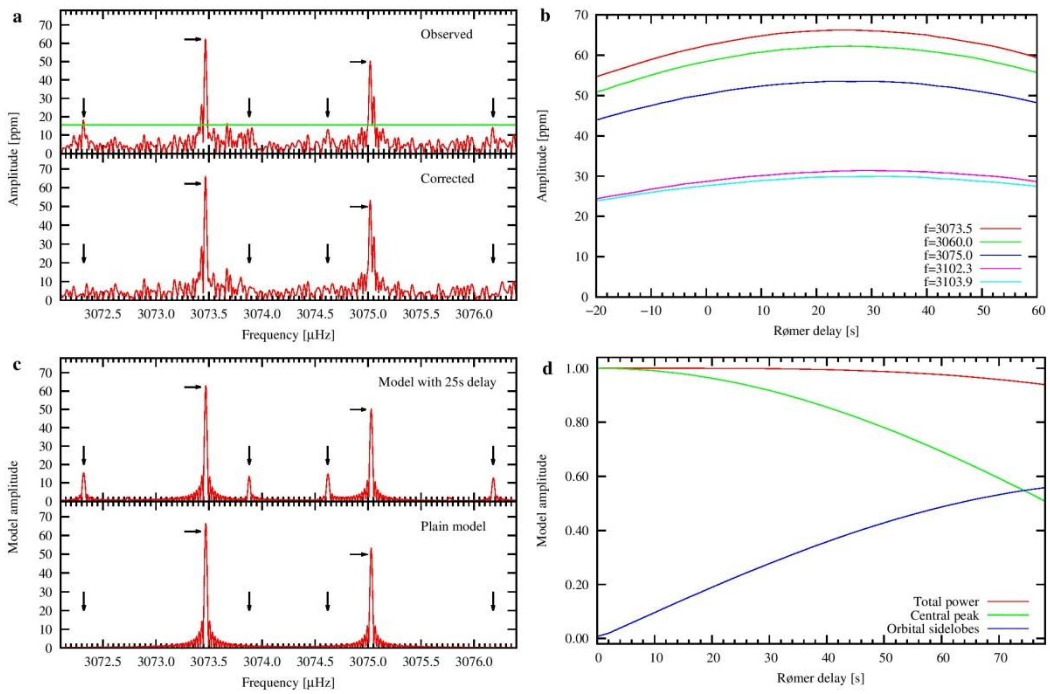

Fig. 5. a) The pulsation spectrum KIC 11 558 725 as observed (*upper panel*), and after correcting for the Rømer delay (*lower panel*). The line in the upper panel indicates our 4-σ detection limit. **b)** The amplitude of five pulsation peaks as a function of Rømer correction. **c)** Same as a), but for a model light curve with the same duration and sampling frequency as the data in **a)**. **d)** The predicted amplitude of the central peak and first alias as computed for a pure sine function distorted by an increasing Rømer delay. The upper curve indicates the total power of the central peak and the aliases. This sum departs from unity when the unaccounted-for second orbital alias pair starts to contribute. Entries in the legends have the same top-to-bottom order as the curves.

a similar level, we started off with the highest-amplitude modes. Subsequently we worked with an $\ell = 1$ sequence consisting only of doublets, and finally all the $\ell = 1$ periods marked in Table 4. For each step we derived mutually consistent values of the period spacing. We recover all the $\ell = 1$ identifications from Reed et al. (2011) except for two periods not detected in the Q6−Q10 data.

Including all 57 $\ell = 1$ multiplet candidate peaks from Table 4 in a linear regression $P(n) = C + n * \Delta\Pi_{\ell=1}$, we find $\Delta\Pi_{\ell=1}$ = 248.87(18) s with rms = 19 s. Here, the mode sequence number n should be equal to the radial number of nodes in the pulsation, n', but shifted by a fixed offset that we cannot determine. When fitting for each of the 29 multiplets (mostly doublets) only the peak closest to this first fit, we obtain a consistent period spacing $\Delta\Pi_{\ell=1}$ = 248.68(23) s, with rms = 14 s.

Given that for the asymptotic g-mode domain we expect $\Delta\Pi_{\ell=2} = \Delta\Pi_{\ell=1}/\sqrt{3}$, we used a spacing of $\Delta\Pi_{\ell=2}$ = 143 s as a starting point for the $\ell = 2$ sequence. Again we iterated adding the highest-amplitude peaks and some frequency multiplets that cannot be $\ell = 1$ modes. Including all 76 $\ell = 2$ multiplet candidate peaks in a linear regression, we find $\Delta\Pi_{\ell=2}$ = 143.44(08) s with rms = 16 s. When fitting for each of the 34 multiplets only the peak closest to this initial fit, we obtain a consistent period spacing $\Delta\Pi_{\ell=2}$ = 143.37(10) s, with rms = 14 s.

Of 166 pulsation frequencies, 23 have periods shorter than 900 s which we did not include as g-mode period-spacing candidates. From the 143 g-mode pulsations we find that 108 can be matched with either the $\ell = 1$ or $\ell = 2$ sequence, when accepting periods deviating up to ~35 s from the linear regression and allowing for any possible value of the azimuthal order m. We plot echelle diagrams for the $\ell = 1$ and $\ell = 2$ sequences in Fig. 6, and list all $\ell = 1$ and $\ell = 2$ matches in Table 4. Periods below 900 s that do match any of the $\ell = 1$ or $\ell = 2$ sequences are indicated as such in Table 4 for completeness.

Obviously, the period spacing in KIC 11 558 725 is not very strict, which makes conclusive identification of individual modes difficult, as by-chance identifications of modes that do not belong to a sequence are probable. However, the fact that the spacings vary within a sequence may hold information about the internal structure that can be derived from detailed seismic modelling. From Fig. 6 we find that between sequence numbers 8 and 18 in the $\ell = 1$ sequence, corresponding to pulsation periods between 3300–5900 s, there is a remarkable bump away from the average spacing. Whereas the $\ell = 1$ sequence shows coherence over a large period range, the $\ell = 2$ sequence is dominated by a clumping of multiplet candidates in the period range 2900−3700 s.

Pulsation modes that could erroneously be accepted in any of the sequences may stem from any of the following: modes with higher degree ℓ that are strong enough to be picked-up by *Kepler*; modes in combination frequencies; modes that are tidally forced to have large amplitudes; modes that originate in the companion.

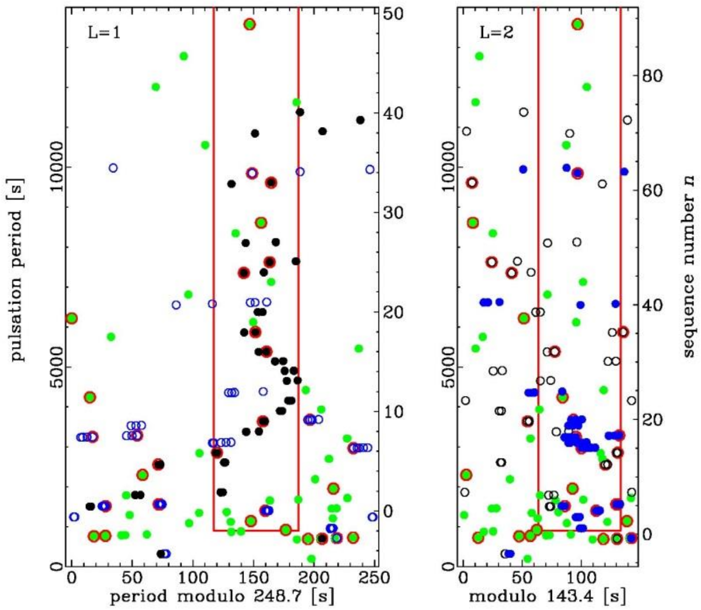

Fig. 6. Echelle diagrams of the ℓ = 1 and ℓ = 2 period-spacing sequences. The red rectangles depict the areas of acceptance to these sequences. Single frequencies are plotted in light green, doublets in black, and multiplets in blue (see Table 4). Modes marked with red circles form frequency combinations (Table 5).

If a mode in a combination frequency is due to non-linear or resonance effects between two other modes, its assignment to a period-spacing sequence may not be justified. Therefore we mark the modes that take part in frequency combinations (see Table 5) with a circle in Fig. 6.

Tidally forced oscillations can have large amplitudes when close to an eigenfrequency of the star, and can in principle be of any degree ℓ, although an $\ell = 2$ excitation can be considered the most probable, in which case tidally induced pulsations should be part of the $\ell = 2$ sequence. The error on the orbital frequency is not small enough to exclude some of the strongest pulsations in Table 4 from being a multiple of the orbital frequency. We note however, that for the observed frequencies in KIC 11 558 725 tidal forcing would occur at very high harmonics of the orbital frequency (i.e. >300 for the strongest pulsation frequencies), which may diminish the forcing efficiency. Nevertheless, a recent case of tidally driven pulsations at high orbital harmonics (90th and 91st) is presented by Welsh et al. (2011).

Even though pulsating white dwarfs are rare as the instability strips are small, possible pulsations in the supposed white-dwarf companion could be picked up by *Kepler*. Assuming a white dwarf with a large radius $0.013\,R_\odot$ ($\log(g) = 8.0$, $M = 0.63\,M_\odot$), with a similar or somewhat cooler temperature as the subdwarf, and with intrinsic pulsation amplitudes at the 10–20% level, we conclude that such a white dwarf would contribute pulsation frequencies at observable amplitudes to the frequency spectrum of KIC 11 558 725, even if the white dwarf is not detected in our spectra, or in the available broad-band imaging. Hence we can not exclude this possibility, when trying to match period spacings or frequency splittings in KIC 11 558 725.

If any of the significant peaks we have detected were to originate from the white dwarf, their amplitudes would not be maximised by shifting to the rest frame of the sdB, as we demonstrated is the case for the short period peaks in Sect. 5.1. Rather, a Rømer delay with the opposite sign and an amplitude corresponding to the radial velocity of the white dwarf would have to be imposed to recover the full amplitude. Using the technique of Sect. 5.1 we found only one peak in Table 4 that shows an orbital phase behaviour that is opposite to that expected for the subdwarf, and hence could originate in the supposed white-dwarf companion: it is the peak with the shortest periodicity at 5053.5 μHz. As this peak is just at the detection limit we cannot rule out that it is just a random effect. If it persists in the next year of *Kepler* observations, it might turn out to be the first indication of an sdB+WD system where both stars are pulsating.

7. Frequency splittings and the rotation period

Fixed frequency splittings are expected as a consequence of rotation. To the first order in the rotation frequency Ω, the observed frequencies of the modes are altered by $m\Omega(1 - C_{n'l})$, with m the azimuthal quantum number of the spherical harmonic. Hence, for non-radial modes of given degree ℓ, we expect frequency multiplets of 2ℓ+1 peaks to occur. However, not all peaks of a full multiplet need to be excited, and, furthermore, cancellation effects for a given inclination angle can favour the observability of some modes over others within a multiplet (see e.g. Reed et al. 2005).

In the case of KIC 11 558 725 the frequencies mostly do not appear as full multiplets, which makes the interpreting of the observed splittings difficult. See Table 4 for the observed splittings. We find many splittings in the range of 0.1–0.5 μHz. In Fig. 7 we show two sample frequency sequences that show a frequency splitting in the 0.4–0.55 μHz range, that seems typical for frequency groups that do not match the $\ell = 1$ period spacing. We also show in Fig. 7 a series of doublets that match the $\ell = 1$ period spacing, which all have a frequency splitting on the order of 0.13 μHz, and which in fact cause the prominent beating seen in Fig. 4. We also detect some doublets with

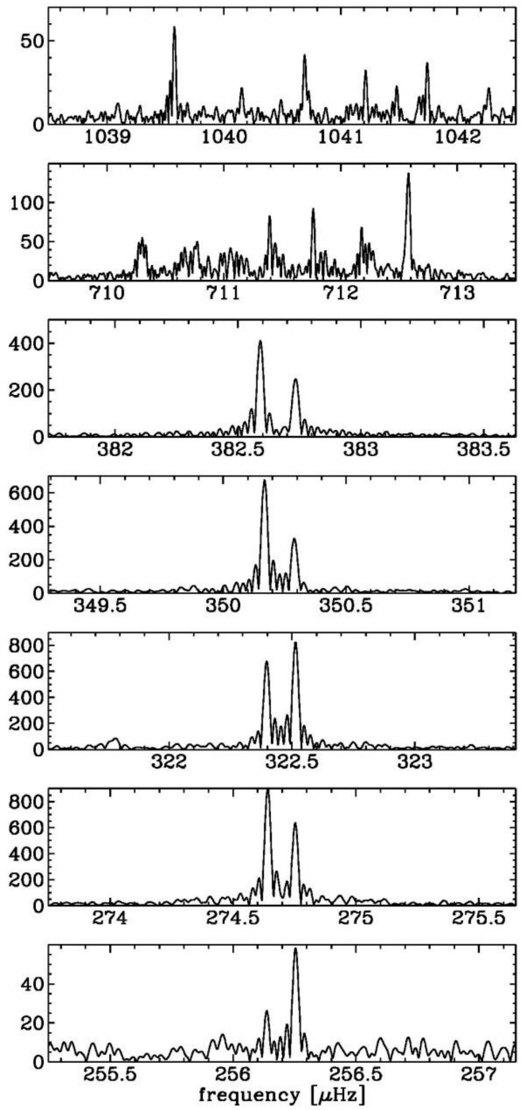

Fig. 7. Selected multiplets. The *bottom 5 panels* show the ~0.13 μHz splitting seen in some of the $\ell = 1$ doublets. The strongest pulsations we detect in KIC 11 558 725 are amongst the $\ell = 1$ peaks shown here. The *top panels* show sample regions with sequences of frequencies with splittings in the 0.37–0.58 μHz range. Amplitudes are given in ppm. The significance cut-off amplitude is 17 ppm.

spacings approximately twice this (~0.23 μHz) and we interpret the smaller frequency spacings as consecutive *m* while the larger spacings would be the $|m| = 1$ pairs. In Fig. 8 we present a histogram of the splittings listed in Table 4.

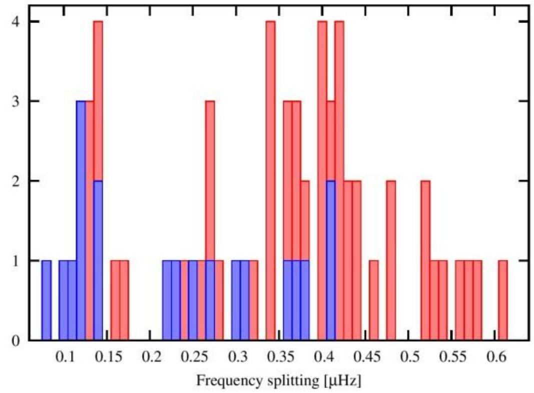

Fig. 8. Histogram of splittings listed in Table 4. The blue boxes reflect splittings from multiplets (mostly doublets) that were matched with the $\ell = 1$ sequence in Sect. 6.

We tentatively identify this splitting of 0.13 μHz as the rotation frequency of the subdwarf in KIC 11 558 725. We regard this result as inconclusive as other doublets that seem to match the $\ell = 1$ period spacing show a larger frequency splitting (>0.3 μHz). We note however that some of the peaks in these $\ell = 1$ doublets also match the $\ell = 2$ period spacing, and hence could be $\ell = 2$ modes instead.

Assuming that the Ledoux constant $C_{n'l}$ can be approximated by $1/(\ell(\ell+1))$ as in the asymptotic *g*-mode regime, the observed frequency splitting of 0.13 μHz in the $\ell = 1$ doublets leads to a rotation period of the subdwarf of 45 d. This consequently implies that the rotation of the subdwarf is not phase-locked with the orbit.

Even if we assume that the larger frequency splittings, in the 0.4–0.55 μHz range, belong to multiplets of $\ell > 1$ modes and are due to rotation, we would still conclude with certainty that the subdwarf rotates subsynchronously with respect to the orbit. Here the case of a splitting of 0.55 μHz for a supposed $\ell = 2$ multiplet provides the lower limit to the rotation period of 18 d.

Pablo et al. (2011, 2012) discuss the frequency splittings in the three of the four known *Kepler* sdB+dM systems, which all three have orbital periods on the order of ten hours. From the frequency splittings they derive that for each of their cases the subdwarf rotation is subsynchronous with respect to the orbit. Following their description of the Zahn (1975) synchronization timescale, we expect for KIC 11 558 725 a much longer synchronization timescale than for those sdB+dM systems, as the orbital period is much longer and the synchronization timescale scales with $P_{\rm orb}^{17/3}$. In fact, we expect that the rotation period we measure now is a good indicator of the rotation period of the subdwarf after it just settled on the extreme horizontal branch.

8. Summary and conclusions

From our new low-resolution spectroscopy we discovered that KIC 11 558 725 is a binary consisting of a B subdwarf and an unseen companion, likely a white dwarf. We found a circular orbit with $P_{\rm orb} = 10.05$ d, and a radial-velocity amplitude of 58 km s^{-1}. From the high signal-to-noise average spectrum we redetermined the atmospheric parameters of the subdwarf: $T_{\rm eff} = 27\,910$ K and $\log g = 5.41$ dex.

Five quarters of short-cadence *Kepler* data of KIC 11 558 725 reveal Doppler beaming at the 238 ppm level. The amplitude of the Doppler-beaming modulation in the light curve corresponds to a radial-velocity amplitude that is fully consistent with that determined from the spectroscopic data.

We developed a new method that uses the pulsations as clocks to measure the orbital light-travel effect, or Rømer delay, directly from the *Kepler* light curve. The measured delay is again in perfect agreement with the spectroscopically determined radial-velocity amplitude. This method allows the light-travel delay to be measured on many pulsations simultaneously, allowing the determination to be accurate, and hence can be useful for stars that have many weak pulsation frequencies such as sdB stars.

For the 300 s *p*-modes in KIC 11 558 725 the pulsation amplitude varies slightly when transforming the observation timings to that of the center-of-mass of the binary. This effect will only show up for short-period pulsations in a long orbit. We have been able to measure the Rømer delay from this effect.

One may wonder if it is still necessary to use spectroscopy to solve orbits for targets in the *Kepler* field. For the case of KIC 11 558 725 the phasing of the spectroscopic results with respect to the *Kepler* light curve proved essential in order to establish that the light-curve modulation is due to Doppler beaming, and not due to reflected light from the companion or to a contaminating object in the course *Kepler* pixel aperture. In general, the Doppler beaming amplitude may not reflect the radial-velocity amplitude in case the companion significantly contributes to the observed combined beaming amplitude. However, the phase and amplitude of the light-travel delay as determined by using the pulsations as clocks provide the same orbital constraints as derived from spectroscopy.

We extracted 166 pulsation frequencies from the *Kepler* light curve, among which 13 are found to be possible combination frequencies. We found 6 *p*-modes, and 160 frequencies in the *g*-mode domain, demonstrating the potential for a seismic analysis of this star.

We showed that many of the pulsation frequencies match period spacings of $\ell = 1$ and $\ell = 2$ sequences, implying that the interior structure of the subdwarf cannot be heavily stratified. The period-spacing sequences will aid in the identification process of the modes in a future seismic study of this object.

Although we detect many pulsation frequencies, we see little evidence for complete multiplets. The frequency splittings are many in KIC 11 558 725 and are difficult to fit in a standard picture. We attribute the smallest splittings that we find to $\ell = 1$ doublets, and derive a rotation period of 45 d. As a lower limit for the rotation period, we derive a value of 18 d, which implies that the subdwarf rotates subsynchronously with respect to the orbit.

KIC 11 558 725 is the first sdB pulsator in the *Kepler* sample with a confirmed compact stellar-mass companion. The 10 day orbit is in the long end of the period range of the ~100 known sdB binaries that have periods compatible with the common-envelope ejection scenario. Assuming a canonical sdB mass of $0.48\,M_{\odot}$, we derived a lower limit for the mass of the companion of $0.63\,M_{\odot}$. The distance between the two companions is $\gtrsim 20\,R_{\odot}$, which implies that if the sdB is a result of a common-envelope phase the progenitor must have been close to the maximum radius for a red giant, near the tip of the red-giant branch.

Acknowledgements. Based on observations made with the Nordic Optical Telescope, operated on the island of La Palma jointly by Denmark, Finland, Iceland, Norway, and Sweden, in the Spanish Observatorio del Roque de los Muchachos (ORM) of the Instituto de Astrofisica de Canarias, and the *William Herschel* Telescope and *Isaac Newton* Telescope also at ORM, operated by the Isaac Newton Group. M.D.R. and L.F. were Visiting Astronomers to the Kitt Peak National Observatory, National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under cooperative agreement with the National Science Foundation. M.D.R. and L.F. were supported by the Missouri Space Grant Consortium funded by NASA. The authors gratefully acknowledge the *Kepler* team and all who have contributed to enabling the mission. Funding for the *Kepler* Mission is provided by NASA's Science Mission Directorate. The research leading to these results has received funding from the European Research Council under the European Community's Seventh Framework Programme (FP7/2007–2013)/ERC grant agreement No. 227224 (PROSPERITY), as well as from the Research Council of KU Leuven grant agreement GOA/2008/04. J.H.T. cordially thanks the Instituut voor Sterrenkunde, KU Leuven, for its hospitality.

References

Baran, A. S., Kawaler, S. D., Reed, M. D., et al. 2011, MNRAS, 414, 2871
Bloemen, S., Marsh, T. R., Østensen, R. H., et al. 2011, MNRAS, 410, 1787
Bloemen, S., Marsh, T. R., Degroote, P., et al. 2012, MNRAS, 422, 2600
Charpinet, S., Fontaine, G., Brassard, P., et al. 1997, ApJ, 483, L123
Charpinet, S., van Grootel, V., Reese, D., et al. 2008, A&A, 489, 377
Charpinet, S., Fontaine, G., Brassard, P., et al. 2011, Nature, 480, 496
Clausen, D., Wade, R. A., Kopparapu, R. K., & O'Shaughnessy, R. 2012, ApJ, 746, 186
Copperwheat, C. M., Morales-Rueda, L., Marsh, T. R., Maxted, P. F. L., & Heber, U. 2011, MNRAS, 415, 1381
Geier, S., Hirsch, H., Tillich, A., et al. 2011, A&A, 530, A28
Gilliland, R. L., Jenkins, J. M., Borucki, W. J., et al. 2010, ApJ, 713, L160
Green, E. M., Fontaine, G., Reed, M. D., et al. 2003, ApJ, 583, L31
Han, Z., Podsiadlowski, P., Maxted, P. F. L., Marsh, T. R., & Ivanova, N. 2002, MNRAS, 336, 449
Han, Z., Podsiadlowski, P., Maxted, P. F. L., & Marsh, T. R. 2003, MNRAS, 341, 669
Heber, U. 2009, ARA&A, 47, 211
Heber, U., Reid, I. N., & Werner, K. 2000, A&A, 363, 198
Hulse, R. A., & Taylor, J. H. 1975, ApJ, 195, 51
Jenkins, J. M., Caldwell, D. A., Chandrasekaran, H., et al. 2010, ApJ, 713, L87
Kawaler, S. D., Reed, M. D., Østensen, R. H., et al. 2010, MNRAS, 409, 1509
Kilkenny, D., Koen, C., O'Donoghue, D., & Stobie, R. S. 1997, MNRAS, 285, 640
Mazeh, T., & Faigler, S. 2010, A&A, 521, L59
Østensen, R. H., & Van Winckel, H. 2012, in The Fifth Conference on Hot Subdwarf Stars and Related Objects, eds. D. Kilkenny, C. S. Jeffery, & C. Koen (San Francisco: ASP), ASP Conf. Ser., 452, 163
Østensen, R. H., Green, E. M., Bloemen, S., et al. 2010a, MNRAS, 408, L51
Østensen, R. H., Silvotti, R., Charpinet, S., et al. 2010b, MNRAS, 409, 1470
Østensen, R. H., Silvotti, R., Charpinet, S., et al. 2011, MNRAS, 414, 2860
Pablo, H., Kawaler, S. D., & Green, E. M. 2011, ApJ, 740, L47
Pablo, H., Kawaler, S. D., Reed, M. D., et al. 2012, MNRAS, 422, 1343
Randall, S. K., Green, E. M., Fontaine, G., et al. 2006, ApJ, 645, 1464
Reed, M. D., & Stiening, R. 2004, PASP, 116, 506
Reed, M. D., Brondel, B. J., & Kawaler, S. D. 2005, ApJ, 634, 602
Reed, M., Kawaler, S. D., Østensen, R. H., et al. 2010, MNRAS, 409, 1496
Reed, M. D., Baran, A., Quint, A. C., et al. 2011, MNRAS, 414, 2885
Rybicki, G. B., & Lightman, A. P. 1979, Radiative processes in astrophysics (New York: Wiley-Interscience)
Shibahashi, H., & Kurtz, D. W. 2012, MNRAS, 422, 738
Silvotti, R., Østensen, R. H., Bloemen, S., et al. 2012, MNRAS, in press [arXiv:1205.2457]
Telting, J. H., Østensen, R. H., & Reed, M. D. 2012, in The Fifth Conference on Hot Subdwarf Stars and Related Objects, eds. D. Kilkenny, C. S. Jeffery, & C. Koen (San Francisco: ASP), ASP Conf. Ser., 452, 147
Van Grootel, V., Charpinet, S., Fontaine, G., et al. 2010, ApJ, 718, L97
van Kerkwijk, M. H., Rappaport, S. A., Breton, R. P., et al. 2010, ApJ, 715, 51
Welsh, W. F., Orosz, J. A., Aerts, C., et al. 2011, ApJS, 197, 4
Werner, K., Deetjen, J. L., Dreizler, S., et al. 2003, in Stellar Atmosphere Modeling, eds. I. Hubeny, D. Mihalas, & K. Werner (San Francisco: ASP), ASP Conf. Ser., 288, 31
Zahn, J.-P. 1975, A&A, 41, 329

Pages 12 to 16 are available in the electronic edition of the journal at http://www.aanda.org

Table 1. Log of the low-resolution spectroscopy of KIC 11 558 725.

Mid-exposure date	Barycentric JD −2 455 000	S/N	RV km s^{-1}	RV$_{err}$ km s^{-1}	Telescope	Observer/PI
2010-07-28 00:24:52.0	405.519273	113.9	−26.6	8.6	WHT	JHT/CA
2010-07-28 05:16:04.8	405.721505	94.6	−30.6	9.0	WHT	JHT/CA
2010-08-12 10:05:19.3	420.922376	57.6	−93.5	10.0	KP4m	MDR,LF
2010-08-12 10:16:03.9	420.929837	60.6	−91.1	9.8	KP4m	MDR,LF
2010-08-13 03:41:29.7	421.655828	68.3	−69.3	7.4	KP4m	MDR,LF
2010-08-13 03:52:04.9	421.663178	74.1	−66.4	8.1	KP4m	MDR,LF
2010-08-14 08:24:41.8	422.852489	59.1	−31.1	8.0	KP4m	MDR,LF
2010-08-14 08:35:42.3	422.860134	59.4	−25.9	8.5	KP4m	MDR,LF
2010-08-14 08:46:01.9	422.867305	60.1	−34.2	6.9	KP4m	MDR,LF
2010-08-25 22:54:52.3	434.456682	91.3	−4.6	2.1	WHT	RHØ/CA
2010-08-25 23:09:46.0	434.467026	106.2	−17.4	5.2	WHT	RHØ/CA
2010-08-27 00:36:26.9	435.527210	117.9	−25.8	9.2	WHT	RHØ/CA
2010-08-27 00:46:36.6	435.534266	112.3	−31.2	7.3	WHT	RHØ/CA
2010-08-27 21:56:54.7	436.416408	93.6	−39.0	8.2	WHT	RHØ/CA
2010-08-27 22:08:29.4	436.424449	90.5	−63.8	4.4	WHT	RHØ/CA
2010-08-28 23:18:34.2	437.473103	74.7	−83.9	8.3	WHT	RHØ/CA
2010-08-28 23:28:43.8	437.480158	71.5	−90.5	6.1	WHT	RHØ/CA
2010-08-29 21:53:35.3	438.414074	105.3	−111.8	9.1	WHT	RHØ/CA
2010-08-29 22:03:44.8	438.421129	107.7	−128.2	10.9	WHT	RHØ/CA
2010-08-31 01:31:47.4	439.565587	119.6	−116.6	6.0	WHT	RHØ/CA
2010-08-31 01:41:56.9	439.572642	109.0	−117.0	6.4	WHT	RHØ/CA
2011-05-31 01:56:05.9	712.581494	49.4	−85.7	18.4	NOT	JHT
2011-05-31 04:48:22.9	712.701140	79.6	−88.5	14.7	NOT	JHT
2011-06-01 02:35:14.4	713.608708	57.0	−41.4	17.1	NOT	JHT
2011-06-07 03:46:43.9	719.658535	67.2	−123.2	9.2	NOT	JHT
2011-06-09 03:34:59.9	721.650444	49.6	−99.0	14.2	NOT	JHT
2011-06-10 04:58:52.1	722.708717	43.9	−103.3	10.0	NOT	JHT
2011-06-20 00:20:10.7	732.515438	53.1	−78.3	14.9	NOT	JHT
2011-06-21 01:27:07.4	733.561953	36.3	−69.3	14.7	NOT	JHT
2011-06-27 21:53:09.0	740.413514	56.4	−148.6	19.1	NOT	JHT
2011-07-22 23:30:41.0	765.481614	38.1	−22.1	14.4	NOT	JHT
2011-07-23 22:43:51.2	766.449100	49.2	−28.4	16.1	NOT	JHT
2011-08-29 00:17:40.9	802.514159	42.1	−110.0	16.6	NOT	RO
2011-08-30 00:38:59.5	803.528944	48.1	−81.2	16.6	NOT	RO
2011-08-31 00:25:05.0	804.519272	38.2	−50.1	13.9	NOT	RO

Table 4. Extracted pulsational frequencies.

Frequency μHz	Period s	Amplitude ppm	S/N	Splitting μHz	$n_{\ell=1}$	$n_{\ell=2}$	
5053.4659 (20)	197.88399 (0.00008)	23 (4)	5.4				
3103.8490 (17)	322.18062 (0.00017)	28 (4)	6.5	1.58			
3102.2724 (16)	322.34436 (0.00016)	29 (4)	6.8				
3075.0214 (09)	325.20099 (0.00010)	50 (4)	11.7	1.55			
3073.4671 (07)	325.36545 (0.00008)	63 (4)	14.8	1.15			
3072.3162 (24)	325.48733 (0.00026)	19 (4)	4.4				OA
3059.8960 (08)	326.80849 (0.00008)	59 (4)	13.8				
1463.3977 (25)	683.34123 (0.00116)	18 (4)	4.2			−1	
1444.0731 (19)	692.48572 (0.00091)	24 (4)	5.6				*
1422.9117 (11)	702.78430 (0.00053)	43 (4)	10.1				
1420.4369 (17)	704.00875 (0.00083)	27 (4)	6.3	0.24			
1420.1919 (22)	704.13022 (0.00111)	20 (4)	4.7				*
1399.2750 (23)	714.65579 (0.00119)	20 (4)	4.7				
1396.5427 (21)	716.05400 (0.00109)	22 (4)	5.1	0.13			
1396.4129 (20)	716.12059 (0.00105)	23 (4)	5.4	0.27			
1396.1397 (20)	716.26072 (0.00104)	23 (4)	5.4				*
1370.4145 (11)	729.70621 (0.00057)	43 (4)	10.1				*
1308.1017 (23)	764.46658 (0.00136)	20 (4)	4.7				*
1292.1409 (13)	773.90943 (0.00077)	35 (4)	8.2				*
1270.2485 (13)	787.24755 (0.00083)	34 (4)	8.0				
1265.4160 (19)	790.25394 (0.00116)	25 (4)	5.8				
1237.3675 (20)	808.16736 (0.00134)	22 (4)	5.1			0	
1139.1458 (23)	877.85072 (0.00175)	20 (4)	4.7				
1128.9600 (21)	885.77098 (0.00162)	22 (4)	5.1				
1083.6435 (26)	922.81273 (0.00220)	18 (4)	4.2		−2		*
1042.2709 (20)	959.44349 (0.00188)	22 (4)	5.1	0.53		↑	
1041.7417 (12)	959.93086 (0.00115)	37 (4)	8.7	0.26			
1041.4816 (20)	960.17062 (0.00183)	23 (4)	5.4	0.27		1	
1041.2151 (14)	960.41633 (0.00131)	32 (4)	7.5	0.52			
1040.6927 (11)	960.89840 (0.00104)	41 (4)	9.6	0.54			
1040.1546 (20)	961.39554 (0.00187)	23 (4)	5.4	0.58			
1039.5769 (08)	961.92981 (0.00073)	58 (4)	13.6			↓	
915.9922 (20)	1091.71231 (0.00240)	23 (4)	5.4			2	
888.0072 (20)	1126.11695 (0.00248)	23 (4)	5.4				
875.0949 (18)	1142.73315 (0.00237)	25 (4)	5.8		−1		*
826.2266 (13)	1210.32167 (0.00189)	35 (4)	8.2				
804.6305 (09)	1242.80646 (0.00134)	53 (4)	12.4	0.44		↑	
804.1940 (26)	1243.48108 (0.00408)	17 (4)	4.0	1.07		3	
803.1235 (14)	1245.13844 (0.00219)	32 (4)	7.5	0.56			
802.5678 (17)	1246.00067 (0.00267)	27 (4)	6.3			↓	
774.4270 (13)	1291.27732 (0.00217)	35 (4)	8.2				
741.5079 (26)	1348.60322 (0.00468)	18 (4)	4.2				
729.2202 (24)	1371.32792 (0.00447)	19 (4)	4.4				
712.5805 (03)	1403.35031 (0.00067)	135 (4)	31.7	0.40	↑	↑	*
712.1802 (07)	1404.13908 (0.00137)	66 (4)	15.5	0.41			
711.7661 (05)	1404.95599 (0.00098)	92 (4)	21.6	0.37		4	
711.3935 (05)	1405.69176 (0.00104)	87 (4)	20.4	0.34	0		
711.0567 (09)	1406.35756 (0.00183)	49 (4)	11.5		↓	↓	
685.7967 (20)	1458.15803 (0.00431)	23 (4)	5.4				
683.9097 (23)	1462.18144 (0.00502)	19 (4)	4.4				
663.5667 (11)	1507.00754 (0.00253)	41 (4)	9.6	0.52			
663.0469 (19)	1508.18887 (0.00439)	24 (4)	5.6				
659.0236 (15)	1517.39631 (0.00335)	32 (4)	7.5	0.34		↑	
658.6855 (14)	1518.17521 (0.00322)	33 (4)	7.7	0.44			
658.2465 (15)	1519.18768 (0.00341)	31 (4)	7.2	0.42		5	
657.8284 (06)	1520.15327 (0.00139)	76 (4)	17.8			↓	*
639.4081 (06)	1563.94636 (0.00144)	78 (4)	18.3	0.48			*
638.9238 (22)	1565.13179 (0.00543)	21 (4)	4.9	0.36			*
638.5688 (11)	1566.00196 (0.00265)	42 (4)	9.8	0.42			
638.1471 (18)	1567.03676 (0.00446)	25 (4)	5.8				
603.9510 (24)	1655.76352 (0.00670)	19 (4)	4.4		1		
595.5174 (18)	1679.21205 (0.00494)	26 (4)	6.1			6	
581.4725 (25)	1719.77176 (0.00730)	19 (4)	4.4				

Table 4. continued.

Frequency μHz	Period s	Amplitude ppm	S/N	Splitting μHz	$n_{\ell=1}$	$n_{\ell=2}$	
559.9286 (26)	1785.94207 (0.00833)	17 (4)	4.0			↑	
557.6564 (21)	1793.21886 (0.00676)	22 (4)	5.1	1.38		7	
556.2798 (13)	1797.65640 (0.00413)	36 (4)	8.4			↓	
536.5423 (09)	1863.78608 (0.00318)	50 (4)	11.7	0.48			
536.0656 (20)	1865.44339 (0.00686)	23 (4)	5.4				
511.0034 (07)	1956.93427 (0.00272)	64 (4)	15.0			8	*
456.4978 (21)	2190.59091 (0.01022)	21 (4)	4.9				
435.3696 (18)	2296.89908 (0.00970)	25 (4)	5.8				*
390.8675 (02)	2558.41205 (0.00129)	233 (4)	54.8	0.29		↑	*
390.5727 (20)	2560.34269 (0.01316)	23 (4)	5.4			12	
382.7335 (02)	2612.78405 (0.00124)	253 (4)	59.5	0.14	↑		
382.5913 (01)	2613.75508 (0.00076)	416 (4)	97.8		5		
370.4606 (12)	2699.34236 (0.00879)	38 (4)	8.9			13	
351.9691 (10)	2841.15865 (0.00788)	47 (4)	11.0				
350.2917 (02)	2854.76388 (0.00125)	299 (4)	70.3	0.12	↑	↑	
350.1676 (01)	2855.77522 (0.00056)	668 (4)	157.1		6	14	*
336.8906 (17)	2968.32256 (0.01499)	27 (4)	6.3	0.34		↑	*
336.5482 (22)	2971.34244 (0.01924)	21 (4)	4.9	0.17			
336.3773 (15)	2972.85207 (0.01342)	30 (4)	7.0	0.40		15	
335.9730 (12)	2976.43006 (0.01099)	37 (4)	8.7	0.40			
335.5761 (14)	2979.94986 (0.01211)	34 (4)	8.0			↓	
322.5146 (01)	3100.63481 (0.00057)	779 (4)	183.2	0.12	↑		
322.3960 (01)	3101.77527 (0.00071)	620 (4)	145.8	0.61	7		
321.7834 (05)	3107.68011 (0.00502)	88 (4)	20.7	0.43		↑	
321.3523 (06)	3111.84932 (0.00603)	74 (4)	17.4	0.42		16	OA
320.9336 (01)	3115.90941 (0.00083)	537 (4)	126.3		↓	↓	
311.3506 (01)	3211.81286 (0.00140)	339 (4)	79.7				
308.5923 (08)	3240.52146 (0.00817)	59 (4)	13.8	0.16		↑	
308.4370 (05)	3242.15289 (0.00510)	95 (4)	22.3	0.34			
308.0959 (03)	3245.74214 (0.00263)	184 (4)	43.2	0.43		17	
307.6612 (02)	3250.32863 (0.00219)	220 (4)	51.7			↓	*
305.0273 (02)	3278.39459 (0.00262)	188 (4)	44.2	0.42			
304.6094 (07)	3282.89325 (0.00777)	63 (4)	14.8	0.40			
304.2116 (08)	3287.18530 (0.00845)	58 (4)	13.6				*
296.1067 (01)	3377.16086 (0.00066)	796 (4)	187.2	0.92	↑	↑	
295.1847 (05)	3387.70993 (0.00587)	89 (4)	20.9		8	18	
283.2231 (05)	3530.78551 (0.00580)	98 (4)	23.0	0.32		↑	
282.9004 (11)	3534.81263 (0.01348)	42 (4)	9.8	0.36		19	
282.5393 (09)	3539.33115 (0.01066)	54 (4)	12.7			↓	
274.7524 (01)	3639.64034 (0.00100)	611 (4)	143.7	0.11	↑		*
274.6415 (01)	3641.11018 (0.00068)	891 (4)	209.6		9		
271.9863 (05)	3676.65540 (0.00682)	91 (4)	21.4	0.14		↑	
271.8489 (14)	3678.51341 (0.01850)	34 (4)	8.0	0.14		20	*
271.7083 (06)	3680.41699 (0.00748)	83 (4)	19.5	0.38			
271.3237 (06)	3685.63425 (0.00758)	82 (4)	19.2			↓	
256.2548 (08)	3902.36612 (0.01218)	58 (4)	13.6	0.12	↑		
256.1353 (23)	3904.18665 (0.03544)	20 (4)	4.7		10		
254.0371 (15)	3936.43229 (0.02272)	31 (4)	7.2				
240.4970 (04)	4158.05561 (0.00728)	109 (4)	25.6	0.14	↑		
240.3552 (01)	4160.50933 (0.00144)	557 (4)	131.0		11		
235.6888 (09)	4242.88224 (0.01617)	51 (4)	12.0			24	*
229.4898 (01)	4357.49261 (0.00270)	325 (4)	76.4	0.13			
229.3626 (07)	4359.90906 (0.01269)	69 (4)	16.2	0.13			
229.2375 (02)	4362.28846 (0.00335)	261 (4)	61.4	1.24			
227.9950 (08)	4386.06201 (0.01570)	56 (4)	13.1		↑	↑	
226.1883 (01)	4421.09470 (0.00206)	434 (4)	102.1		12	25	
214.8602 (05)	4654.18897 (0.01078)	92 (4)	21.6	0.41	↑	↑	
214.4538 (01)	4663.00855 (0.00262)	381 (4)	89.6		13	27	
204.0365 (01)	4901.08376 (0.00331)	333 (4)	78.3	0.31	↑		
203.7217 (01)	4908.65758 (0.00262)	420 (4)	98.8		14		
194.4829 (04)	5141.84071 (0.01050)	115 (4)	27.0	0.25	↑	↑	
194.2320 (02)	5148.48327 (0.00583)	208 (4)	48.9		15	30	
185.9787 (12)	5376.95929 (0.03514)	38 (4)	8.9	0.23	↑		

Table 4. continued.

Frequency μHz	Period s	Amplitude ppm	S/N	Splitting μHz	$n_{\ell=1}$	$n_{\ell=2}$	
185.7520 (09)	5383.52087 (0.02650)	50 (4)	11.7		16		*
183.1588 (16)	5459.74210 (0.04837)	28 (4)	6.5				
173.8372 (09)	5752.50813 (0.03087)	49 (4)	11.5				
170.5770 (05)	5862.45349 (0.01651)	95 (4)	22.3	0.27	↑	↑	
170.3090 (06)	5871.67950 (0.02219)	71 (4)	16.7		18	35	*
163.4371 (06)	6118.56357 (0.02383)	72 (4)	16.9		19	37	
160.8351 (13)	6217.54915 (0.05208)	34 (4)	8.0				*
156.9593 (03)	6371.07649 (0.01259)	149 (4)	35.0	0.10	↑		
156.8617 (07)	6375.04157 (0.02766)	68 (4)	16.0		20		
152.6142 (04)	6552.46996 (0.01839)	107 (4)	25.1	0.69		↑	
151.9237 (05)	6582.25067 (0.02006)	99 (4)	23.2	0.72		40	
151.2009 (10)	6613.71905 (0.04546)	46 (4)	10.8	0.08	↑		
151.1162 (09)	6617.42475 (0.03923)	53 (4)	12.4	0.22	21		
150.8946 (10)	6627.14155 (0.04458)	45 (4)	10.5		↓		
146.8171 (11)	6811.19663 (0.05080)	42 (4)	9.8			42	
140.2879 (05)	7128.19949 (0.02788)	83 (4)	19.5		23	44	
135.9729 (05)	7354.40412 (0.02817)	88 (4)	20.7	0.30	↑		*
135.6687 (11)	7370.89720 (0.06169)	40 (4)	9.4		24		
131.1578 (01)	7624.40245 (0.00545)	486 (4)	114.3	0.37	↑		*
130.7852 (04)	7646.12630 (0.02057)	130 (4)	30.5		25		
123.4258 (10)	8102.03660 (0.06511)	46 (4)	10.8	0.38	↑	↑	
123.0479 (07)	8126.91403 (0.04350)	69 (4)	16.2		27	51	
119.8705 (04)	8342.33836 (0.02940)	108 (4)	25.4		28		
116.1148 (03)	8612.16711 (0.02395)	142 (4)	33.4		29		*
104.3568 (03)	9582.50490 (0.02625)	160 (4)	37.6	0.36	↑	61	
104.0008 (07)	9615.31517 (0.06067)	70 (4)	16.4		33		*
101.5403 (05)	9848.30600 (0.05298)	84 (4)	19.7	0.41	↑	↑	*
101.1341 (05)	9887.85717 (0.04481)	100 (4)	23.5	0.59	34	63	
100.5486 (15)	9945.44211 (0.14413)	31 (4)	7.2	0.37			
100.1774 (05)	9982.29229 (0.05201)	88 (4)	20.7			64	
94.7358 (12)	10555.67247 (0.13476)	38 (4)	8.9			68	
92.2056 (19)	10845.32955 (0.22353)	24 (4)	5.6	0.47			
91.7333 (14)	10901.16609 (0.16491)	33 (4)	7.7			70	
89.4365 (15)	11181.11603 (0.19143)	30 (4)	7.0	1.56			
87.8741 (11)	11379.91791 (0.14794)	40 (4)	9.4				
86.0158 (16)	11625.76501 (0.21525)	29 (4)	6.8				
83.2845 (13)	12007.03178 (0.19272)	34 (4)	8.0			78	
78.2703 (04)	12776.24508 (0.06990)	107 (4)	25.1				
73.6556 (04)	13576.69795 (0.08256)	102 (4)	24.0		49	89	*
49.7780 (11)	20089.18155 (0.45588)	40 (4)	9.4				*
37.8572 (18)	26415.06723 (1.22748)	26 (4)	6.1				

Notes. The columns marked n_ℓ list the sequence number obtained from period spacing, for the $\ell = 1$ and $\ell = 2$ sequences. Multiplet candidates used to derive the period spacings are indicated by the span of the arrows above and below the sequence numbers; for doublets only an up-arrow is used. The last column lists OA for orbital alias, or an asterisk if the frequency is part of a combination, as listed in Table 5.

Table 5. Possible frequency combinations.

F_1 μHz	F_2 μHz	F_3 μHz	$F_3 - F_2 - F_1$ μHz	A_1 ppm	A_2 ppm	A_3 ppm
1.1521 (02)	3072.3162 (24)	3073.4671 (07)	–0.0012	223	19	63
49.7780 (11)	135.9729 (05)	185.7520 (09)	0.0011	40	88	50
49.7780 (11)	1370.4145 (11)	1420.1919 (22)	–0.0006	40	43	20
73.6556 (04)	638.9238 (22)	712.5805 (03)	0.0011	102	21	135
101.5403 (05)	170.3090 (06)	271.8489 (14)	–0.0004	84	71	34
104.0008 (07)	1292.1409 (13)	1396.1397 (20)	–0.0020	70	35	23
116.1148 (03)	274.7524 (01)	390.8675 (02)	0.0003	142	611	233
131.1578 (01)	304.2116 (08)	435.3696 (18)	0.0002	486	58	25
135.9729 (05)	1308.1017 (23)	1444.0731 (19)	–0.0015	88	20	24
160.8351 (13)	350.1676 (01)	511.0034 (07)	0.0007	34	668	64
235.6888 (09)	639.4081 (06)	875.0949 (18)	–0.0020	51	78	25
307.6612 (02)	350.1676 (01)	657.8284 (06)	–0.0004	220	668	76
336.5482 (22)	1083.6435 (26)	1420.1919 (22)	0.0002	21	18	20

Notes. All combinations $F_3 = F_2 + F_1$ are significant to within the errors of the observed frequencies. The rightmost columns list the amplitudes. The top entry is an orbital alias (see Sect. 5.1).

Appendix C: *Female Independence and How to Achieve It*

Courtesy of Dr. Sharmistha Self

Female Independence and How to Achieve It

In her corner office at Missouri State University, Dr. Sharmistha Self keeps paperwork in stacks on her bookshelves. Her book collection covers the back table, and potted plants balance precariously on piles of textbooks and journals. The scribbles and drawings from children hang in places of pride: above the calendar and on the side of the filing cabinet, facing the entrance. It is not just an office—it is an extension of her, and it feels like a home.

Southwest Missouri was not always her home, however; Self is from India, and although she now resides in Springfield, Missouri, her passion remains in Southern Asia. As a professor of economics and someone who was raised in a developing country, she decided to study development economics. As a woman from a developing country, she began looking into gender-related issues—and she found them.

What stood out to her was that women, specifically in the rural area of northern India, have little independence or control over their own decisions. When women gain independence and the ability to make their own choices, research shows that the benefits are abundant. Violence against women by male family members decreases significantly, and their entire household, including their children, feel the overall benefits. But what decides their level of independence? How can such an enormous problem as gender equality even begin to improve?

Uttar Pradesh, in the northern part of India, is the home of over 200 million people. There are more inhabitants in the state than in any other Indian state, and it is the biggest subdivision in the world. Self decided to center her research in the rural state because there are large gaps in gender equality in areas such as employment and the data covers a variety of individuals and households. After viewing the public data, with tables of percentages and rows of statistics, Self found that there are several factors that may determine the level of female independence, including politics, economics, and societal conventions.

In her research, Self chose one situation as a measurement of female independence: mobility, the freedom of a woman to move about. Instead of looking at overall female mobility, she further focused her view on two scenarios:

- the ability of a woman to visit a doctor without permission from a male family member
- the ability of a woman to visit a doctor without a male escort

The scenarios include a definite purpose and a destination outside the home.

The results were unsettling, especially for those in Western culture. Slightly more than a third of all 1,963 surveyed women from the Uttar Pradesh dataset need the permission of a male family member to visit the doctor. Similarly, more than a third need a male escort. However, the data was not cut-and-dry: proportions ranged from 0 percent to 69 or 76 percent. But what causes such variation within and across villages?

Several societal factors contribute to the level of female independence. Women who are older, marriages in which there is a small age gap between husband and wife, and the education of females all give women a better chance of choice. Caste (social status) and religion (Hindu, Muslim, etc.) have an impact as well. A big societal factor includes assumptions that are almost common sense: If a woman is the head of her household, she will have more control. On the other hand, if a woman has infant children, she will have less freedom of mobility. While the influence of society only covers some of the factors, it is an important piece.

When women have the option of working outside of their home, they gain financial independence and have more of say in their household and life. By taking part in household finances, women influence purchases and monetary decisions. In a culture where women are expected to do housework and men work outside of the house, women can tip the balance of power by spending more effort outside of her home than inside it. The threat may be necessary—

husbands could put on a show of power and threaten their wives with divorce; in turn, if she works outside of her home, she has options. Financial independence gives women control and allows them to make choices.

Surprisingly, Self found that the political data returned unexpected results. In areas where a woman held the title of Pradhan, the village leader, female independence was not improved overall. However, in areas where a female rose to power from the lower caste and gained political experience, women are much more likely to have more control over their choices.

Though societal factors are difficult to change in a short amount of time, Self suggested policy changes to improve female independence overall. By drafting policies that advertise employment outside of their homes and politically reforming the caste system, women in Uttar Pradesh have the chance of gaining more independence and the power to make their own choices.

In Springfield, Missouri, both men and women are allowed to leave their homes—either with a purpose, like visiting the doctor, or to wander around aimlessly—without permission or escorts. In developing countries such as India, that is not necessarily true. As Self continues researching gender inequality and uncovering new data, her conclusions will continue to reveal the solutions to this global problem. With work such as hers, there is a hope that someday both men and women will have the option of visiting the doctor, alone and without permission.

Appendix D: *Invisible Dwarf*

Courtesy of Dr. Mike Reed

Invisible Dwarf

Even on the darkest nights and with the strongest technology, astronomers cannot see everything the night sky has to offer. Of the many mysterious aspects of space and the sky, one involves a quiet friendship between two stars in the Milky Way galaxy, one more shy than the other. There is an invisible star circling its visible companion, and Dr. Mike Reed, in cooperation with astronomers from across the world, uses measurements and observations to prove its existence.

When the NASA space telescope *Kepler* was launched in 2009, its mission was to search a small portion of the Milky Way galaxy for Earth-like planets. Although it continues to meet its goal—based on data from *Kepler*, astronomers have determined that there may exist as many as 40 billion habitable Earth-like planets orbiting sun-like stars—it also accomplished the task of collecting data on everything in its viewpoint. Although that field of view is limited, and it only covers around 0.25% of the sky, it includes a subdwarf star named KIC 11 558 725.

Even without its unseen companion star, KIC 11 558 725 is rare; it is one of only 16 pulsating subdwarf B stars in the entirety of the *Kepler* viewing field. KIC 11 558 725 is a subdwarf B star, which is a type of subdwarf star with spectral type B. Subdwarf B stars are much brighter and hotter than typical subdwarf stars, and KIC 11 558 725 is no different. It pulsates, and the changes in its brightness make it look like the twinkling star from the childhood song.

Pulsating stars are what caught Dr. Reed's interest. As an undergraduate student, he spent his time working with stars. In graduate school, he changed his focus to whole galaxies. Then technology improved, pulsating subdwarf B stars were discovered, and he wanted to make a contribution. After years of research, and in collaboration with astronomers from Belgium, Spain, Poland, Australia, and California, Dr. Reed presented his discovery of an invisible star, most likely a white dwarf, that circles KIC 11 558 725.

It was not easy to prove the existence of the subdwarf B star's invisible companion star, but one indication of its existence was hidden in *Kepler's* data. When collecting data on light wavelengths from the subdwarf B star, there was always the chance that the subdwarf's invisible companion could eclipse the other and skew the data. It was *Kepler* that saved the day—it applies algorithms to give accurate light curve data regardless of contamination from other influences, so it continued to gather useful information.

Dr. Reed and the team of astronomers spent more than fifteen months working with observations from *Kepler*, but it was worth it—they also used that data to learn more about the internal structure of KIC 11 558 725 and of subdwarf stars B stars in general.

There is a deep beauty to the idea of an invisible star circling another, unseen for countless years. It is even more overwhelming to realize that white dwarf stars are old; they are stars at the end of their lifespan. Subdwarf stars eventually become white dwarf stars, and so KIC 11 558 725 is being continuously circled by its fate. The invisible star is no longer unseen—it has been seen, it has been recorded, and it will not be forgotten.