# Listening to the sounds of stars
# Molodi wa dinaledi

by Prof. Thebe Rodney Medupe

Mafikeng campus rector, vice rector research, vice rector quality and learning, other members of the senior leadership of the university, baruti, bishop, all the VIPs, ladies and gentlemen, good evening. I would like to introduce myself as Mosimane wa Motswana, Morolong, namane ya Tholo, mmina Tshipi ya noto. I was born and raised in Mahikeng, in one of the villages around here. I feel honoured and priviledged to be able to present my inaugural lecture at my place of my birth. There is a saying that "a prophet never gets recognition at his home", However, this evening is an exception, and I wish to thank my university, my town and people for coming here to give me recognition and to celebrate with me.

I wish to take this opportunity to thank my family, and my mother for their support and love and wish to tell them that without their support,and understanding I would not be here today to give this inaugural lecture. I wish to dedicate tonight to my late Father, Mr. Justice Mothibi Medupe for everything thing he did to ensure that I become what I am today. I also wish to give thanks to two great astronomers who have groomed me from when I was quite young until today. These are professor Donald Wayne Kurtz (currently at University of Central Lancashire in Preston, UK) and professor Joergen Christensen-Dalsgaard (currently at university of Aarhus Denmark). Finally, I also want to thank professor Ebenso for supporting me and mentoring me since I joined Mahikeng campus in 2010.

## Introduction

I am an astronomer. At the heart of astronomy lies our attempt to answer the three most fundamental questions that has occupied our minds since time immemorial: where do we come from? What will happen to us in the future, and are we alone in the universe. As I will briefly show, the answers to these questions are found in stars. The fourth question of where do we fit in the big scheme of things, deserves many lectures and I will not go into it today. There is no doubt that our lives and future are tied to the future of the nearest star to us, the Sun. First, the chemicals that we are made of (the Carbon, Oxygen, Nitrogen) were created in the Universe only after the stars were formed. We believe that the first stars were formed about 400 million years after the big bang, an event that created the universe 13.7 billion years ago. At the time of the big bang only hydrogen and helium were formed, the rest of the elements of the periodic table did not exist. Thus, we are indeed children of stars, for without stars there would have been no carbon, oxygen and nitrogen to make us. Secondly, the nearest star, the Sun is very important to life on earth; without the heat and light from the Sun, there is no us and no life in general.

When answering the question about our ultimate origin, we need to know the history of the Sun from its formation. When, where and how did the Sun form. It is thus very important that we learn as much about our Sun as possible in order to know about its history and what will happen to it in the future. We need to know how it was formed, how old it is, how does it produce light, how different it is from other stars and what is the fate of the Sun. As to whether we are alone in the universe, we need to search for earth like planets in the solar system and elsewhere in the universe. Since planets mostly do not produce their own light, detecting them amongst other stars require us to have a very good understanding of how these stars work. This, ladies and gentlemen, is why I study the physics of stars.

Where do we come from? We live on the earth which was formed not long after the sun formed, from the leftover material that was surrounding the young Sun in a form of a disk. The Sun itself formed out of a giant cloud of dust and gas (called a nebula) nearly 5 billion years ago. A part of that cloud contracted, and became hot . When the temperature near the centre of this contracting section of a cloud became high enough to start the fusing of hydrogen into helium, the Sun was born.

When the hydrogen is all finished at the centre (also called the core) of the Sun, the core will contract and heat up. In response to this, the rest of the Sun will swell up, possibly engulfing the inner three planets (Mercury, Venus, Earth). The core of the Sun will get hot enough to fuse helium, creating oxygen and carbon in the process. This is far as the Sun will go in terms of nuclear fusion. It will never get hot enough to fuse carbon and oxygen. Once all the helium at the centre of the Sun is finished, the Sun will stop producing energy and light, it will become a white dwarf. Eventually will become a “lifeless” star that does not produce light any, dark and called a black dwarf. This will happen billions of years from now. This is a summarized and simplified play out of the future of the earth and solar system and gives an indication of what we think will happen to our future.

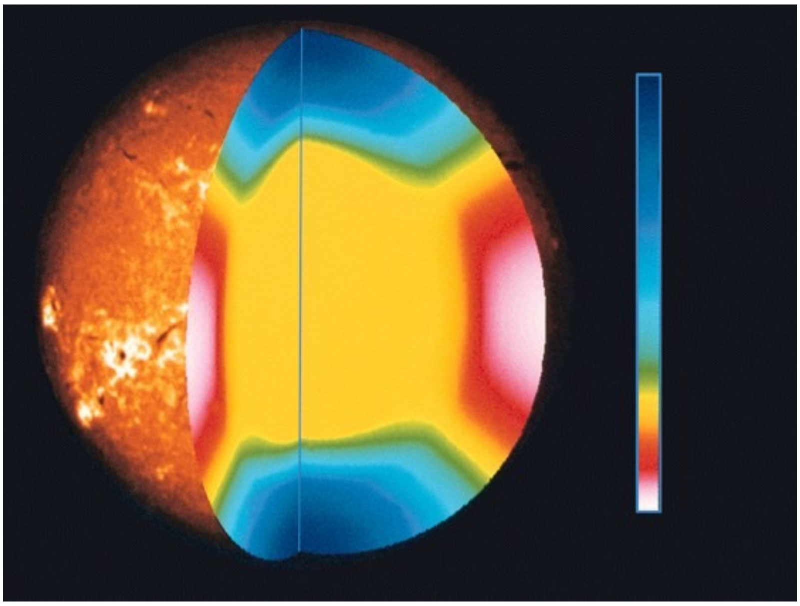
So, what is a star? A star is a giant ball of heated gas. For example, the Sun is so big that 1.3 million earths can fit inside it! Stars are so hot that for example, the central temperature of the Sun is 15 million degrees. Whereas the surface temperature is only 6000 degrees! Inside the Sun, as you move from the centre to the surface, you will pass through its core, where the Sun’s energy is generated by nuclear fusion (the joining together of atomic nuclei). The core occupies about 20% of the radius of the Sun. Above the core, as you move towards the surface, you will encounter the radiation zone where not much energy is generated but rather here the energy is transported by photons upwards. Above the radiation zone is the convective zone (which occupies another 30% of the radius) and finally the very thin outer layer of gas called the Sun's atmosphere. The thickness of the Sun's atmosphere is only 0.2% of its radius. Therein lies the challenge. Through our telescopes and eyes, we can only see the atmosphere of a star! The rest of the layers of the star I have mentioned above are totally opaque and we cannot directly access them! How can we know about an object when we can only access 0.2 % of it! At this point, I wish to remind you, ladies and gentlemen, that distances in space are so huge that the furthest celestial object that humans have visited is the Moon which is only 384,400km away! The problem is that we have not been able to build spaceships that are fast enough to cover distances in the solar system within reasonable times. For example, the Sun is 150 million km away it would take us 223 days to reach its surface (travelling at 28000km/hr, the speed of the Space Shuttle). It can take us only half a day to go to the Moon. It would take us 4.5 years to reach the nearest star to the Sun, Proxima Centauri if we were travelling at the speed of light! These distances are so vast, that the only way we can learn about celestial objects (i.e the planets, stars, galaxies etc) is by studying the light they emit.  We cannot visit them and take measurements!

**Why are the waves important?**

The light that a star emits come from its atmosphere, a very shallow and thin part of a star. Therefore, how do we access the inaccessible parts of a star? This is where my sub-field of stellar astronomy (called astero-seismology) comes in. We make use of waves (p-modes, of which a sound wave is an example) that are generated inside stars to learn about the physics of the parts of the star where these p-modes are travelling in. The good thing about these waves is that a variety of them travel through different parts of a star. Furthermore, a p-mode wave is sensitive to the conditions inside the material that they travel through. Thus, for example, the sound speed is sensitive to Temperature, pressure, density and composition of the gas it travels through. Therefore, detecting and measuring speeds of p-modes inside a star enables us to infer these properties of the stellar gas.

I can hear someone saying, but how do we even detect sound waves coming from stars when there is vacuum between stars and our earth? Afterall, sound waves do not travel in vacuum (remember this from physics 118?). The answer is that we do not detect and measure the sound waves directly, but we detect the sound waves through their effect on the starlight. The waves, that are generated deep inside a star may travel through to the surface. As a wave arrives at the surface, it compresses and rarefies gases of a star. The compressed gas becomes slightly hotter, and the rarefied gas cools a bit. It is these repetitive cooling and heating of the surface gases that makes the starlight to brighten and dim (slightly) in a repetitive way. Also note that the surface area of a star becomes bigger and smaller as a the p-modes pass through it. We thus can detect these often-small changes in the brightness of a star. The waves also cause movement in the surface gases of a star and we can measure the speeds of the gas as well by taking the spectrum of a star. A spectrum is taken by passing starlight through a telescope and a prism.

In summary, my field of study is called astero-seismology. It is the study of the interior physics of the stars by analyzing seismic waves that travel inside stars. This allows us to access most of the interior of a star, giving us a better understanding of how a star works. A good example is of how seismology of the Sun (called helio-seismology) has lead to the detailed understanding of how the Sun rotates. By detecting and measuring the many waves of different frequencies in the Sun, astronomers were able to infer the rotation rate of the Sun from its surface down to the core as shown below:



The different colours show different rotation speeds of the Sun, from the core to its surface

Astronomers were able to show that below the convection zone, the Sun rotates like a solid object (i.e its rotation speed is the same everywhere). In the convection zone the Sun rotates faster in its equator and slower at the poles (as shown in the picture above)

A wave is a disturbance that repeats itself over a period of time. From the period of repetition we obtain frequency. The higher the frequency the shorter the period. Amplitude is the size the disturbance. The smaller the amplitude, the harder it is to detect the disturbance and measure its period.

**My contribution to astero-seismology**

The different colours of stars indicate their surface temperatures. Blue stars are the hottest with surface temperature of over 30,000 degrees, whereas the red stars are much cooler with surface temperatures of around 2500 degrees. The Sun, for example is a yellow star, with surface temperature of around 5500 degrees and is classified as a G star.

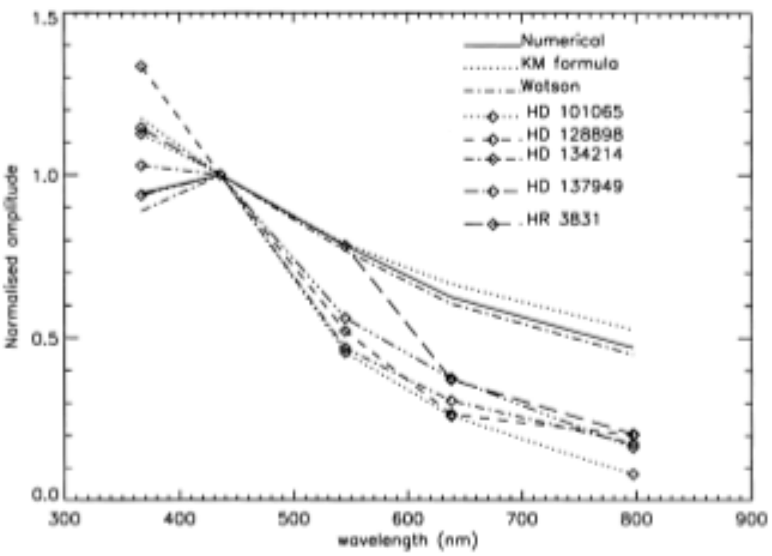
The type of stars I have studied over my career are white-ish in colour with surface temperature ranging from about 6500 to 10000 degrees. They are classified as A and F stars. Their light changes periodically with typical periods of between 5 and 23 minutes. The stars are called the rapidly oscillating Ap stars because of their short vibration periods and their strange light spectra. They also have strong magnetic fields, much stronger than that of the sun

We collect data in two different ways. One way is to put an electronic camera at the eyepiece part of the telescope and take pictures of a star you wish to study. This method is called photometry. In another method, a prism is used to split light into many colours, allowing us to look at the distribution of starlight in different wavelengths of light.

In the following pages I will present selected works from my career. I have mainly worked on detecting and measuring frequencies in  various pulsating stars. I have also worked on making computational models of the vibrations. My publication list is included in pages 15 until 19.

**Understanding the amplitudes of roAp stars**

When vibrational (or pulsation) amplitudes of the roAp stars are measured in different filters (colours), it is found that they decrease very rapidly from blue to longer wavelength (red) filters. This is demonstrated with a plot taken from Medupe & Kurtz (1998) below where models are compared to the data.




The boxes show data for different star names (HD 101065 for example). Solid line and dashed line are the two different models

The model amplitudes decrease less steeply than the actual data.

The suggested idea to explain this discrepancy between the models (theory) and observations was that a strongly wavelength dependent limb-darkening was responsible for the difference. Limb-darkening is the brightening of the surface of a star from the edge of the disk to the centre of the disk. This is clearly noticeable on the projected image of the Sun. This brightening (or darkening depending on which way you look at it) is modelled using a parameter β.

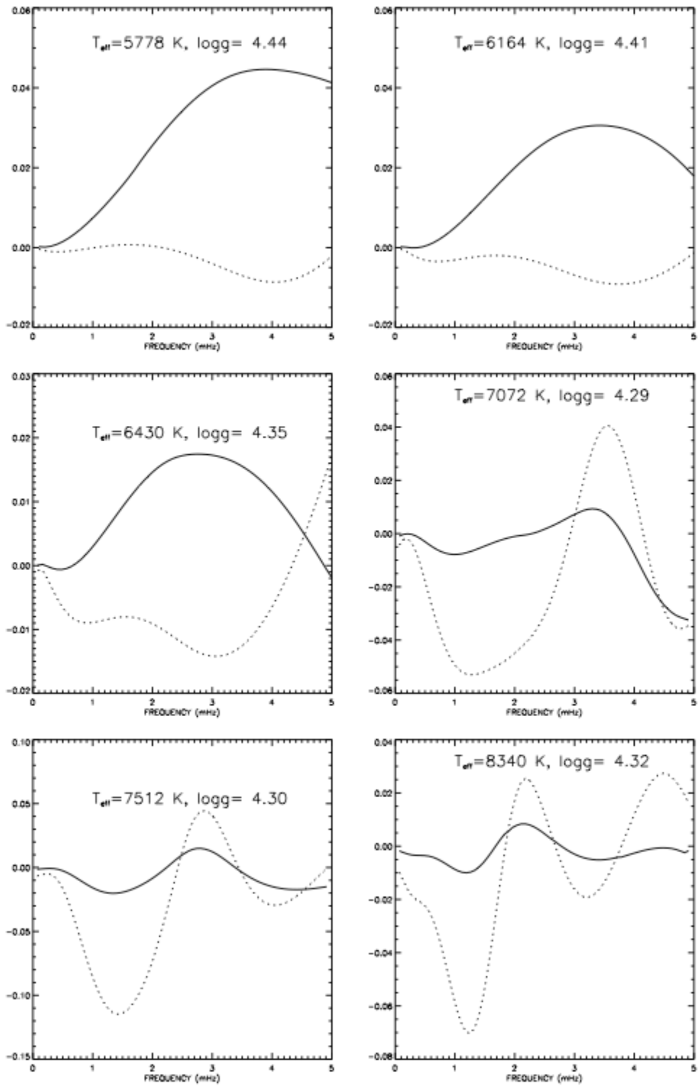
We demonstrated that this explanation does not work by deriving an equation that showed that limb-darkening effect is too small to explain the discrepancy between theory and observation. The equation which relates vibration amplitude to limb-darkening parameter and temperature amplitude (ΔT) is shown below

$$\Delta m(\lambda, t) = +1.086\sqrt{\frac{3}{\pi}}\,\frac{1}{4}\,\frac{(4-\beta_\lambda)}{(3-\beta_\lambda)}\cos\alpha\;\frac{hc}{\lambda k T_\circ}\,\frac{\Delta T}{T_\circ}.$$

This was published in Medupe & Kurtz (1998). This article has 27 citations and was published in a journal with 4.95 impact factor.

## Modelling pulsations in atmospheres of A- type stars

I wrote a computer program to solve fluid dynamics equations that includes pulsations and radiation in the atmospheres of A- type stars. The idea was to be able to compare the models with the data in different filters. Upon testing and debugging the program we came across the the following discrepancy:




Here the light out put amplitudes ($\Delta H/H$) is plotted against the frequencies of vibration for stars of different temperature and masses and radii. The solid line is the results of my code. The dotted line is what is expected by simple theory.

The two curves do not match.

To explain the difference between my computer programme I derived this equation for the amplitude of light ($\delta H/H$):

$$\frac{\delta H(0)}{H(0)} = \frac{1}{2\,H(0)} \int_0^1 \int_0^\infty \delta B\,(\tau)\, e^{-\tau/\mu}\, \mathrm{d}\,\tau\, \mathrm{d}\mu \qquad (47)$$
$$- \frac{1}{2\,H(0)} \int_0^1 \int_0^\infty \frac{\delta\kappa}{\kappa}\,(I - B)\; e^{-\tau/\mu}\, \mathrm{d}\,\tau\, \mathrm{d}\,\mu.$$

The first term on the right-hand of this equation comes from temperature vibration, the second term comes from the interaction of light with gases inside a pulsating star. With this equation we are able to show that the discrepancy between the results of my code with the standard theory is because of the effect of the waves on the interaction between light and gas particles in a pulsating star.

We published on this in Medupe et al (2009). This is work in progress with my PhD student, who is adding the effect of surface area changes due to the p-modes.

We were also able to extend the equation that is normally used to describe the vibrations of the radius of a star for the case where the waves are not impacted by radiation or other heat sources to include the effects of radiation. The original equation looks like this:

$$\delta r(r) \simeq A\,\rho(r)^{-\frac{1}{2}}\,c(r)^{-\frac{1}{2}}\,r^{-1}\,\cos\left(\omega\tilde{\tau} - (\tfrac{1}{4}+\alpha)\,\pi\right)$$

My computer programme allowed us to show that in the more realistic case, where radiation plays a role in the vibrations, the equation becomes:

$$\begin{aligned}\delta\hat{r} = &\left[B_{+\mathrm{r}}\cos\left(\omega_{\mathrm{r}}\tilde{\tau}\right) - B_{+\mathrm{i}}\sin\left(\omega_{\mathrm{r}}\tilde{\tau}\right)\right]e^{-\omega_{\mathrm{i}}\tilde{\tau}}\\ &+\left[B_{-\mathrm{r}}\cos\left(\omega_{\mathrm{r}}\tilde{\tau}\right) + B_{-\mathrm{i}}\sin\left(\omega_{\mathrm{r}}\tilde{\tau}\right)\right]e^{\omega_{\mathrm{i}}\tilde{\tau}}\\ &+\mathrm{i}\left[B_{+\mathrm{r}}\sin\left(\omega_{\mathrm{r}}\tilde{\tau}\right) + B_{+\mathrm{i}}\cos\left(\omega_{\mathrm{r}}\tilde{\tau}\right)\right]e^{-\omega_{\mathrm{i}}\tilde{\tau}}\\ &+\mathrm{i}\left[B_{-\mathrm{i}}\cos\left(\omega_{\mathrm{r}}\tilde{\tau}\right) - B_{-\mathrm{r}}\sin\left(\omega_{\mathrm{r}}\tilde{\tau}\right)\right]e^{\omega_{\mathrm{i}}\tilde{\tau}}\end{aligned}$$

The usefulness of these equations is in improving the modelling of surface vibrations of A-type stars, and possibly other type of pulsating stars. They might also assist us in identifying the mode of pulsation.

### An example of my work on observations of an roAp star

In 2015 I published the results of combining photometric data of an roAp star (HD 217522) collected by other observers in 1981, 1989 and by myself and student in 2008 to show that one of the frequency can grow and decay in less than a day. This is confirmed by the spectroscopic data collected on this star and reported on the same article

This was published in Medupe et al (2015)

### International campaigns to search for pulsations in stars

I have also been involved in observing pulsating stars from Sutherland observatory at the same time as other astronomers from different locations around the globe are observing them. This improves the detectability of the frequencies and improves the accuracy of measuring properties of stars.

An example of such an international collaboration is an article by Handler, Shobbrook, Jerzykiewicz, Krisciunas, **Tshenye**, Rodríguez, Costa, Zhou, **Medupe, Phorah,** et al. (2004). In this article, my students and I contributed data that we observed from Sutherland observatory in the Northern Cape. My students name is highlighted in boldface. The data was combined and as a result of precision attained , 22 frequencies were detected. Remember that the more the frequencies you can find in a star, the more the information you can determine for a star in question. The article was was cited 75 times.

### Using Space Telescope (KEPLER) to measure distance to a cluster

Last year, my PhD student, Dr. Oyirwoth Abedigamba , myself and Oyirworth's co-supervisor, Dr. Luis Balona published an article where Kepler data was used to estimate the distance to a star cluster called NGC 6819. This was done by searching for highly evolved stars that were pulsating like the sun in the cluster. The properties of the pulsations were used to estimate the distance of 6564.7 light years for NGC 6819.

The article was published in Abedigamba, Balona & **Medupe (**2016).

## On going and future work

We are continuing with our research on stellar pulsations in our research group. We are building expertise in spectroscopy so that we can make follow-up ground observations of interesting targets that are discovered by the future space missions such as TESS (Transiting Exoplanet Survery Satellite) which will be launched in 2018 by NASA. We continue to improve on our computer models and we are putting together a research-capable telescope called the Mahikeng Astronomical Telescope (MAT). I believe you will be given opportunity to observe through the telescope this evening


The new Mahikeng Astronomical Observatory. Getachew Mekonnen, one of my PhD students, is posing next to it

## History of Astronomy in Africa

It is a common misconception that all of Sub-Saharan African history (with exception of Ethiopia and Sudan) is oral and that therefore Science started in this region of Africa after European colonization when writing was first introduced. This misconception was dispelled when ancient manuscripts, written in the Arabic language, were discovered over 100 years ago from West Africa and in the Sudan. Although much work has been done to translate these ancient books to reveal their content, not much attention was made to search for science literature in them. I started a big project, in collaboration with several scholars from the University of Cape Town, and University of Bamako in Mali in 2005. The project was funded by the Department of Science and Technology and was one of the major projects in the Science bilateral agreements between the governments of Mali and South Africa. I was the project leader.

We translated 35 ancient manuscripts from the Ahmed Baba Library in Timbuktu over three year period. Our team included professional Arabic-to-English translators. We also collaborated with the Institute of History of Islamic Science at Frankfurt, Germany. We discovered the following in the manuscripts we studied:

- Geocentric models of the solar system were studied at schools in the Timbuktu area as far back as the 1700s (and probably earlier, but we have not found books on astronomy older than this)
- Numerical algorithms to calculate things like leap year in their Islamic calendars
- Geometric methods for finding direction to Mecca
- Commentaries of older astronomy books
- Lost data tables (zij) by 10th century Islamic astronomers from North Africa

All of these were reported and published in Medupe (2015) and Medupe et al (2008).

All of my work on this subject of history of Science was put together in a chapter for a book prepared by the Smithsonian Museum of African Art (see Medupe 2012)

Sketches from one of the Timbuktu manuscripts showing diagrams of Mercury in orbit around the earth (left) and the Sun in orbit of the earth (right).

Most of the translated manuscripts were incomplete, with important pages missing. These are pages that reveal the author name and the date on which the manuscript was written. I decided to start a group within our main project to learn how to use techniques from chemistry and physics to determine the physical and chemical characteristics of the manuscripts. This information is useful for manuscript conservation. As a result we started a collaboration with the university of Pretoria (they are experts on Raman Spectroscopy etc). We co-supervised a PhD student from our department here in Mahikeng, now Dr. Kaitano Dzinavatonga ,to work on the samples of the manuscripts. Unfortunately in around 2008, there was a coup de tat in Mali, and a subsequent invasion of Timbuktu by Islamists. This made it hard to access manuscript samples and brought the project to an end. We decided to apply the techniques to historical paper from the South African national Museum instead. We presented the results in Dzinavatonga, Medupe, Ebenso, & Prinsloo, 2013 and Dzinavatonga, Bharuth-Ram & Medupe, (2014)

We received international recognition for  this work on the involvement of Africa in Astronomy:

- In 2007 our Timbuktu projecte was featured in the New Scientist magazine on the 18 August 2007 issue
- In 2011 and 2014 , I was listed amongst 100 Influential Africans by the New African magazine

## Growing the South African Astronomy

Another passion of mine has been to contribute towards growing a diverse astronomy community in South Africa. To this effect, I participated in the National Astrophysics and Space Science Programme (NASSP) which is currently hosted at the Universities of Cape Town and Kwazulu-Natal, and at our Potchefstroom campus. To add to the diversity of the NASSP programme I founded the annual NASSP winter school which is hosted at the grounds of the South African Astronomical Observatory in Cape Town. We bring final year physics and mathematics majors around the country to learn about astronomy. Since inception in 2007 we have reached more than 300 students and have changed the student profile of the NASSP programme significantly. Now, Black South

African make up more than 70 % of NASSP student population, whereas before 2007, it was less than 10%

## Conclusions

Understanding the physics of the Sun and other stars enables us to know where we come from, and the origin of the earth and life on earth. A good knowledge of the Sun also helps us to know for how the earth and the solar system will become habitable as the Sun evolves in the future. Furthermore, in order for us to know about earth-like planets orbiting other stars, we need to know in great deal the light coming from the parent stars of these planets. It is not enough to use standard techniques to study all of these, stellar seismology provides us an opportunity to probe the interior of stars (including the Sun) in unprecedented way with high precision.

My other works have also shown that African history of Science exists, centuries ago African people in West Africa were certainly learning about ancient models of the solar systems and about numerical algorithms for  determining various aspects of their calendar.

## Publication list

### Refereed Journals

1. Handler, G., Mendez, R. H., **Medupe, R**., Costero, R., Birch, P. V., Alvarez, M., Sullivan, D.J., Kurtz, D. W., Herrero, A., Guerrero, M. A., Ciardullo, R., Bregler, M., 1997, "*Variable central stars of young planetary nebulae - I. Photometric multisite observations of IC 418*", Astr. Astrophys., 320, 125 – 135.

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