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1 Proposed Research: Solar and Stellar Seismology

1.1 Introduction

The objective of this project is to build the infrastructure needed for New Mexico to become nationally competitive for funding in the fields of solar and stellar seismology. These are two of the quickest growing research areas of astrophysics because they provide essential information about the structure of the Sun and other stars that has never before been available. No other university-based effort currently exists within the country that targets these areas. Project goals are tied to NASA Strategic Goal 3B ”Understand the Sun and its effect on Earth and the solar system” and its space-weather focused ”Living With a Star” program. The importance of these research areas is reflected in the number of major current and future NASA space missions devoted to them. These include the Solar and Heliospheric Observatory (SOHO), the NASA Solar Dynamics Observatory (SDO), and the Kepler mission. This NASA EPSCoR proposal leverages the scientific talent within the state by forming a partnership among scientists at New Mexico State University (NMSU), the University of New Mexico (UNM), Los Alamos National Laboratory (LANL), the National Solar Observatory (NSO), and the Air Force Research Laboratory Center for Excellence in Space Weather (AFRL). Our NASA center partner is the Goddard Space Flight Center (GSFC). In accord with the EPSCoR goal of creating infrastructure, two new tenure-track faculty members with expertise in the project research areas will be hired at NMSU. Currently, very few university faculty members in New Mexico have expertise in solar and stellar seismology. These new faculty members will provide a nucleus around which state-wide proposals will be developed. This group will also lead state efforts to increase collaborations with our partner institutes.

We have three major research goals:

- Develop the theory and software needed to explore the interior structure of the Sun
- Broaden the use of the solar model to other stars through the analysis of the pulsation spectra of solar-like and more massive stars
- Characterize the stars that have been discovered to have planetary systems and to contrast their likely planetary environment with that of the solar system

A longer-term project goal is to use the New Mexico Computing Applications Center’s supercomputer, Encanto, to develop a near real-time analysis pipeline of the Sun’s sub-structure as one tool for the eventual prediction of severe space weather. Specific NASA EPSCoR objectives addressed by our effort include:

- Developing the research infrastructure of solar and stellar seismology among New Mexico’s universities (NMSU, UNM), national laboratories (LANL, NSO, AFRL) and the New Mexico Spacegrant Program
- Establishing self-sustainability from sources such as the NSF, NASA, and the AFRL
- Strengthening ties between New Mexico and out-of-state NASA centers through increased scientific collaborations
- Contributing to the NASA Education Strategic Coordination Framework by increasing the number of under-represented students in astronomy, by providing faculty and students with research support, and through targeted investments in the state’s academic infrastructure

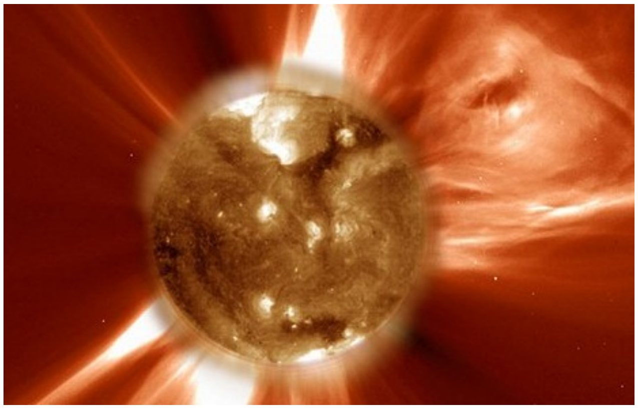

Figure 1: Composite image of the Sun and its extended corona. All of the dynamics and activity of the Sun are due to the magnetic field which is clearly outlined in this image. Helioseismology provides a means of studying the magnetic properties and thus the origin of solar eruptive behavior. Image courtesy of NASA/SOHO.

1.2 Technical background

Just as earthquakes reveal information about our planet's sub-surface structure, seismic waves created in the Sun and other stars allow their internal structure and dynamics to be determined. Seismic studies of stars are of interest to NASA because sub-surface stellar activity triggers highly energetic events that alter the stars' space environment. When applied to the Sun, this field of study is called helioseismology. Asteroseismology, the study of seismic waves in other stars, examines stellar structure from a broader context and permits the environment in which extrasolar planets exist to be modeled and contrasted with that present in our own solar system.

It is well known that highly energetic events that take place on the Sun, such as flares and coronal mass ejections (CMEs), can significantly affect the heliosphere. These types of phenomena are intrinsically connected to the magnetic properties of the Sun, which extend from deep beneath the solar surface out to the corona and beyond (see **Figure 1**). Knowledge about the magnetic field and its interaction with the solar plasma both above and beneath the Sun's surface are essential for the understanding of the root causes of space weather and its possible future prediction.

The driver of the magnetic activity inside the Sun is the solar dynamo, believed to reside about 200 megameters (Mm) beneath the surface at the bottom of the convection zone, and sustained by the interaction of large-scale plasma flows with magnetic fields. The field generated by the dynamo can be highly correlated over enormous spatial scales (at least several solar radii). However, only features above the surface are directly observable, and even in this case, are rather difficult to measure accurately and decipher. Localized magnetic structures observed on and above the surface of the Sun offer some clues about the dynamo and thus about high-energy solar events, but not many. Information about the sub-surface structure and dynamics would reveal how magnetic fields are transported, dissipated, and strengthened in the turbulent convection zone, and also provide critical input into dynamo models.

Helioseismology uses the information encoded in solar seismic waves to make maps of the properties in the interior of the Sun. Local helioseismology, [Gizon and Birch, 2005], a relatively young and more sophisticated extension of the global method, aims to produce three-dimensional images of the flows, sound speed, magnetic fields, temperature, and other quantities throughout the solar interior.

In this project we will predominantly utilize the methodology of time-distance helioseismology [invented by one of our team members, Duvall et al., 1993], which measures and interprets the travel times of acoustic seismic waves between any two points on the solar surface. Time-distance helioseismology typically consists of three main steps. The first step is to use Doppler velocity data (most commonly from NASA satellites) to measure many sets of travel times of the seismic waves that propagate through various regions of the the solar interior. The second step is linear forward modeling, which involves the computation of travel-time sensitivity kernels. These are functions that relate the travel times to particular perturbations in the Sun, and are absolutely necessary for the correct interpretation of seismic data. The last step is to 'invert' the observed travel times using a prescribed inversion procedure along with the computed sensitivity functions to determine the desired sub-surface quantities such as mass flows, sound speed, rotation, temperature, etc. **Figure 2** shows an example of these three steps for the case of determining mass flows beneath the surface with time-distance helioseismology.

Another approach we will employ to analyze solar magnetic activity is based on a heuristic methodology developed at UNM. It forecasts the peak smoothed sunspot numbers (SSNs) and the "rise time" of the solar cycle to maximum after its onset [Ahluwalia, 2000, 2003]. The forecast for solar cycle 23 was very accurate: it predicted peak smoothed SSNs of 131.5 (versus 122 observed) and a rise time of 43 months after the onset (versus 47 months observed). The technique permits the forecast to be made 3 to 4 years in advance of the cycle peak after its onset is confirmed and utilizes NASA OMNI solar wind data. The heliosiesmology research described in this proposal will be used to provide the causal basis for this approach, which ultimately needs to be validated by a successful solar dynamo model.

For asteroseismology, we follow a similar procedure. The main difference is that we do not have spatially-resolved Doppler images. This leads to difficulties in mode identification and requires an additional step that connects their pulsation modes with a single unique age for the star. After mode identification, the methods of global helioseismology can be applied. Sensitivity kernels are first computed. Then frequency differences between a model and the measured frequencies are inverted to determine a one-dimensional profile of a specific quantity in the star, such as rotation or sound speed. These techniques have been used for the Sun for well over a decade.

1.3 Specific science objectives

The scientific goals of this project fall into three broad categories: (1) apply the general time-distance technique sketched above to obtain high-resolution synoptic maps of three-dimensional flows and sound-speed perturbations over an entire solar cycle; (2) analyze the resulting data products and compare them to other solar data and numerical simulations to search for physical connections between solar eruptions and sub-surface conditions; (3) apply a wider variety of inputs to current solar models to test the sensitivity of the model results of these inputs. Longer-term goals are to use this refined solar model to estimate the stellar environment in which other newly discovered solar systems exist, and to incorporate project results into predictive models of space weather. A related long-term goal is to use galactic cosmic ray data from various world-wide detectors and a technique that measures how this spectrum is modulated by the solar wind [Ahluwalia and Fikani, 2007]. A forecasting algorithm for fast interplanetary CMEs will be developed that could give a warning time as much as 20 hours in advance of Earth arrival.

1.3.1 Seismology of the Sun

The main science objectives of the helioseismology component of this EPSCoR program outlined below have been chosen based on their scientific impact, relevance to NASA objectives (see Section 2.1), feasibility, and potential for significant student participation and contribution.

1. **Measure travel times for an entire solar cycle.** This will involve obtaining and analyzing publicly available SOHO high-resolution and full-disk Doppler data, as well as SDO data when it becomes available in the autumn of 2009. Combined, these data comprise more than a solar cycle. Travel times are typically measured for different geometries which give sensitivity to different quantities such as sound speed, flows, etc. [Duvall et al., 1997]. It will be important to build a database of these high-level products for easy retrieval and implementation of later inversion and analysis steps.
2. **Compute relevant sets of travel-time sensitivity kernels for vector flows and sound-speed perturbations for use in inversions of SOHO and SDO data.** Finite-frequency sensitivity kernels in Cartesian geometry will be computed in the first Born approximation [Gizon and Birch, 2002] in a linear theory, which has been shown to be appropriate for the perturbations that we wish to consider [Jackiewicz et al., 2007]. We choose only to compute flow and sound-speed maps for two reasons. The first is because these are the quantities for which there already exists kernel codes in some form [Birch and Gizon, 2007, Birch et al., 2004]. The second is because flows and sound-speed perturbations, while interesting in themselves, are also likely sensitive to magnetic fields.
3. **Produce three-dimensional maps of vector flows and sound speed throughout the upper convection zone for a solar cycle.** Raw maps of the three components of the velocity and sound-speed variations at high resolution in the top 20 Mm of the convection zone will be computed, as well as flow vorticity and divergence. Of particular importance will be the retrieval of the vertical flows, which have been difficult to measure [except, see Jackiewicz et al., 2008]. These products will be made public after appropriate testing. To efficiently handle a solar cycle's worth of data, current codes that perform large-scale inversions [Jackiewicz et al., 2008] will be optimized and parallelized for the New Mexico Supercomputer, Encanto. High-resolution inversions will be attempted with Hinode intensity data for comparison.
4. **Test inversion codes on artificial data produced from realistic numerical simulations.** High-quality simulation data that are publicly available, such as those from Benson et al. [2006], are very useful for validating local helioseismic techniques [Zhao et al., 2007]. Comparing inversion results with a known answer will allow us to assess the depths and spatial and temporal resolutions over which the techniques we will employ are valid in the real Sun.
5. **Analyze and interpret results to learn about the Sun.** One of the first strategies will be to compute various spatial averages of the flow results to reveal the surface meridional circulation profile with depth and its variation over 11 years. How does this compare with dynamo models? How deep beneath the surface can we observe? How is the meridional flow affected by magnetic active regions [Švanda et al., 2008]? What type of sub-surface flow configurations and magnetic topologies (observed from, say, SDO vector magnetograms) are the most common progenitors of flares? Can we observe convective flows that have dragged field lines into twisted and unstable flux loops in the chromosphere as seen by the Transition Region and Coronal Explorer (TRACE) satellite?

As stated above, mapping flow and sound-speed structure in quiet and magnetic regions is an important and necessary first step in determining details about magnetic fields. Once the necessary infrastructure and expertise for this project is in place at NMSU, a future goal will be to perform magnetic field inversions and to automate the entire above procedure to produce real-time maps of the interior of the Sun. Reaching these objectives will have clear impacts for the broader solar

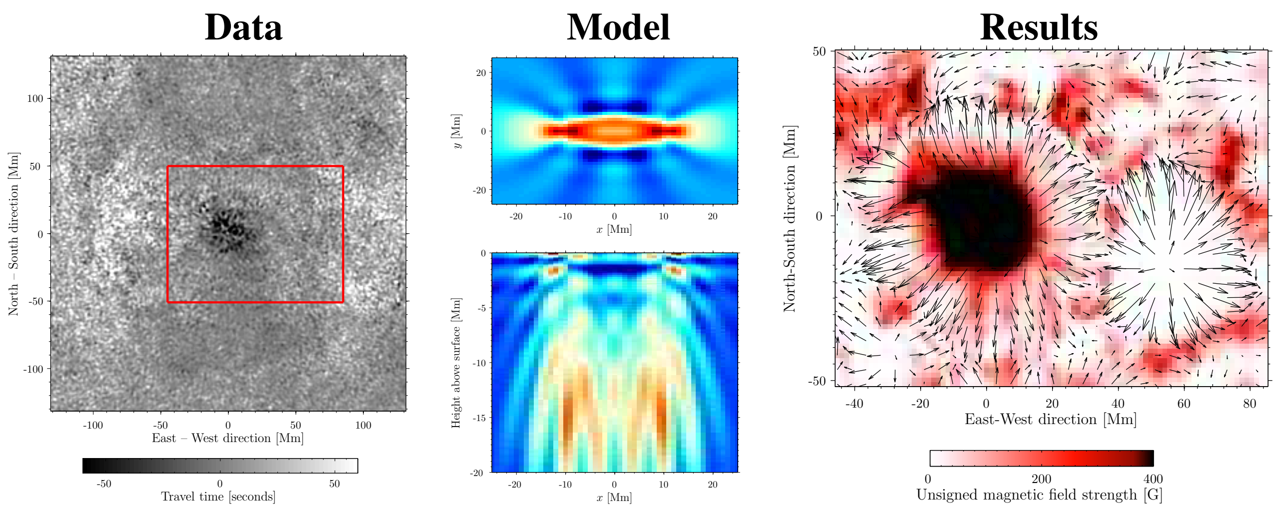

Figure 2: A simple example demonstrating the main components of a time-distance helioseismic analysis. The left panel is a map of measured travel times for acoustic waves near a sunspot (dark patch in middle) propagating between points separated by about 10 Mm as measured from 6 hours of SOHO Doppler data. This data is then mathematically inverted using sensitivity kernels (middle figure) computed from a solar model to produce the flow map seen in the right panel. The arrows denote vector flows at a depth of 1 Mm and the background color scale is a surface magnetogram. This region is outlined in red in the travel-time map. The outflow around the sunspot is called the moat flow, and the large convective cell next to the sunspot is a supergranule. This project will produce similar maps for many depths over an entire solar cycle.

astrophysics community since the data products will be publicly available for further study.

1.3.2 Seismology of solar-like and more massive stars

A fundamental problem faced by helioseismology is that it has largely been applied only to a single object, the present-day Sun. It is difficult to assess the sensitivity of solar model predictions to small structural and composition anomalies since models simultaneously fit several parameters. Currently we are unable to match the Sun's pulsation spectrum to within its observational errors. By modeling other stars where the effects of different physical inputs may have a more extreme impact on the observed frequencies, we hope to shed light on what we may not be doing correctly for the Sun.

There is little debate among astronomers about the need to acquire and analyze additional stellar pulsation spectra. However, two obstacles severely limit the accuracy to which they can be measured. First, the pulsation amplitudes of main-sequence stars are normally quite small. This is caused by partial cancellations between regions of a stellar disc that are oscillating in anti-phase with one another. For the $\ell = 1$, 2, 3, and 4 modes, theoretical models suggest that B-star light curves should have maximal amplitudes of only 49, 23, 5, and 10 mmag respectively [Townsend, 2002]. Second, to measure the periods in these stars multi-site campaigns are required. These are difficult to coordinate and their results are severely degraded if a single site experiences bad weather, has instrument problems, or used different detectors or filters. As a consequence of these issues, ground-based studies generally only detect two or three of the larger-amplitude modes. However, to provide useful insights about a star's structure, at least 4 pulsation modes are needed. If two modes can be accurately measured, a star's mass and age can be determined to an accuracy of about 15% [Thoul et al., 2003]. If three independent modes can be measured the boundaries of a star's convective region and internal rotation profile are provided Dupret et al. [2004]. If four independent modes can be measured the internal rotation rates of a star's convective envelope and core can be contrasted, evidence for chemical stratification is provided, and the chemical composition near pulsational driving zones can be determined [Pamyatnykh et al., 2004].

To measure the pulsation spectra of solar-like and more massive stars, our project will use two large data sets that are being acquired to search for extra-solar planets. These data-bases are from the NASA Kepler satellite and the Sloan Digital Sky Survey III "Multi-object APO Radial Velocity Exo-planet Large-area Survey," or, MARVELS. By itself, Kepler will revolutionize the field of asteroseismology. Proof of this is provided by the pioneering space missions WIRE (Wide-Field Infra-Red Explorer) and MOST (Microvariability and Oscillating Stars). These two micro-satellites were able to detect pulsation amplitudes of 1-10 mmag in a sample of very bright stars [Buzasi, 2002, Bruntt and Southworth, 2007, Matthews et al., 2004, Walker, 2008]. These amplitudes are about a factor of 3 smaller than normally obtained from multi-site campaigns. However, the small size and relatively short observing seasons (several weeks) of these satellites limit their usefulness. Very few pulsating upper main sequence stars are bright enough to have their pulsation spectra measured and the short observing season limits the accuracy to which the waveform parameters can be determined.

The capabilities of Kepler far exceed those of WIRE and MOST and will allow vastly superior pulsation spectra to be obtained. Kepler will use a 0.95m aperture telescope to *continuously* monitor the light from over 100,000 stars for over three years. These stars will be up to 10,000 times fainter than can be observed by WIRE and MOST. The light variations of a typical star having V=12 will be measured to an accuracy of 20 parts per million using an integration time of 6.5 hours. Numerical simulations of the Kepler data show that amplitudes that are about 100 times smaller than can be measured by these two micro-satellites will be detectable. The large size and longer observing period of Kepler represent an advance of a factor of about one-million over that provided by WIRE and MOST. MARVELS provides complementary data to Kepler. It will measure the radial velocity variations of 10,000 stars located over the entire northern hemisphere that have magnitudes between 8 and 12. Started in Fall 2008, it will continue to acquire radial velocity measurements until spring 2014. The velocity error of these measurements is 12 $m\,s^{-1}$ for a star having V=12. This data will be used to make mode assignments and will also permit particularly interesting stars outside of the Kepler region of study to be found.

Our project work will involve research in two main areas that leverage the measurements provided by Kepler and MARVELS and match NASA strategic goals.

1. **Refine the models of helioseismology using Kepler data for pulsating solar-like stars**. Publicly available Kepler and proprietary MARVELS data will be used to compute the pulsation spectra of main-sequence (core hydrogen-burning) gamma-Doradus and delta Scuti stars. The gamma Doradus stars have masses between 1.1 and 1.6 solar masses, surface temperatures appropriate to F-type main sequence stars, and have multiple periods between 0.4 to 3.0 days. They pulsate in the high-order, low-degree non-radial gravity modes that are created by a convective blocking mechanism in an envelop that extends inward to temperatures of several hundred thousand Kelvin.

   The δ-Scuti stars are A-type main sequence pulsators. They pulsate in low-order radial modes and non-radial acoustic modes, although some of their modes have a mixed *p*- and *g*-mode character. Their pulsations arise from a helium ionization region that regulates the radiation flow in the envelop layers where the temperature is 50,000 K. As one moves up the main sequence from the gamma-Doradus and delta-Scuti stars their internal structures are expected to be increasingly different from the Sun. Therefore, their pulsation spectra will allow us to measure the sensitivity of solar models to a progressively wider range of structural inputs. Hundreds of these variable stars will be observed by Kepler. Our study will target about 50 of them that have rich pulsation spectra.

2. **Determine the physical properties and environments of main sequence stars with masses larger than the Sun**. This goal will be accomplished by completing seismology on 30 additional F-B stars in the Kepler and MARVELS target lists. This spectral range includes stars with masses between 1.1 and 17 solar masses. Their masses, luminosities, and surface temperatures change rapidly with spectral type and their ages extend from a few million years to 4.5 billion years. They also possess a variety of pulsation spectra, consisting of multi-periodic radial and non-radial modes that oscillate in low-order p and g modes with periods of 1.5 hours to a few days [Stankov and Handler, 2005]. As Kepler and MARVELS discover new stars with solar systems, they will be added to our sample. Our goals in measuring the pulsation spectra of these stars are (1) to contrast the properties of stars that do and do not have planetary systems, and (2) to use their pulsation spectra to estimate the properties of the space environments in which newly discovered planets exist.

The Period04 software of Lenz and Breger [2005] will be used to analyze our sample of 80 stars. This software package is widely employed in the study of multi-periodic, low-amplitude, pulsating stars. Spectroscopic and multi-color photometric observations will be obtained using the NMSU 1m and 3.5m telescopes at the Apache Pointy Observatory for some of the more interesting stars whose periods have already been determined from the Kepler data. We have guaranteed time on both of these telescopes.

1.4 Work plan and key milestones

Year 1: In the first year we will obtain the solar cycle's worth of Doppler data from SOHO. Our NASA collaborator, Duvall, will assist with this task, as he is a member of the SOHO science team and has vast experience selecting appropriate data sets. SDO data are expected to be available towards the end of the first year. Additional tasks are: (2) begin the measurement of relevant sets of travel times of SOHO data [Duvall, Jackiewicz]; (3) screen Kepler and MARVELS data sets for stars with rich pulsation spectra [McNamara, Guzik]; (4) use the NMSU 1 m and 3.5 m telescopes to collect additional data useful for pulsation mode identifications [McNamara]; (5) determine and download relevant NASA/OMNI data for solar-cycle 24 prediction and analysis [Ahluwalia]; (6) adapting the helioseismology and stellar atmospheres codes to the NM supercomputer [Jackiewicz, Ahluwalia, Bala, Uitenbroek]; (7) advertise for our first tenure-track faculty position and recruit project graduate students [Jackiewicz, McNamara].

Key milestones: (1) the creation of a data base of SOHO, Kepler, and initial SDO Doppler observations; (2) advertise position for the first faculty hire; (3) creation of pipe-line programs for Kepler and MARVELS data sets; (4) recruitment of 2 graduate students.

Year 2: Tasks include (1) computation of sensitivity kernels (flows, sound speed) that match the travel-time geometries measured in year 1 [Jackiewicz, Duvall, Guzik]; (2) first runs of the inversion codes with parallel implementation [Jackiewicz, Guzik]; (3) testing of these codes using realistic simulations [Jackiewicz, Duvall]; (4) computation of power spectra of stellar pulsators and initial mode identifications [McNamara, Guzik]; (5) screening and hiring of first faculty member [all]; (6)

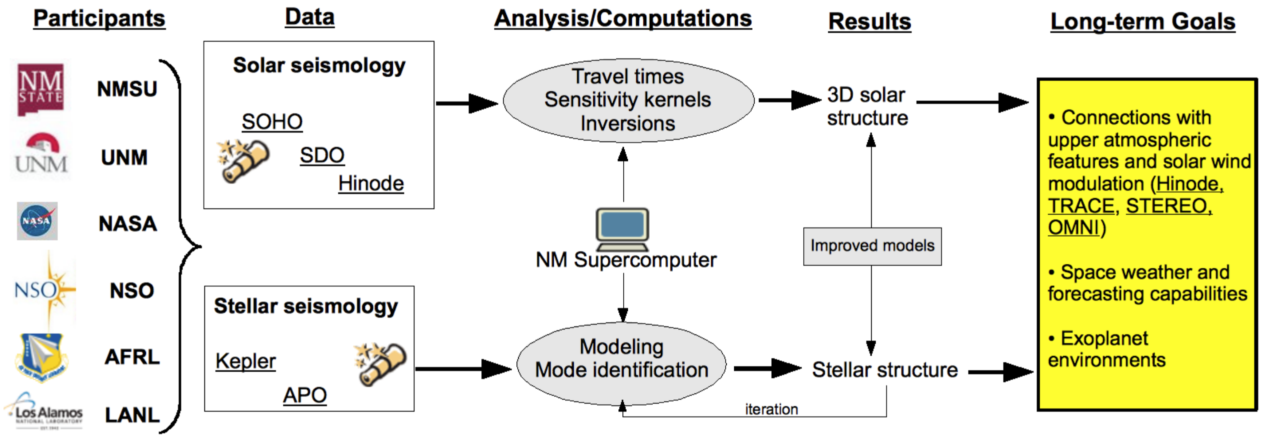

Figure 3: Schematic of the major scientific components of this New Mexico EPSCoR program.

recruitment of graduate students and second NMSU faculty member [Jackiewicz, McNamara].

Key milestones: (1) arrival of first new faculty member; (2) successful test of helioseismology programs on supercomputer; (3) identification of asteroseismology candidates from Kepler and MARVELS data; (4) first demonstration of improved solar model; (5) first partnership external grant application submitted; (6) first project paper submitted; (7) advertise position for the second faculty hire; (8) addition of 2 new graduate students.

Year 3: Third year tasks are (1) implementing parallel inversion pipeline of SOHO Doppler data on supercomputer and making necessary adjustments to handle the travel-time measurements for SDO data [Jackiewicz, Duvall, Guzik]; (2) constructing maps of sound speed and plasma mass flows and subsequent analysis for magnetic signatures at surface and various atmospheric heights [Jackiewicz, Duvall, Guzik, Uitenbroek, Bala, Ahluwalia, Hire 1]; (3) begin analysis of the stellar models for refined parameters [McNamara, Guzik]; (4) incorporation of projects results into new models for solar-cycle forecasting [Jackiewicz, Ahluwalia, Uitenbroek]; (5) analysis of cycle 24 prediction with actual observations (year 3 will be heading towards maximum) [Ahluwalia]; (6) hiring the second faculty member [all]; (7) continue to recruit graduate students for future projects [all].

Key milestones: (1) arrival of 2nd faculty hire; (2) successful demonstration of helioseismology program pipeline on supercomputer; (3) initial characterization of Kepler and MARVELS stellar properties and space environments; (4) submission of two partnership proposals; (5) two papers discussing project result accepted; (6) 2 new graduate students join project; (7) initial work on two masters and/or Ph.D. theses by student participants.

All work above assumes the inclusion of project graduate students throughout. A work-flow diagram of the planned scientific research program is shown in **Figure 3**.

1.5 Scientific impact of this work

This project will make progress on several fronts in solar and stellar seismology. Our plan is to initially implement a time-distance pipeline for analysis of SOHO and SDO Doppler data for flows and sound speed. At the present time, no such pipeline exists. Currently, data from a ground-based network in a pipeline that employs ring-diagram analysis is used to determine sub-surface flows.

While this is a useful tool, ring-diagram analysis does not produce maps of sufficiently high spatial resolution that time-distance helioseismology does, thus limiting its value. The final data products will be of great use to the solar physics community in determining more details of magnetic field, as well as possibly constraining current dynamo models. Having a second group of scientists to analyze the massive amount of expected SDO Doppler data sets is also a step forward for the field. Our asteroseismic results will be among the best ever obtained because of the availability of the Kepler and the MARVELS databases. They will allow the sensitivity of several model inputs used to study the Sun to be determined. For the first time, the structure of several main-sequence stars will be directly measured. The stellar environment of these stars will be characterized and compared to that which exists within our solar system.

1.6 Existing Research

Jackiewicz is currently a Co-I in a NASA project to develop a science center for SDO, with emphasis on using helioseismology to determine the magnetic characteristics of the Sun. The overlap with our EPSCoR program will have obvious benefits in terms of shared expertise between both projects and for training students to meet NASA's future human needs. McNamara is working with AFRL astronomer Balasubramaniam on models to predict the formation of solar active regions and their strength. An NMSU graduate student is also involved with this effort.

2 NASA Alignment and Partnerships

2.1 Relevance to NASA and jurisdiction

Fulfilling the science objectives laid out above will contribute dramatically to some of NASA's most important pursuits in helio- and astrophysics. Of particular relevance is sub-goal 3B of Strategic Goal 3 laid out in NASA's Strategic Plan, which aims to "Understand the Sun and its effects on Earth and the solar system." This covers the domain of Heliophysics, a broad topic connected to the "Living With a Star" program that is thoroughly detailed in NASA's Heliophysics Roadmap document. In the Heliophysics Roadmap, sub-goal 3B has 3 main research focus areas (RFAs) that are labeled F, H, and J, each with its own specific topics and questions. Below, we have chosen the most relevant science questions within these three RFAs and explain their connection with the research described in Section 1.3.

RFA F4: *Understand the creation and variability of magnetic dynamos and how they drive the dynamics of solar, planetary and stellar environments*. Probing the deepest regions of the solar convection zone is one of the main goals of helioseismology. The solar dynamo, believed to reside 200 Mm beneath the surface but also having a near-surface component, is the result of the interaction of plasma flows and magnetic fields and therefore understanding these properties in the Sun is of vital importance. The time-distance helioseismology maps produced by this effort and the advanced forward modeling techniques it uses will provide new insights into the operation of stellar dynamos.

RFA H1: *Understand the causes and subsequent evolution of solar activity that affects Earth's space climate and environment*. Violent solar activity is intimately linked to the sub-surface conditions and emergence of magnetic active regions. Once emerged, near-surface plasma flows advect, sustain, dissipate, and alter large regions of concentrated magnetic fields. Our study of near-surface flows and sound-speed variations at high spatial and time resolutions will shed light on some of these factors. Recent numerical simulations [Cheung et al., 2008] have shown the importance of the effect of convective flows on magnetic flux and its role in determining if this flux becomes a full-scale sunspot or just magnetic network elements.

RFA J2: *Develop the capability to predict the origin and onset of solar activity and disturbances associated with potentially hazardous space weather events*. While the above two RFAs will be addressed by developing methods to make high-quality science products of sub-surface solar conditions over a solar cycle, this RFA requires the physical interpretation of the helioseismic results as well as detailed comparisons with other observations. From analyzing helioseismic inferences and their correlations with known eruptive events in the upper atmosphere, we will be able to better ascertain if predictive capabilities of solar space-weather activity is possible.

NASA's Strategic Goal 3D targets the search for Earth-like planets. The Kepler mission is largely dedicated to this goal. One of the Kepler mission's primary objectives (Goal 6) is to use asteroseismology to "Determine the properties of those stars that harbor planetary systems." The work to be completed by this project is directly tied this goal. This program also supports five current and future NASA space missions besides Kepler:

1. **The NASA Solar Dynamics Observatory (SDO)**: Scheduled to be launched in fall 2009, this satellite is designed to measure solar oscillations using the Helioseismic and Magnetic Imager (HMI) on-board instrument. It is the biggest NASA mission ever undertaken for helioseismology. Our NASA team member is an SDO Co-I.
2. **The Solar and Heliospheric Observatory (SOHO)**: This joint NASA and European Space Agency satellite was launched in 1995 and continues to return data. One of its core missions is to study the Sun's interior with its Michelson Doppler Imager (MDI) instrument.
3. **The Transition Region and Coronal Explorer (TRACE)** provides very high resolution images of the the chromosphere where magnetic events appear to be connected to the photosphere below. Combining the near-surface helioseismic measurements with TRACE data provide insights into the connection between dynamics of active regions above and below the surface.
4. **Hinode (Solar B)** data has recently been used for helioseismology [Kosovichev et al., 2008]. Its primary advantage is its very high spatial resolution – important for these studies.
5. **The Solar Terrestrial Relations Observatory (STEREO)**: This NASA satellite was launched in 2006 and also continues to return data. Its mission is to observe the solar wind and solar mass ejections that are connected to the underlying structures we will directly measure.

2.2 Alignment with jurisdiction's goals and priorities

Within the state of New Mexico there is a strong commitment to the strengthening of science, technology, and economic capabilities that are aligned with NASA's goals and objectives. In 2003, Governor Richardson outlined an economic growth package that included making New Mexico a national leader for advanced technology [Richardson, 2003]. In 2005, the 21st Century Space and Aerospace Cluster was established as one of five interdisciplinary research groups on the NMSU campus. Its aim is to "form a mutually supportive group of educators, researchers, and practitioners to advance 21st century space-related opportunities for research, teaching, and economic development at NMSU and in the region." NMSU has already hired one faculty member during the last year to work in project-related research areas (Co-I Jackiewicz). This project is also closely aligned with the research and economic objectives of the following four major non-university organizations within our jurisdiction:

1. **The AFRL Center for Excellence in Space Weather.** This group is relocating its staff from Hanscom AFB, MA. to Albuquerque NM. It has a strong interest in sub-surface structures in the Sun that lead to the solar mass ejections that are responsible for Earth's space weather. The AFRL is currently supporting two NMSU graduate students who are working in this area. Dr. Balasubramaniam, a senior scientist in the AFRL Center for Excellence in Space Weather, is a project collaborator.
2. **The National Solar Observatory, Sunspot, NM.** Our project objectives match the four long-term research goals of the NSO. These are (1) to understand the mechanisms generating the solar cycle, (2) to understand the coupling between the interior and the surface of the Sun, (3) to to understand the coupling of the surface and envelop of the Sun: transient events, and (4) to explore fundamental plasma and magnetic field processes on the Sun. Dr. Uitenbroek, a staff astronomer at the NSO, is a project collaborator.
3. **Los Alamos National Laboratory.** This national laboratory has a continuing interest in solar and stellar physics. One of the focus areas of the LANL Institute for Geophysics and Planetary Physics is solar dynamics and several of its scientists actively work on problems associated with the prediction of space weather. Helioseismology and asteroseismolgy are the main research interests of our LANL collaborator, Dr. Joyce Guzik.
4. **The New Mexico Computing Applications Center supercomputer.** With the assistance of Intel, New Mexico has recently made a major commitment to high-performance computing. The New Mexico Computing Applications Center (NMCAC) now operates the world's 7th fastest supercomputer in Rio Rancho, NM. The purpose of this facility is to assist New Mexico high-tech business and to support science and technology education in New Mexico. Our research plan utilizes this facility to produce the near real-time three-dimensional maps of the Sun required for the prediction of space weather.

2.3 Partnerships/sustainability

Collaborations will continue to be built with NASA Mission Directorates and/or Centers, UNM, LANL, NSO, and the AFRL using the following mechanisms: (1) Dr. Duvall will assist in strengthening connections among NMSU, UNM and GSFC scientists; (2) additional contacts will be made with the solar physics group at the NASA Marshall Space Flight Center and a colloquium exchange will be put into place for Fall 2009; (3) graduate student summer work will be conducted at GSFC, LANL, NSO, and the AFRL; (4) increased faculty visits will occur with the AFRL Center of Excellence in Space Weather as they relocate to Albuquerque, NM; (5) joint partnership proposals will continue to be developed and submitted. Project work will be sustained through the hiring of the new faculty members and the submission of proposals to the NSF, AFRL, and NASA. LANL also funds a program for New Mexico universities to conduct research projects of mutual interest. Finally the New Mexico Institute for Advanced Studies (headquartered at UNM) provides support for the construction of large interdisciplinary grants and for state-wide collaborative meetings. Our graduate students will secure future employment at NASA Centers through fellowships such as the NASA Postdoctoral Program. We will develop the appropriate expertise within our partnership to position ourselves for future science mission opportunities.

2.4 NASA interactions

Previous and current interactions

Our primary NASA collaborator, Thomas L. Duvall Jr is based at the Goddard Space Flight Center. He is widely known as the inventor of time-distance helioseismology and continues to develop this technique. He is a Co-I of the main helioseismic instrument on board SDO. He and Co-I Jackiewicz have collaborated on several helioseismic studies over the past few years. One of our expected graduate-student participants, Kirk, recently worked at Goddard SFC with solar physicists and developed an important automated procedure for determining polar coronal holes using extreme ultraviolet intensity data from SOHO. Jackiewicz is currently a Co-I for the NASA-funded SDO Science Center project headed by Doug Braun at NWRA CoRA in Boulder. There is overlap between these two projects which should benefit both of them, such as shared access to important numerical simulations of sunspots and state-of-the-art forward and inverse procedures.

Future collaborations

Future collaborative solar research will continue with Duvall, in particular with the SDO data processing pipeline to be developed over the next four years. We will also begin work with Dr. Dean Pesnell at NASA Goddard to improve and extend the automated coronal hole detection method he developed with NMSU graduate student Kirk. This will be another important software analysis tool allowing us to make connections between near-surface and upper-atmosphere solar activity. Dr. Pesnell is the project scientist for the entire SDO mission. The solar physics team at the Marshall Space Flight Center is heavily involved in solar-cycle forecasting methodologies and we will initiate interactions with them, in particular with Dr. David Hathaway.

2.5 Educational program and diversity

Project scientists and students will work with several groups to increase STEM education and interest within the state. Dr. Susan Brown, NMSU Director of STEM Outreach and a recipient of a NASA 2007 Trailbazer Award, will serve as a project advisor. Activities will consist of (1) public school presentations, (2) speakers for the New Mexico Space Grant Consortium and NSO public outreach programs, and (3) monthly public events at NMSU observatories during the academic year.

An additional objective is to increase the number of graduate students earning advanced degrees in areas of interest to NASA. To help our students succeed, we will implement a multi-faceted effort that starts with recruitment, includes retention and progression components, and then assists them in their entry into the professoriate or workforce. Admission into our program will be open to all students, regardless of ethnicity or gender. Since New Mexico State University is an Hispanic Serving Institution, we would be remiss not to make a special effort to recruit superior Hispanic students. Each year two newly-recruited or presently-enrolled graduate students will enter our program. Most students will be recruited by our graduate departments which already have programs in place that use direct mailings, individual contacts, campus visits, and face-to-face meetings at national conferences. We will also target students participating in the NSO Research Experiences for Undergraduates (REU) Program and the Western U.S. Louis Stokes Alliance for Minority Program (LS-AMP). A rigorous selection process will be used to identify highly skilled students. Students will then be provided with (1) a nationally competitive stipend, (2) summer support, and (3) funds for conference travel and publications. Entering students will be assigned a faculty mentor who will meet with them on a regular basis. Student research skills will be developed as they work on the

Table 1: Ph.D. degrees awarded in astronomy by ethnicity in the U.S. Subsequent data were not available.

	2001	2002	2003	2004	2005
Awards (all)	124	106	130	115	120
Awards to whites	104	86	104	93	100
Awards to unknown ethnicity	5	4	14	8	8
Awards to all minorities	15	16	12	14	12
Awards to Hispanics	7	4	3	6	3

project research topics described earlier. Communication skills will be developed through group and conference presentations [Adams, 1992, Antony and Taylor, 2004, Nyquist and Woodford, 2000]. Project scientists from the AFRL, NSO, NASA/GSFC and LANL will engage in person-to-person contacts to help graduating students obtain NASA, academic, or private sector jobs. By the third year of this project, 6 graduate students will be participating and 2 will be conducting project-related research toward their Ph.D. degree.

The impact this program will have on advancing diversity in astronomy is indicated by **Table 1**. Based on the latest NSF statistics it is clear that the representation of Hispanics in astronomy is low. Between 2001 and 2005, 579 Astronomy Ph.D. degrees were awarded to U.S. citizens or permanent residents, but only 4% of these degrees were earned by Hispanics. When this program reaches a mature state, it will produce an average of 1-2 Hispanic Ph.Ds each year. Although this may seem like a small number, it represents a 25-50% increase in the national award rate to Hispanics.

3 Management and Evaluation

3.1 Results of NASA EPSCoR research projects in the past five years

New Mexico joined NASA EPSCoR in 2007. Two projects are active, but neither is complete.

3.2 Personnel

Principal Investigator (PI): Dr. Patricia C. Hynes is the Director of the New Mexico NASA EPSCoR Program and Director of New Mexico Space Grant Consortium.
Science-PI: Dr. Bernard McNamara is a Regents Professor of Astronomy at NMSU. He is an expert in stellar variability and evolution and has extensive experience in observations and time-series analysis.
Co-I Dr. Jason Jackiewicz is an Assistant Professor of Astronomy at NMSU. His main research focus is theoretical forward and inverse modeling applied to local helioseismology and asteroseismology.
Co-I Dr. Tom Duvall Jr. is a SDO Co-I located at the NASA/GSFC. He revolutionized helioseismology in the 1990s with his time-distance technique and he continues to develop the field. Responsible for, among many other discoveries, what is now known as Duvall's Law.
Co-I Dr. Harjit Ahluwalia is a Professor of Physics and Astronomy at UNM. Dr. Ahluwalia has made many contributions to the study of heliospheric physics by studying the modulation of galactic cosmic rays by the solar wind which ultimately gives insight into solar magnetic activity cycles.
Collaborator Dr. K.S. Balasubramaniam (Bala) is a Senior Scientist AFRL Center for Excellence

in Space Weather, Sunspot, NM. He is an expert in modeling the magnetic structure and dynamics of the solar chromosphere and corona.

Collaborator Dr. Han Uitenbroek is an Associate Astronomer at the National Solar Observatory, Sunspot, NM. Dr. Uitenbroek's research studies the fundamental plasma physics processes that take place in the Sun to understand its complex observational characteristics.

Collaborator Dr. Joyce Guzik is a Laboratory Fellow in the LANL Applied Physics Division, Los Alamos, NM. She is an expert in solar and stellar modeling and has made important contributions to stellar pulsation theory.

Six Graduate Students at NMSU and UNM, yet to be identified, will be supported by this effort. All will be U.S. citizens. The New Mexico EPSCoR is committed to supporting diversity and will encourage females, minorities, and person with disabilities to participate in this program.

3.3 Research program management

Science-PI Dr. Bernard McNamara will oversee the technical aspects of the proposed research. He will ensure that the work plan outlined above is followed. He will be the primary person responsible for graduate-student recruitment into the program, their retention, and progression. All administrative questions from NMSU and the partner institutions will be addressed by him. He will supervise at least two project graduate students. He will work closely with our off-campus collaborators to address their individual questions. He will coordinate project activities and will be responsible for the dissemination of project results.

Co-I Dr. Harjit Ahluwalia will work with Dr. McNamara in the recruitment of project graduate students. He will meet with UNM administrators on a regular basis to address their questions and will seek to identify additional faculty at UNM who are interested in participating in the project research areas. He will supervise one graduate student.

Co-I Dr. Jason Jackiewicz will assist Dr. McNamara in maintaining robust communications with the scientific staff at the GSFC, NSO, LANL, and the AFRL. He will oversee daily activities associated with the helioseismology component of the project. He will supervise at least two graduate students. He will also provide assistance in the dissemination of project results. He will also seek faculty from the NMSU and UNM Colleges of Arts and Sciences and Colleges of Engineering who might be interested in participating in project research.

New Mexico EPSCoR Director and the Technical Advisory Committee (TAC) will continue to integrate our research goals with NASA and New Mexico research priorities. The EPSCoR office will be responsible for contract requirements including budgeting and reporting requirements. The New Mexico NASA EPSCoR office will also organize annual meetings for New Mexico faculty to facilitate research collaborations.

3.4 Program evaluation

The objectives for the proposed research, as outlined in Section 1.3, will be achieved through the completion of the tasks provided in the work plan (see Section 1.4 and Figure 3. Metrics that will be used to assess progress in our research include conference presentations, journal publications, and follow-on funding proposals that capitalize on the experience and knowledge gained through this program. The peer-review process used in journal publications and the review of follow-on research funding proposals will serve as an external and objective means of evaluating the success of the research program.

Evaluation is a key consideration not only in the demonstration of effectiveness of the program, but also in continuous improvement and program refinement. New Mexico EPSCoR Director Dr. Patricia Hynes has conducted extensive activities in assessment. She will design and implement the evaluation plan. Evaluation data will be collected from researchers each year as part of their report to NASA EPSCoR. The evaluation will allow us to monitor our progress and document benchmarks toward achievement of program goals and objectives. The evaluation will be both formative and summative. Formative evaluation will include an annual assessment of the proposed research metrics. Formative evaluation results will be brought to the NASA EPSCoR (TAC) for feedback and strategies to increase program success. Annually, we will be looking for faculty and research areas which show promise for additional funding. Summative evaluation will include a comparison of pre-award and post-award data analysis. Research faculty will involve graduate students in their research. This will not only contribute to workforce development in NASA research areas but will encourage student retention. Students receiving $5,000 or more in support will be tracked through first employment using the university registration systems, confirming that students are succeeding with their STEM degrees.

The goals and their metrics for this New Mexico EPSCoR are to:

1. *Improve our knowledge of the internal structure of the Sun and stars.*
   Metric: Number of SDO, Kepler and other data sets analyzed.
   Metric: Number of conference presentations and invited colloquia,
   Metric: Number of papers in preparation, submitted, and accepted.

2. *Contribute to and promote the development of research infrastructure in New Mexico in areas of strategic importance to the NASA mission while leveraging existing capabilities in the state.*
   Metric: Number of participating partner staff, university faculty, and graduate students.
   Metric: Evidence of how EPSCoR activities have furthered jurisdiction priorities.
   Metric: Financial commitment from the jurisdiction, industry, and participating institutions.

3. *Improve the capability of New Mexico to gain support from sources outside the NASA EPSCoR program.*
   Metric: Number of follow-on grant proposals submitted and/or funded.

4. *Develop partnerships between New Mexico institutions and NASA Centers.*
   Metric: Extent to which collaborations with New Mexico agencies, industry, research and academic institutions and with NASA have evolved.

5. *Work in close coordination with the New Mexico Space Grant Consortium (NMSGC) and other educational groups to improve the environment for science, mathematics, engineering, and technology education in New Mexico.*
   Metric: Number of talks and presentations given at NMSGC and non-NMSGC events and the number of people in attendance.
   Metric: Number and gender/ethnicity of students participating in the program research. We will track student persistence through to degree completion and beyond graduation.
   Metric: Number of professional teacher development activities conducted and the number of teachers served.

3.5 Tracking of program progress

Progress in this program and the potential for achieving self-sufficiency beyond the award period of this grant will be assessed using the metrics discussed above. If the goals of the proposed research and of the New Mexico EPSCoR program are achieved, then the likelihood for securing future funding for this research is high. The potential for the proposed research area to continue to grow in importance in future aerospace fields will be assessed by the evaluation and monitoring of NASA's planning documents, funded proposals, and calls for new research efforts throughout the award period. Trends indicating the importance of helioseismology, heliophysics, and stellar pulsation will be noted and we will respond accordingly in our efforts to secure follow-on funding toward the end of the award period.

3.6 Continuity

During the past 5 years, the NMSGC has provided scholarships to 32 NMSU astronomy students. Since the goals of this project are closely aligned with those of NASA, we expect this level of support to continue. This project will also facilitate the involvement of our graduate students in future employment and internship opportunities at GSFC and MSFC. After working with these scientists, they will be well-positioned to apply for the NASA Graduate Student Researchers Program and ultimately the NASA Postdoctoral Program. We will continue to work with the NMSGC to connect project participants to new NASA education projects.

Two new young researchers will be added to the faculty at NMSU. They will be provided with the research time and graduate student assistants required to become rapidly engaged in research. Four sources of future funding will be pursued by the end of the NASA EPSCoR award period to sustain this program:

1. **NASA**: Within NASA there are several research programs that are closely aligned to this project's research goals. These include the following programs: Solar and Heliospheric Physics, Heliophysics Guest Investigators, Living With a Star, Kepler, and Astronomy and Physics Research and Analysis.
2. **The National Science Foundation**: Within the NSF the Astronomy and Astrophysics Research Grant program supports efforts in our research fields. Given the interdisciplinary, multi-institutional nature of our project, the NSF Partnerships in Astronomy and Astrophysics Research and Education (PAARE), and Integrative Graduate Education and Research Traineeship Program (IGERT) are also possible funding sources. Like NASA, the NSF also funds graduate fellowships and post-doctoral research.
3. **The Air Force Research Lab (AFRL)**: The AFRL is interested in building educational and research ties with New Mexico universities because of their relocation to New Mexico and their continuing need for trained personnel in space weather. Currently they support two NMSU graduate students in projected related areas. The AFRL continuously seeks applications for funding in solar activity research.
4. **The Los Alamos National Laboratory (LANL)**: LANL provides two sources of funding. The first is through their Institute of Geophysics and Planetary Physics and the second is through a program specifically targeting the development of collaborative research activities with NM universities. LANL is interested in space weather, stellar pulsation, and solar physics: all areas that are aligned with this project.

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