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G-133: A SOFT X-RAY SOLAR TELESCOPE

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ABSTRACT

The GOLDHELOX Project, NASA payload number G-133, is a robotic soft x-ray solar telescope designed and built by an organization of undergraduate students. The telescope is designed to observe the sun at a wavelength of 171-181 Å. Since we require observations free from atmospheric interference, the telescope will be launched in a NASA Get-Away-Special (GAS) canister with a Motorized Door Assembly (MDA). In this paper we primarily discuss the most important elements of the telescope itself. We also elaborate on some of the technical difficulties associated with doing good science in space on a small budget (about $100,000) and mention ways in which controlling the instrument environment has reduced the complexity of the system and thus saved us money.

I. INTRODUCTION

The "GOLDHELOX" Project ("GOLD" for the color of the sun and "HELOX" for HELiocentric Observations in X-rays) is a near-normal incidence soft x-ray robotic telescope being built by an undergraduate student research organization. The organization is composed of a cabinet, a science team, and three systems teams (optical, electrical, and mechanical), all staffed by undergraduate students. The project has been financed by two NASA grants, the BYU colleges of Physical & Mathematical Sciences and Engineering Technology, and by a number of private contributors. The completed telescope, after installation in a NASA GAS canister with an MDA, will fly in the bay of a space shuttle for the purpose of photographing the sun. The telescope will take a sequence of 700 photographs of the solar x-ray emissions in a wavelength band of 171-181 Å. The target date for completion of the Goldhelox payload is the fall of 1992. We are scheduled to fly our telescope on the STS-57 Atlantis mission scheduled for launch in April 1993[1]. The telescope will produce full-disk images of the sun with a spatial resolution of 2-2.5 arc seconds, and a time resolution of less than 0.1 seconds. The photographs will be taken at a number of different levels of image intensification in order to investigate a wide range of intensities across the solar disk. Once obtained, the photographs will be analyzed by graduate students and professors at Brigham Young University and published.

Our bandpass was chosen to sample Fe IX, Fe X, and Fe XI emission lines. The solar plasma that emits those wavelengths corresponds to temperatures upwards of 0.8 million degrees Centigrade. These temperatures only occur in the region of the corona near the upper transition region and are characteristic of a number of solar features such as active regions, flares, micro flares, and x-ray bright spots. Our observations are designed to address the following questions:

1. What is the structure of solar plumes, and what is the source of the solar wind?
2. What mechanism causes the initial energy release in a solar flare[2]?
3. What is the relationship between the occurrence of coronal mass ejections, the occurrence of microflares, and the high resolution upper transition region magnetic structures[3]?
4. How does the transition region between the corona and chromosphere respond to the impulse phase of flares[4]?

The purpose of this paper is to introduce the project from an instrumental and operational point of view. In section 2 we present an overview of the telescope design. Section 3 addresses the principles of restricting the instrument environment to reduce cost and complexity. We discuss the methods this project has utilized to produce a complex experimental device capable of making a contribution to solar physics on a low budget (about $100,000).

II. THE GOLDHELOX TELESCOPE

It is convenient, for the purpose of discussion, to separate our telescope into three main elements: 1) the optical system which collects, filters, amplifies, images, and records light from the sun, 2) the mechanical structure which supports and protects the optical and electronic elements of the system as well as providing the telescope with several motional freedoms, and 3) the electrical system which monitors and controls all functions of the instrument through the use of two partially redundant computers. This section describes each of these elements.

The Optical System

The Goldhelox telescope is a two mirror optical system consisting of a concave parabolic primary mirror and a convex hyperbolic secondary mirror in a cassegrain configuration. Solar x-rays are first collected by the primary mirror, then reflected towards the secondary mirror which in turn sends them through the one inch hole in the center of the primary mirror to the detector assembly. The focal plane is 2.25" behind the primary mirror.

X-ray reflecting mirrors are more complicated than the common visible-light mirrors. When dealing with visible, infrared, or even near-ultraviolet light, it is common to find that a mirror reflects as much as 90% of the incident light intensity. In the X-ray wavelengths, however, most incident light is absorbed or transmitted by a mirror rather than reflected. To improve the x-ray reflection efficiency, we use a mirror material with an internal layer structure radiation can be reflected off the multiple surfaces in the material and then recombined. The layer thickness is spaced such that x-rays reflecting off of the individual surfaces combine constructively, resulting in a stronger reflection at certain angles. It is the thickness of the layers in the mirror material that determines these angles. These X-ray mirrors are generally one of two types: 1) grazing-incidence or 2) multilayer coated.

Grazing-incidence telescopes use the natural layer structure of crystalline materials to obtain multiple reflections. The lattice spacing in most crystals is, unfortunately, such that constructive reflection occurs only for incident light that is nearly parallel to the mirror surface. Hence the name grazing-incidence telescopes. Because effective reflection occurs only at grazing angles, these telescopes typically have to be long and bulky to effectively focus light into any sort of image.

Because of the size constraints on our telescope, we have instead elected to use multilayer mirrors, a more recent development in x-ray optics. They are made by alternately applying thin coatings of two different materials onto a smooth substrate. Our mirrors use 100 layers, each consisting of 50 Å of Silicon above 50 Å of Molybdenum . Because the layers are man made, the layer thicknesses can be chosen to produce good reflections at almost any angle desired, even normal incidence. Thus multilayer mirrors have made it possible to manipulate x-rays in almost the same way that visible light is manipulated.

Our multilayer mirrors are made to have 40% reflectivity at near normal incidence for soft x-rays in our bandpass (171Å to 181Å). They act as partial filters because light outside this range is not effectively reflected through the telescope. To properly filter out all the radiation outside our bandwidth, we have also added two additional radiation filters (1000 Å thick sheets of aluminum).

In spite of the fact that multilayer mirrors significantly improve reflectivity, intensity losses in the telescope remain a problem. The total efficiency of the optical system is only about 2%, furthermore only a very small fraction of the energy emitted from the sun falls in the wavelength range in question[5]. This makes it difficult for an optical instrument as small as ours must be (3" in diameter) to gather enough light for an adequate film exposure. Therefore, to amplify the image, we use a microchannel plate (MCP) image intensification device. The maximum factor by which the MCP can boost the incident image intensity is about 5000 times (the actual image intensification factor will vary according to a pre-programmed sequence which will be executed by the telescope's computer). When the MCP is bombarded by x-rays, the x-rays stimulate cascades of electrons that are accelerated toward a phosphor screen which emits in a visible wavelength. A visible light image is then conveyed from the phosphor to the

35 mm film via a glass cylinder composed of parallel interfused fiber optic cables, each cable having an internal diameter of 10 microns.

The Mechanical System

The telescope itself (composed of the optical elements just described and the mounts that hold them in alignment) is mounted between two vertical support walls 7 inches apart. The walls extend up from a rotating plate (see figure 1). This plate rotates upon the barrel-shaped sealed container containing the telescope control computers and other electrical components. The sealed container is airtight to maintain a normal gaseous atmosphere inside. The telescope also rotates about a pivot axis extending between it's support walls. The pivot is located near both the center of the GAS canister and the center of the telescope.

The telescope has two motional freedoms: first, rotation in the azimuthal plane (the plane of the rotating table), and second, rotation in the plane of declination (the plane normal to the upper pivot axis.). The rotating table moves atop a 10 inch diameter turntable gear (see figure 2). The teeth around the outer edge of the turntable gear are matched to a smaller gear on the shaft of a stepper motor. This stepper motor which drives the azimuthal telescope motion is mounted on top of the rotating table, with it's shaft reaching down through the table.

Rotation in the plane of declination is also driven by a stepper motor, but in this case a worm gear assembly is used. The motor and worm are attached to one of the support walls, and the worm gear itself is attached to the telescope body. The telescope body can assume any declination between vertical and 43° off vertical and can rotate through the entire 360° in the azimuthal plane.

Within the telescope itself, the mirrors and mirror mounts are attached to the telescope housing. The MCP flange, which is mounted inside of the camera, and acts as an image window. The camera is attached to the telescope housing, and the housing is fastened to the telescope pivot. The telescope has an alignment tolerance between 1/10,000 and 1/1,000 inches. Because this tolerance is difficult to meet with ordinary materials, we have chosen to use a composite with very low coefficients of thermal expansion for the walls of the housing and other parts of the mirror mounts. This composite is light, strong, resistant to vibration, and space environment compatible.

The Electrical System

The electrical system centers around two partially redundant computers. The first computer receives input from the tracking system and controls the positioning of the telescope. It also warms up the MCP prior to use and performs picture taking operations. The second computer is the ultimate instrument controller. It puts the instrument into a low power hibernation mode when the sun in not in view and controls the distribution of power to every other element of the electrical system. It monitors and controls the temperature of the environmentally sensitive elements of the system, and takes over control of the photographic functions of the MCP in the event that the first computer fails.

Four power supplies are required to operate the entire instrument. One power supply provides the various DC voltages between 5 and 20 Volts needed by the many electrical system circuit elements. Another high current supply drives the three stepper motors used for telescope positioning and film advancing. The last two, called switching power supplies, provide the 1000 Volt lead and the 5000 Volt lead required to operate the MCP. Picture taking is actually done by switching the MCP on and off using exposure times which will vary according to a pre-programmed sequence between .1 and .01 seconds.

Another important feature of the electrical system is the tracking circuitry. The sun-tracking system provides continuous information to the telescope control computer regarding the location or absence of the sun in the telescope's field of view. There are three tracking sensors. The first we call the "daylight" sensor, which we place near the top of the telescope allowing it to indicate to the control computers whether or not the sun is in the instrument field of view. If the sun is discovered to be in the field of view, the telescope is rotated through the azimuthal plane until the second or "coarse" sensor indicates that the sun is within 8° of the plane of declination of the telescope. When the coarse sensor tests positive, the controllers check the third or "fine" sensor. The fine sensor has a 2¥2 array of photodiodes. When a light source illuminates the array, this fine sensor circuitry determines the amount of light incident on each photodiode and

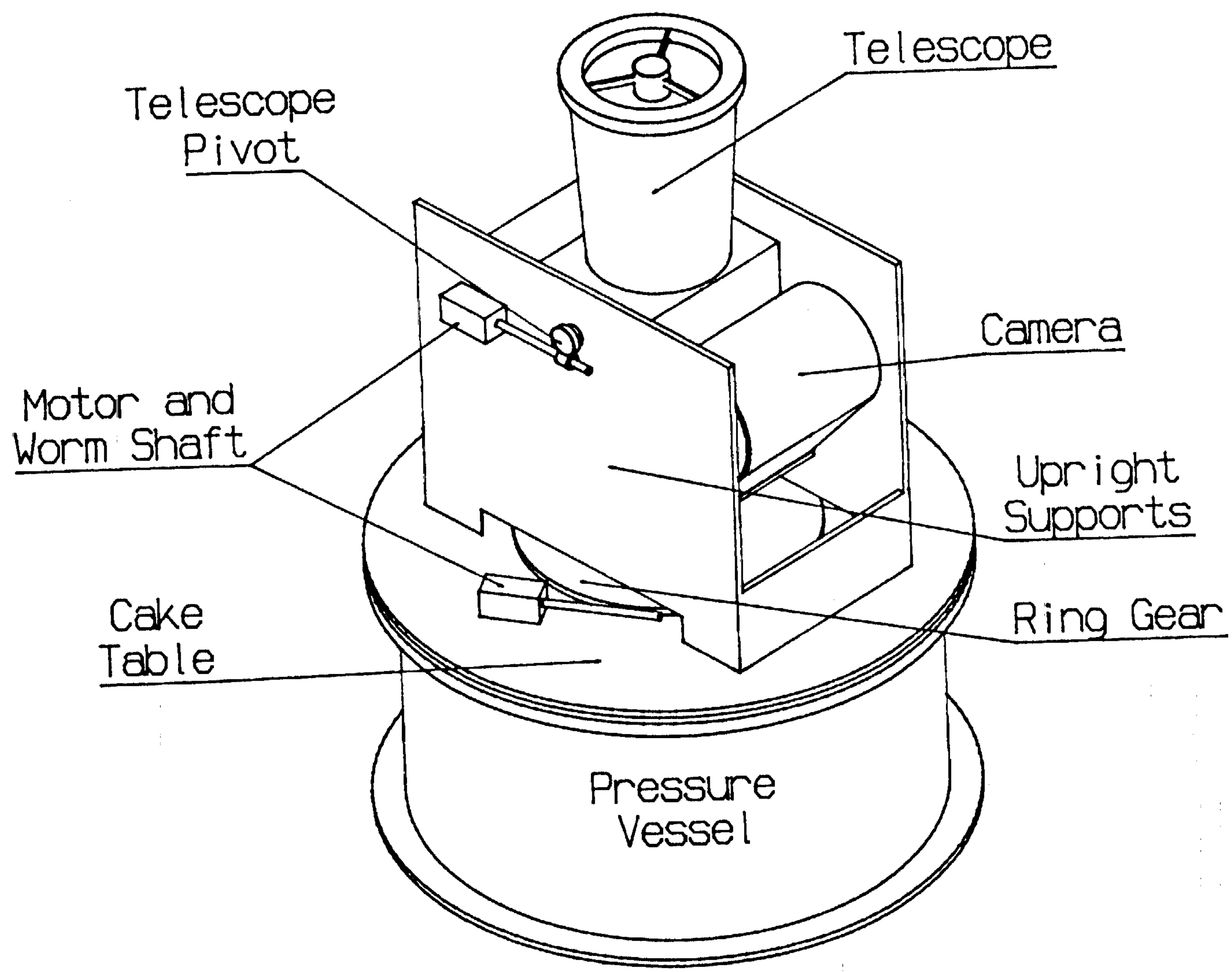

FIGURE 1: An external view of the entire GOLDHELOX soft x-ray robotic telescope, with key mechanical components indicated. Dimensions are not to scale.

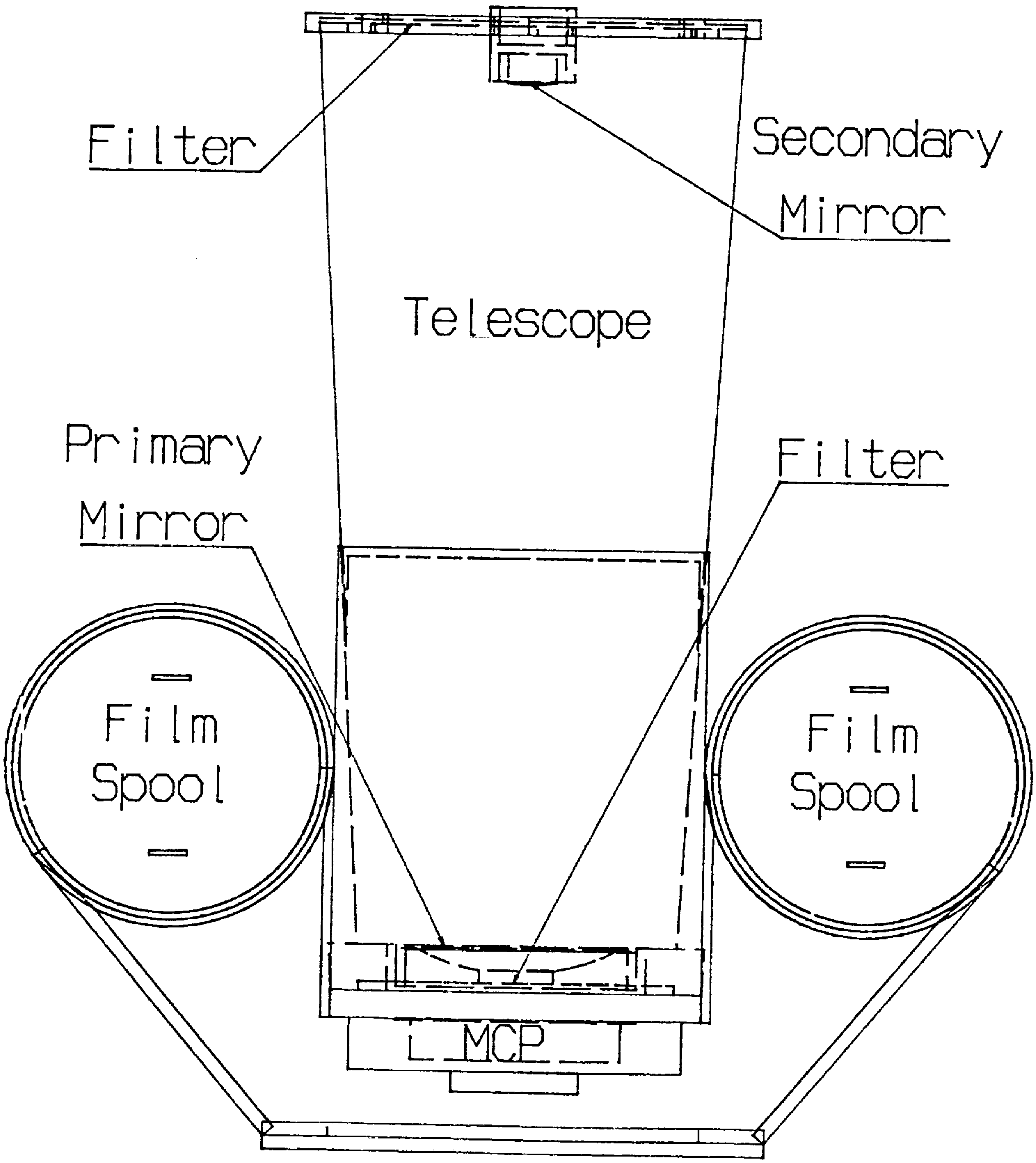

FIGURE 2: A cross-sectional side view of the GOLDHELOX telescope, with all optical components indicated. Dimensions are not to scale.

returns two voltages (an 'x' and a 'y' coordinate) indicating how far off the sun is from the optical axis of the telescope. The computer accordingly repositions the telescope and again checks the fine sensor. This procedure is repeated until the telescope is within 1/10 of a degree of being aimed directly at the sun.

III. REDUCING COST AND COMPLEXITY BY RESTRICTING INSTRUMENT ENVIRONMENT

There are many instances during the design stage of a space bound instrument in which cost and complexity can be significantly reduced by restricting the instrument's environment. In much the same way as a decision to have a barbecue in the back yard as opposed to a picnic in the park eliminates the need to pack half the kitchen into the trunk of the car, making a few restrictions on the operating environment of an instrument can eliminate the need for many of the auxiliary functions, fail-safes, and precautions that burden the instrument without increasing the value of the data that it obtains.

When we first began to plan the design of the Goldhelox telescope, we learned that much could be done on a small budget if we didn't try to do everything. For example we looked for several months for an extremely sensitive, high resolution camera film that was vacuum compatible (won't become brittle) over a wide range of temperatures, and obtained cost estimates from a few companies to custom process or even develop the film we required at a price of around $1000/yard, with a minimum purchase requirement of $10,000. Such an expenditure was well out of our reach. Then a team member suggested that we just use regular 35 mm film and simply not let the film be exposed to the space environment. He pointed out that this would be possible if our MCP were mounted in a standard vacuum flange and sealed onto the front of the camera with the atmosphere inside. Although the inside of the camera is now less accessible, this simple design modification saved thousands of dollars and greatly simplified our film processing requirements.

The most difficult technical problems that our project has had to deal with has been 1) temperature control and 2) tracking our target, the sun. It is difficult to find affordable optical and electronic components that won't malfunction or even fail completely at the hot and cold temperature extremes. Tracking sensors for example, can be purchased from stock, unless you want them guaranteed at temperatures ranging from -100°C to 100°C (a temperature range which is standard in a space environment). The tracking system also had three problems of it's own, in addition to the temperature problem. First, the instrument must be able to determine when the sun is in view and when it isn't, properly discriminating against all other sources including the brightly illuminated earth which frequently fills the entire telescope field of view. Second, the telescope has no advance information regarding when the sun will be in view. And third, high resolution pictures require that the telescope maintain it's orientation with respect to the sun without deviating more than two seconds of arc during picture taking. This is a challenge even for state of the art tracking systems when the many different types of orbital motion assumed by the shuttle on a typical mission are all considered.

NASA provided a way for the complexity of the electrical system to be greatly reduced through the availability of standard options, which not only solved our tracking problem but also eliminated the extreme temperatures previously anticipated, thus permitting us to purchase less expensive electrical components. By allowing for as many as six actions to be performed for a GAS payload by the shuttle crew during flight. This way the crew will be activating our instrument only during a few specific time intervals in which the shuttle bay is directly facing the sun. Hence the telescope will only have to cope will minor amounts of rotation, eliminating the need for complicated tracking subroutines. Also the MDA on our canister can now be closed during nearly all of the mission, protecting our instrument from the more extreme temperatures common to open lid flights, and saving us tens of thousands of dollars of additional expenditure on military specification electrical components. This illustrates the general principle (which many with more experience than we have already know) that for cost-effective space research, regularly consider the possibilities of trading instrument freedom for more simplicity.

SUMMARY

The GOLDHELOX Project is an unusual effort in that it is both managed and staffed by undergraduate students. The project, if successful, will prove that a real contribution to space research is possible in a university setting, and on a low budget. The current trend in space exploration is towards 100% reliability, requiring researchers to purchase only the highest quality components, and at great cost. If the GOLDHELOX telescope satisfies the hopes and wishes of it's makers, it will not only help us gain a greater understanding of the sun, but will set a precedence for others who are interested in space research, but believe it to be out of their financial reach.

ACKNOWLEDGMENT

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