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Status report for the Keck/Solar Two Gamma Ray Observatory

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Abstract: There is strong interest in the rapidly growing gamma-ray astrophysics community to make sensitive observations in the unexplored 20-300 GeV energy range which is largely inaccessible to present ground-based telescopes. The abandoned solar power farms utilizing a central receiver surrounded by a large field of steerable heliostats (mirrors) provide a way to make observations below 300 GeV at a relatively small cost as shown by CELESTE, GRAAL and STACEE. The Solar Two Power Plant in Barstow, California, has more than 2,000 steerable mirrors and is an order of magnitude larger than any solar farm in the world. As such, it has the potential to be the most sensitive ground-based gamma-ray detector in the 20-300 GeV energy region.

Using a grant from the W.M Keck Foundation, we have built a camera, which collects light from 32 heliostats at the Solar Two site. We are using this assembly to observe the Crab Nebula, the standard candle of gamma ray astronomy, and concurrently expanding the telescope to include 64 heliostats. The celestial gamma rays can be discriminated from the more abundant hadronic Cosmic Ray background by sampling the photon density in the Cherenkov wavefront and using the well known signatures of gamma rays and hadronic showers. The status of the Keck Solar Two Gamma Ray Observatory is presented and the test results for the first 32heliostat telescope are discussed.

1 Introduction

The field of High Energy (HE) gamma-ray astronomy expanded dramatically during the last decade largely due to the success of two instruments: the EGRET telescope onboard the Compton Gamma Ray Observatory (CGRO) satellite (100 MeV-20 GeV). These exciting results were complemented by four ground based Very High Energy (VHE) gamma ray telescopes; CANGAROO, CAT, HEGRA and Whipple observatories with unprecedented confirmed observations of five sources including the Crab Nebula. However, the energy range between 20 and 300GeV have been left unobserved until recently. Now there are observations of the Crab Nebula extending into this energy range (< 100 GeV)

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Fig. 1. Solar Two Pilot Power Plant in Barstow California in operation during 1997-8.

by CELESTE (Smith et al, 1999; de Naurois et al., 2001) and STACEE (Chantell, et al., 1998; Oser, et al., 2001), the two ground based telescopes using small heliostat fields with a central tower in the Pyrenees, France, and the Albuquerque, USA, respectively. Unfortunately, these observatories, including GRAAL (Arqueros et al., 1999) are not yet able to cover the entire unobserved energy range, 20 to 300 GeV.

The new Keck Solar Two Gamma Ray Observatory (Fig.1) under development at Barstow, USA, is the largest solar power plant in the world with over 2,000 heliostats (the next largest solar facility has ≈200 heliostats) and, therefore, it has about an order of magnitute larger light collection power. The light collection power of Solar Two has been demonstrated in Fig.2. Thus, Solar Two has the potential to be the most sensitive gamma-ray telescope of its kind and, most likely, the only candidate to entirely open this energy window for observation with high sensitivity. It will be an excellent observatory to complement the future observatories such as the space borne GLAST, and ground based HESS, MAGIC and VERITAS. The solar power plant detectors have two advantages over the ground based Atmospheric Cherenkov Telescope (ACT) arrays and satellite borne detectors: 1. They can be ready for observation sooner and, more importantly, 2. They can be built for 1/10th the cost of ACT arrays and 1/100th the cost of satellite borne detectors.

The solar power plant concept was first proposed in 1982 (Danaher, 1982) but only recently built due to difficulties overcoming the large background caused by overlapping

Fig. 2. The airglow caused by the converging beams of sunlight reflected off of the heliostats demonstrates the light gathering power of the Solar Two pilot power plant facility.

heliostat images. Tumer (1990 and 1991) solved this background problem by proposing a secondary optic (camera) system on the central receiver to separate the individual heliostat images.

2 The Keck Solar Two Gamma-Ray Observatory

The present 32 heliostat Keck Solar Two Gamma Ray Observatory detects gamma rays by sampling the Cherenkov light generated as gamma rays interact with the atmosphere.

Fig. 3. Photograph of the first 32 heliostat telescope, showing the 3 x 5 m^2 secondary mirror with the PMT camera at the focal plane.

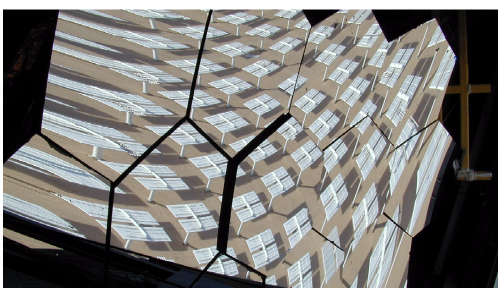

Fig. 4. Photograph of the 3 x 5 m^2 secondary mirror with the reflections of the heliostats in the field .

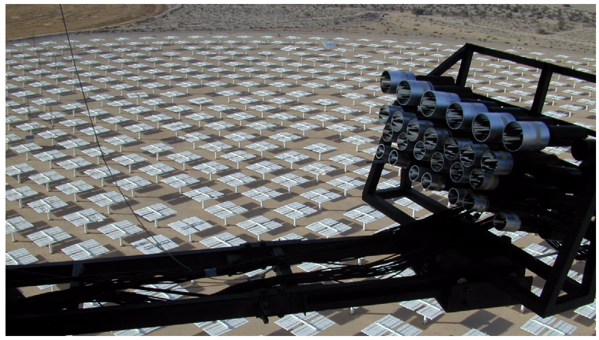

Fig. 5. Photograph of the first 32 heliostat telescope showing the camera under construction with Winston cones infront of each PMT. Camera is placed at the focal plain of the secondary mirror. The Solar Two helisotat field can be seen in the background.

Heliostats reflect the Cherenkov light to a secondary mirror on the central receiver which then focuses the light onto a PMT camera where the light from each heliostat is collected by a single PMT (Fig. 3). Figures 4 and 5 show the images of the heliostats on the secondary mirror and the PMT camera positioned at the focal plane of the secondary mirror. Each Winston cone/PMT module is carefuly placed to envelop the image of a selected heliostat (Fig. 6) so that it can detect the most of the Cherenkov light that heliostat reflects into the secondary mirror.

To sample the full extent of the Cherenkov light pool on the ground, it is necessary to view a heliostat field that is larger than 300 meters in diameter. While the current 32 Heliostat/PMT detector at Solar Two views heliostats distributed over a 150 x 175 m^2 area, during the Fall of this year we will finish another secondary mirror system bringing the total to 64 heliostats covering a 350 x 200 m^2 area (Fig. 6). Over the next 3 years, if we can obtain sufficient funds, we plan to expand to a three secondary, 96 PMT detector, which will view a 350 x 325 m^2 area (the 64 heliostats in Fig. 6 plus extra 32 closer to the central tower at North-East Direction).

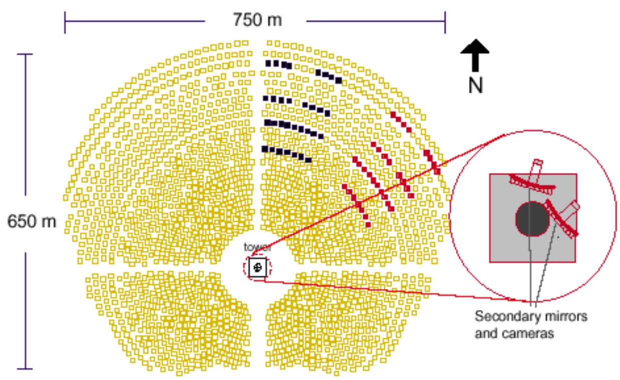

Fig. 6. Schematic aerial view of the Keck Solar Two Gamma Ray Observatory heliostat field and tower. The 32 heliostats that will be viewed by the first secondary are the filled, blue squares in the upper left of the northeast quadrant. The filled, red squares on the east side of the northeast quadrant are the 32 heliostats to be viewed by the second secondary mirror. We plan to build a third secondary to view an additional 32 heliostats at North-East closer to the tower.

The construction of the first 32 Heliostat/PMT telescope has been completed (Figs. 3-5), and the detector is being calibrated (Mohanty, 2001; and Tripathi, 2001). The filled blue squares in Fig. 6 show the heliostats which are viewed. Since each heliostat is >40 m^2, the effective heliostat mirror area is >1,300m^2). Construction of the next secondary will begin soon to bring the number of heliostats viewed to 64 (>2,600 m^2 of total Cherenkov light collection area).

The second 32 Heliostat Telescope will be built similar to the first telescope. We are designing a slightly improved version of the hatch opening in the tower (Fig. 3) to make it easier to open before observations and close after the work is completed.

The design of the hatch is completed and the manufacturing of the hatch door, secondary mirror mount and the PMT camera structure is started. Work on a new electronics system with 1 GHz Flash ADCs is being developed at UCR. Also a new 1 GHz trigger system capable of real-time temporal pattern recognition is being designed at UCD. The manufacturing and installation of the second 32 Heliostat Telescope is expected to be completed sometime during Fall of 2001. After the second telescope is completed the testing of 64 Heliostat Telescope will start. The testing will be complemented with the observation of the Crab Nebula when ever possible.

3 Discrimination of Cosmic Ray Background

The discrimination of Cosmic Ray background is an important factor to enhance signal-to-noise ratio. For gamma-ray showers, the wavefront is roughly spherical with a radius of curvature of about 10 km with a thickness of a few ns. The image of the gamma ray initiated atmospheric Cherenkov shower front extents to about 300 m diameter at ground level. Given the large available Cherenkov light colection area, solar power farms can provide significant improvements in signal-to-noise ratio for HE gamma ray detection, thereby lowering the operating energy threshold. This technique has both vast light collection power and also the ability of imaging the same optical signature on ground, as imaged by the highly successful telescopes such as CANGAROO, CAT, HEGRA and Whipple. However, the number of heliostats used at present is low, 32-64, and produces a large grain image of the Cherenkov light pool on the ground. This is compensated by the enlarged image of the light pool on ground, compared to the imaging telescopes as listed above. Therefore, the well known smooth image of gamma ray originated showers and patchy features of a Cosmic Ray shower can be clearly discerned. Also Solar Two is the only telescope, either existing or planned, that has an array of mirrors large enough to contain the entire Cherenkov light pool. The second 32 Helisotat Telescope will increase the instrumented heliostat array diameter to about 300 m. Increasing in the future the number heliostats used at Solar Two to 96, 128 or 256 will increase the sensitivity, the quality of the Cherenkov light pool image and also improve Cosmic Ray discrimination.

4 Test Results of the First 32 Heliostat Telescope

The present 32 Heliostat Telescope has been tested during 2001. The Keck Solar Two Gamma Ray Observatory is described first below and then the test results are presented.

The Solar Two heliostats are individually steerable in both elevation and azimuth, and thus the telescope functions as a directed instrument that can be used to track a celestial source. They are controlled by a doubly-redundant system running on a mixed network of OpenVMS and Linux computers. The pointing of the heliostats is checked periodically by measuring and correcting for biases observed in tracking the sun and individual stars. The cumulative tracking and pointing error for each individual heliostat is estimated to be about 0.1°. The spherical secondary mirror, located inside the central tower, is made of 13 hexagonal facets, each with a diameter of 1 m and radius of curvature of about 6 m. The composite secondary has an aperture of about 5 m x 3 m and reduces the 3 m diameter Cherenkov light spot-size from the heliostats to much smaller diameters that match entrance apertures of light-collecting parabolic Winston cones which further focus the photons onto PMTs. Thus, each PMT views a single heliostat: the field-of-view in the sky being about 1° across, defined by the sharp angular cutoff imposed by the Winston cones. The secondary mirror facets were individually aligned using a laser-pointer fixed to the center of the selected heliostat and double-checked by imaging the full moon onto the camera.

The readout and trigger system used at Solar Two is largely based on the STACEE-32 design (Chantell, 1998). The trigger electronics are intended to solve two main problems: First, the uniformity and extent of the gamma-ray Cherenkov light pool makes it advantageous to utilize narrow coincidence intervals and impose predetermined majority logic within the various PMTs. The signal from each PMT is discriminated, and digital logic is used to demand a coincidence of 5 out of 8 PMTs in a cluster, and a further coincidence of 3 out of 4 clusters. The coincidence trigger also affords significant rejection of less uniform, background cosmic-ray showers. Second, relative delays need to be added in between channels in order to compensate for the different times of light from different heliostats. Because this depends on the position of the source in the sky, the delays need to be changed as the source moves across the sky. This is achieved by a combination of programmable delays at two levels, and by low-loss analog delay cables. The delays can be adjusted in steps of 1 ns to a maximum of 1 μs, allowing observation of sources to a zenith angle of 45°. Two data-recording paths are available. The first are the time-to-digital converters (TDCs) that record the time of arrival of the discriminated pulse on each channel. The second, more sophisticated, path is the 1GSamples/s digitizers that are continuously sampling a separate analog output on each channel. When a trigger occurs, acquisition is stopped and the data corresponding to a 1μs slice of time on each side of the trigger are read out. The available memory segmentation, and the high-speed cPCI bus allows accurate characterization of the Cherenkov pulse on each channel with small deadtime even at high trigger rates. The digitizers also provide an absolute time-stamp with the data so that both amplitude and time information are preserved in the data stream.

The typical gamma-ray signal is small compared to the dominant cosmic-ray showers. Thus, data are taken in an ON/OFF mode, where a putative gamma ray source is tracked for a given amount of time and then the heliostats are slewed back to track an OFF-source region corresponding to the same range of elevation and azimuth angles. The simplest mode of analysis is to subtract the two TDC distributions, revealing any excess from the source. We are in the process of developing a more detailed technique that uses a semi-analytical model for the development of a gamma-ray shower (Hillas 1985; and Bohec et al., 1998) to predict temporal as well as amplitude distributions for the Cherenkov light at each heliostat as a function of various parameters such as the energy of the primary particle, the impact point of the shower core, etc. This makes full use of the detailed information from the digitizers, and is expected to provide significantly better background rejection. When the 64 Helisotat Telescope is fully functional we also plan to discriminate background using the differences in the Cherenkov light pool images on the ground.

We started observations in late 2000, focussing initially on testing and calibration. We also took data on the Crab Nebula and MRK-421. Although, we have recorded some ON-source data on the Crab Nebula and MRK-421, the experiment was still in debugging phase and few hours of data on these sources did not allow any definitive conclusions. Hence, we present here the preliminary test and calibration results obtained.

Fig. 7 shows the TDC distributions for triggered events from 8 representative channels out of the 32. All channels show similar, sharply-peaked distributions with a typical FWHM of 2-5 ns, which demonstrates that most of these events do indeed come from Cosmic Ray air-showers. Fig. 8 shows number of PMTs involved in each event in a MRK-421 run. It shows both the actual measured number of PMTs and after software reimposed trigger criteria. PMT distributions are shown before and after for both the actual measurement and the software reimposition of the trigger criteria. As expected from the trigger criteria there are no triggers involving 15 PMTs in the software decided results. Software reimposinion of the trigger conditions, which is 5 out 8 helisotats for each group and 3 out of 4 groups imposed by the hardware. However, in real measurements a small number of trigers happen with number of PMTs less then the hardware tigger criteria.

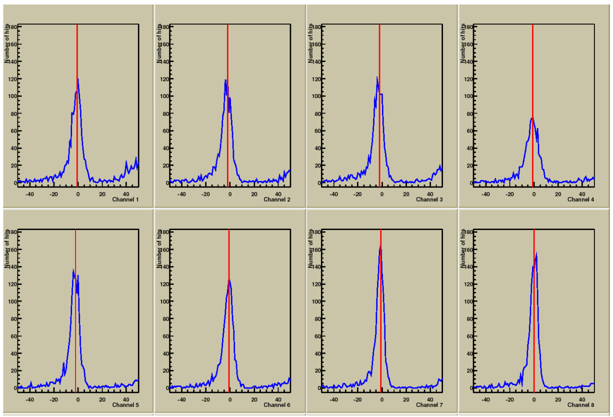

Fig. 7. Histogram of the time difference between the measured and predicted TDC values of each event for a test run. The Cherenkov events are predicted in the data analysis software since the source position and the photon path through the telescope are accurately known. The clean peaks seen verify that we are detecting real atmospheric Cherenkov events. The timing variation width is approximately 2 to 5 ns FWHM.

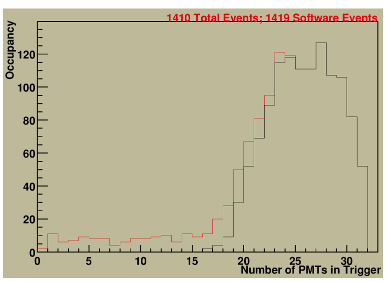

Fig. 8. Histogram of number of PMTs involved in each event in a MRK-421 run. It shows both the actual measured number of PMTs and after software reimposed trigger criteria. PMT distributions are shown before and after for both the actual measurement and the software reimposition of the trigger criteria. As expected from the trigger criteria there are no triggers involving 15 PMTs in the software decided results.

5 Future Development

We are in the process of upgrading the electronics so as to maintain a bandwidth of about a GHz through the entire chain. Amplifiers with a 1 GHz bandwidth have already been built and installed. In order to further lower the energy threshold, we plan to employ a new trigger system capable of real-time temporal pattern recognition, also at a 1 GHz bandwidth. The optical throughput is also expected to increase due to improvements in the camera box and Winston cones. We are planning to complete the scheduled expansion to 64 heliostats by early 2002. The heliostats for the second set of 32 channels have been selected, and the design of the second port in the tower has been completed. The secondary mirror facets are already on-site and construction of the port, secondary mirror and camera is expected to begin shortly. When this expansion is completed, the Keck Solar Two observatory will be the largest gamma-ray astronomy facility and will have the unique capability of containing the gamma-ray Cherenkov light pool in one direction. Longer term plans include increasing the number of heliostats upto about 256 and coverring the full Cherenkov light pool with excellent high resolution imaging.

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