Converting PETAL, the 25m solar collector, into an astronomical research facility

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ABSTRACT

We propose to modify the solar collector PETAL (Photon Energy Transformation & Astrophysics Laboratory) for astronomy. The mirror is a segmented parabolic dish collector, which has a relatively poor imaging quality. The conversion can be done by either of two principal methods: (1) phasing the surface of the collector itself or significant sections thereof; (2) transforming the structure into an optical interferometer by mounting small telescopes around its rim, and using fibre optics to combine the light at a common focus.

Keywords: Solar collectors, Large telescopes, Astronomical interferometers

1. INTRODUCTION

The largest telescopes on earth are presently the twin 10m Keck telescopes in Hawaii, with excellent image quality. They will probably continue to hold this title for a while. Even larger telescopes exist, such as the Texas Hobby-Eberly telescope with an 11m primary mirror, but they are limited in imaging quality and pointing ability. On the other hand, the largest optical interferometers span tens to hundreds of meters, but suffer from having a limited number of collecting stations and limited collecting area. Hence they can only observe a limited number of objects. The trend is now to combine small and large aperture, such as the VLT telescopes and the outrigger 1m telescopes in Chile, the similar Keck interferometer in Hawaii, and the Large Binocular Telescope in Arizona.

The need for more collecting area and for better resolution are two main directions of observational astronomy today, as they always were. Ground based telescopes have a large advantage over space observatories in their sheer size, enabling them to probe deeper into space, and see finer and finer details. The addition of adaptive optics systems actually allows these details to be realized. The high optical quality available with the Keck telescopes resulted in many scientific breakthroughs: indeed the number of significant papers from that facility does not seem to cease. In the future, the 30m California Extremely Large Telescope and the 50-100m European telescopes will lead the scene. The benefits of larger telescopes and interferometers were discussed recently at a number of meetings\textsuperscript{1-3} including this meeting.

PETAL (Photon Energy Transformation & Astrophysics Laboratory) is a 25m diameter segmented parabolic dish recently constructed at Sede Boqer, on the Negev plateau (elevation 475 m) for the main purpose of performing solar energy research, but also with a view to other possible research uses (Figure 1). This solar collector, which has presently a relatively poor imaging quality (by astronomical standards), can be modified for astronomy. This can be achieved by phasing the surface of the collector itself, or its image by active and adaptive optics; low quality segments will be blocked. Another alternative is using the structure as a basis for an optical interferometer, attaching many small telescopes onto it, and combining the light with fibre optics at a common focus. Either option would place a device the size of PETAL in the forefront of observational astronomy. Recent advances in adaptive optics and in fibre technology make this modification viable. With upgraded optical and mechanical assemblies, a fully diffraction-limited PETAL telescope might be able to see galaxies fainter by three magnitudes than the Keck, and details finer by 2.5.

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2. SOME ASTRONOMICAL TARGETS

With excellent light collection and resolution in a converted PETAL, the number of objects to observe is very large. Subjects that come to mind are very early objects, active galactic nuclei, accretion discs, galactic centres, planetary systems in our galaxy and more. We expand on two subjects that are active now in Israel, out of the many possible.

One of the most exciting recent discoveries with the Hubble Space Telescope (HST) is that possibly all bulge galaxies have a massive black hole at their core. This discovery has fundamental importance for the understanding of the formation and evolution of active galaxies, and the relation of these processes to galaxy formation. The existence of massive black holes is inferred by probing the host galaxy stellar velocity dispersion close to the black hole. The steep rise in velocity dispersion with decreasing distance from the core, and the absence of associated rise in the amount of starlight, indicates a rise in the mass to light ratio. The stellar dynamics can be explained by a central point-like "massive dark object", most likely a massive black hole. The limiting factor in these studies is the spatial resolution of the optical spectroscopy. The HST allows spectroscopy down to 0.1", which is sufficient for identifying massive black holes only for a limited number of nearby galaxies. Increasing this angular resolution by an order of magnitude (and the collected light by up to two orders) will allow two important advancements: (1) Extend the detection distance by an order of magnitude, and thus the number of galaxies by three orders of magnitude. (2) In nearby galaxies we will be able to probe the stellar velocity dispersion to radii closer to the center by an order of magnitude, and thus we will be able to detect black holes with an order of magnitude lower masses. In addition, we will be able to map much more accurately the stellar kinematics close to the core, which could yield important clues on the black holes formation mechanism.

A telescope with a large collecting area and with reasonable, even if not excellent, angular resolution would be an ideal instrument to perform areal spectroscopy of galaxies. Disk galaxies closer than $z \approx 0.05$ are resolved into objects tens of arcseconds or larger across, except for the compact ones. It is important to obtain spectroscopic information from all regions of their disks both for reasons of testing the element abundances as well as deriving the dynamics of these disks. Large telescopes are now equipped with suitable instruments for such tasks. The methods employ either an image dissector, which directs light from different regions of the image to different heights on a spectrometer entrance slit, or with a coherent bundle of fibers where each fiber extracts the light from a different part of the image. The instrument end of the fiber bundle is arranged into a flat one-fiber-wide ribbon that feeds the spectrometer.

Another exciting and fast developing area is the detection of extrasolar planets. One arcsecond corresponds to a planet at 1AU at a distance of 1pc. Thus, increasing the angular resolution to 0.04" at 5 micrometers (where the contrast is higher: $10^6$ compared to $10^{10}$ in the visible) will allow direct imaging of planets at 1AU around stars up to ~25pc away, and thus survey hundreds of stars for planets. A way to reduce the light from the central star is by coronography and by nulling interferometry, where the central star is interfered destructively whereas the planet is not. However, direct imaging or even nulling interferometry require little scattering in the telescope and a very tight image, which we cannot guarantee to achieve. Other methods, such as Doppler techniques and direct photometry of eclipses, are now being applied on smaller telescopes, and will gain from the larger collecting area.

The less ambitious option of a tracking, circular interferometric array will have the same resolution but will be limited to brighter objects of less complex structure. Stellar interferometry, in the visible and infra-red, is now a well established astronomical tool. Such devices have realized their potential in measuring the size of cepheids, and the structure of pulsating atmospheres and symbiotic stars, to name a few results. We think we could have a unique device in an all-fibre interferometer placed on a tracking dish, whose base-lines are comparable to medium interferometers such as IOTA, MARK III and GI2T, but contain many more telescopes.
3. CONVERSION OF PETAL FOR ASTRONOMY

The solar collector we propose to use is an existing research tool designed to concentrate sunlight as a source of energy. It is located at the Jacob Blaustein Institute for Desert Research, on the Sede Boqer campus of Ben-Gurion University. It is currently operational and in its final check-out stage, so some of its operational details are still unknown.

While the location of the large telescopes on tall, dry mountains is much preferable to the Israeli desert plateau location, the advantage of a convenient site is clear. This convenience has to be weighed against poorer turbulence, higher dust and water content, and more light pollution.

PETAL’s paraboloid collecting surface is made of 216 triangular panels, each 2.1m along the edge (Figure 2). Because of (as yet) non-optimized initial alignment, probable thermal variations and gravitational sagging, the surface has a relatively poor collecting efficiency. Half the power falls within 22cm whereas it would need to be a micrometer. Moreover, the pointing now is accurate only to 1mrad and the tracking to 2mrad (and improving). According to current measurements, all the surface errors are expected to be on the 2mm rms level relative to a perfect paraboloid, with maximum errors of 20mm. The estimated lateral scale of these errors is 100mm. Furthermore, PETAL’s mirrors are reflective on their rear surface, as they have to be exposed to the elements, and the reflecting surface is chemically deposited silver.

Two main options exist for using this collector for astronomy. It is possible to use a large fraction of PETAL’s 400m² of surface and achieve high sensitivity at all wavelengths that reach the detector. The other possibility is to make use of the 25m diameter of the dish as a mechanical frame for optical long base line interferometry.

How can the large surface of the dish be used? The simple answer is to use active and adaptive optics. Active optics is for correction of slow and recurring errors in the structure of the dish, which depend on its temperature and elevation. Adaptive optics is for smaller, faster errors that might arise because of vibrations of the dish and because of atmospheric turbulence. The placement of these corrections can be at the surface itself or at its image: mechanical or electro-mechanical pistons that push and pull on the primary surface, on a secondary mirror, or on a deformable mirror placed at the image of the primary. In addition, the most offending parts of the surface, those with the largest deviations, can be
blocked in this secondary image of the surface. This allows high-resolution measurements even without adaptive optics, as was demonstrated on the Keck.13

The fact that the solar collector was not explicitly planned to be used for astronomical purposes raises some unusual problems. First, the collector does not have any shielding. Because of constant dust deposits on the surface, it is covered at the rate of 0.1% per day, and has to be cleaned periodically. On the other hand, as the reflecting surface is protected by being deposited on the back side of transparent panels, the cleaning process consists of a simple washing procedure. Daily solar heating of the ground near the low-lying dish may expose it to large turbulence of unknown temporal and spatial scales. Winds may cause shaking of the structure. In addition, the quality of guiding and tracking leaves a lot to be desired as regards astronomical purposes. For example, the telescope is not balanced since its supports are not directly beneath its centre of mass (Figure 3). Some of these problems may be overcome by installing covers on the mirrors, by increasing the local ground albedo and by improving the quality of the mechanical drives. In addition, an active secondary or focal plane assembly (such as at the Hobby-Eberly telescope, liquid mirror telescopes and the Large Binocular telescope) may be designed to cover some of these problems.

The optical quality of the existing dish is aimed more towards light collection rather than proper imaging. The focal distance is relatively short (f/D ~ 0.5), and there is no possibility for a central opening in the reflector surface. An optical folding or prime focus design might take care of these problems. The mirrors are on the back surface of the glass, which adds another weak reflection to the main reflection of the beams towards the focus. It might be possible to add a front reflective surface, at least for the perimeter panels of the telescope, and block the rest of the light. These perimeter panels have a rather large area (approximately 100m²) and provide the best spatial resolution. The wave length reflectivity of PETAL will be thus extended to the infra-red; this regime is favoured anyway for adaptive optics because of its higher tolerance. At 3 micrometers and longer the problem of the hot spaces between the mirrors will have to be solved. Another problem to be solved is the formation of dew as soon as the dish cools in the evening. This problem was solved in the nearby Wise Observatory by thermal insulation of the dome, but a different approach might have to be considered here in the absence of a dome.

Figure 2: Side view of PETAL.
Using only the perimeter is similar to the other option raised above, namely, to use the collector dish for its structural rigidity and the large diameter that it provides. In the past we proposed to use old radio dishes to serve as a base for long base line optical astronomy: Mount around the boundary of the dish a number of optical telescopes, and use fibre optics to combine their light. Adaptive optics holds the phase of all of the reflected wave front to within a fraction of a wave length. It might be easier to control the perpendicular location of the telescopes to that accuracy. While the collection area will be much diminished, the servo problem becomes more manageable. By now, many parts of this scheme have been proved experimentally – fibre length control, visible and infra-red stellar interferometry, beam combination in surface (wave guide) devices.

Another important, non-scientific aspect of this conversion is the ratio of performance to cost of an astronomical observatory. First the MMT and now the Keck have shown us that using lower quality, segmented mirrors and correcting them by active and adaptive optics can reduce significantly the price of astronomical observation. Even a partial fulfillment of the proposed PETAL conversion will be a step in the direction we now see in the automobile and airplane industry, from fully mechanical systems to the “fly by wire” approach. According to this new paradigm, a complex control mechanism allows much better performance from large, complicated systems. Even if the full conversion of PETAL would cost many times its current price of approximately $700,000, it will be much less than any existing large observatory of much less collecting area or diameter.

Other efforts are under way, or have been proposed, at both PETAL and elsewhere in the world to upgrade solar collectors and towers for high-energy astrophysics. These experiments measure Čerenkov radiation produced in atmospheric showers that are the by-product of high-energy radiation and particles hitting earth. We wish to achieve diffraction-limited astronomical imaging, but we also intend to learn from the relevant experience accumulated in these experiments.

We are also looking for possible collaborations, which might contribute to the experience and enhancement of future stages of the project, i.e. the actual modification of PETAL for astronomical observations. In addition, the field of electro-optics is well developed in Israel, and local industry could both gain from and support such a project.

4. FEASIBILITY STUDY

There are a number of issues to be tackled in deciding to operate an astronomical observatory, such as the fit of the site to observation. Then there are the issues of using the existing PETAL facility for high quality imaging, in the two directions mentioned above – imaging and interferometry.

Fortunately enough, the Wise Observatory lies only 30km south of the PETAL site and 150m above it, so many of its astronomical characteristics are already known. There should not be a large difference in the number of clear nights or water content. However, some surveys should be done within the time period allocated for this research, such as an accumulation of data by the local weather station. These will be correlated with astronomy-related parameters such as humidity, cloud cover, local radiation balance, wind direction and speed. In addition, a measurement of the quality of seeing should be taken, such as with a differential image movement measurement (DIMM), which provides details about the vertical distribution of turbulence. This is done by measuring and comparing simultaneously two nearby traces of the same star, or of two nearby stars.

The next measurement also refers to both modes of operation – imaging and interferometry. We shall have to find the tracking and the optical quality of PETAL. This will be done by both mechanical and optical means. We shall attach vibration sensors to the PETAL dish to see its behaviour during tracking and under wind conditions. This will provide us with knowledge regarding the smoothness of movement, and its response to energy impulses. In parallel, a small telescope will be attached to the rim of PETAL, at various locations around it. As in the measurements of the stellar trace we will record the temporal trace of the image. This should not exceed the error measured on the ground, but one should not be too optimistic. If the error will be larger, we will analyse the data and find out what are its sources: thermal and gravitational sag, tracking vibrations, or errors due to winds. These correspondences will have to be supported by direct measurements of the same: movements, temperature and wind conditions.
A very difficult measurement will be that of the optical quality of the telescope. The method now envisioned is some sort of a Hartmann wave front sensor; covering the whole area of the dish, with an array of holes in the cover. Behind the focus, set up a large white screen, on which these holes will be imaged by means of a large lens or mirror. This screen will be imaged again onto a large format camera, which will take the time traces of these holes (or by a smaller camera, a section at a time). Similarly, Hartmann, shearing interferometry or curvature wave front sensing can yield the optical quality of each panel, albeit with reduced accuracy of the latter because of the weakness of the boundary conditions. This would require covering of the other panels during the measurement.

Before modifying PETAL, we shall start with such a feasibility study of the project. The quality of the existing dish and structure will have to be measured and studied. After this, the different options will have to be weighed: full aperture correction, partial correction, or interferometry mode. The astronomical and technical benefits and drawbacks of each of these approaches will have to be compared. Future stages will follow the results of this feasibility study.

5. REFERENCES