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Ultraviolet astronomy with small space telescopes

N. Brosch[1], **Ana I. Goméz De Castro**[2], **J. Murthy**[3], **E.N. Ribak**[4], **E. Behar**[4] **and V. Balabanov**[5]

[1] *Tel Aviv University, Tel Aviv, Israel (E-mail: noah@wise.tau.ac.il)*
[2] *Complutense University, Madrid, Spain*
[3] *Indian Institute of Astrophysics, Bangalore, India*
[4] *Dept of Physics, Technion, Haifa, Israel*
[5] *Asher Space Research Institute, Technion, Haifa, Israel*

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Abstract. After describing the present situation with astronomy in the ultraviolet (UV), reviewing a few past and proposed future missions, we present options to develop space missions that have been realized for modest costs. In this context, we bring together a few aspects of different missions and projects that, when combined, might result in a low-cost mission for imaging or low-resolution spectroscopy in the UV.

Key words: cubesat – ultraviolet – space astronomy

1. Five decades of UV astronomy

The UV astronomy started with rocket flights that offered only short observation windows. The first major advance was the survey mission by the TD-1 satellite from 1972 to 1974 that surveyed the entire sky to the relatively bright limiting magnitude of 8.8 (Boksenberg et al., 1974). The TD-1 catalog comprised 31,215 sources measured in a single spectral band centered on 275 nm. TD-1 also had modest spectroscopic capabilities since it used also a spectrometer for the 130-255 nm region for the brighter sources. The magnitude system used is "monochromatic" such that

$$m_\lambda = \, -2.5\, log(f_\lambda) - 21.175 \tag{1}$$

where f_λ is the source flux density in erg sec^{-1} cm^{-2} $\mathring{A}^{-1}$ at wavelength λ.

Following the first all-sky survey by TD-1 the next all-sky survey was started only in 2003 by the GALEX satellite (Martin et al., 2005). GALEX, a NASA "small" (Small Explorer=SMEX) mission, operated until 2012 albeit with gradually degrading efficiency. Originally it observed in two spectral bands, the Near UV (NUV: 175-280 nanometers) and the Far UV (FUV: 135-174 nanometers). The FUV detector failed in May 2009 due to overcurrent and for the rest of the mission observations were performed only with the NUV channel. The GALEX all-sky catalog contains some 65.3 million sources to a depth of about 19.9/20.8 FUV/NUV (ABmag). The AB magnitudes are defined as

$$m_{AB} = \; - 2.5\, log(f_\nu) - 48.600 \tag{2}$$

The GALEX mission's life-cycle cost to NASA was $150.6 million. A sizable fraction of the sky was not surveyed at all in order to avoid bright stars that could have damaged the detectors and the emphasis was put on high galactic latitude regions to sample as many galaxies as possible.

The long time span between TD-1 and GALEX, and the lack of other survey missions since the decommissioning of GALEX, make it difficult to retain retaining scientists and engineers specialized in UV technology and data analysis. The lack of a clear vision of future missions has become a major problem to retain the know-how in the field. This paper point to a possible solution using the now-popular CubeSat philosophy and offers a preliminary concept for such a missions.

2. Small missions

In this section we describe a few small missions, selecting specifically a few in the UV, and pointing out that significant science can be done with small optics and small payloads.

2.1. Chang'e-3

The China National Space Administration (CNSA) landed on the Moon, on 14 December 2013, a mission called Chang'e-3. The spacecraft carried a small rover and a number of experiments operating on the lander. One of these, called Lunar-based Ultraviolet Telescope(LUT), was a 15-cm telescope equipped with a orientable folding mirror to allow observations of sources in different sky directions. The operation of LUT during the first 18 months was described by Wang et al. (2015).

LUT observes in a band rather close to the NUV one of GALEX ($\sim$ 270 nm) and can access sources in the vicinity of the lunar north pole in a sky area of $\sim$3000 square degrees. By observing UV standards, Wang et al. determined the zero point of the LUT photometry, showed the relative photometric stability, and determined that lunar dust does not affect observations as much as previously feared.

2.2. PISAT-UV

The PES Institute of Technology in Bangalore, India developed a series of small satellites of which the first was launched in a sun-synchronous orbit on 26 September 2016. PISAT-1 is a three-axis stabilized structure with dimensions 25$\times$25$\times$18 cm with a mass of 5.3 kg carrying an Earth-imaging payload (a

CMOS color camera in the visible for Earth observation experimentation manufactured by GomSpace). Each image covers an area of $\sim 165 \times 125$ km with a spatial resolution of 80-m.

One of the future PISATs will carry an ultraviolet imaging telescope that will be designed and built at the Indian Institute of Astrophysics (IIA) in Bangalore. The preliminary design is for a 10.8-cm aperture Ritchey-Chrétien design that will operate in the NUV to cover a three-degree wide field of view with an angular resolution of 13-arcsec (Ambily et al., 2016). The detector will be a solar-blind multi-channel plate optically coupled to a CMOS detector read out with a FPGA based data acquisition board. The entire telescope masses 2.5-kg and requires less than 5W to operate (excluding thermal control). Its development costed less than 10,000 US$.

2.3. Duchifat, Hoopooe, and ABIR

The Herzliya Space Laboratory (HSL) is a student satellite building laboratory. The students are upper high-school, primarily from the Herzlyia (Israel) area, but now HSL is collaborating with same-level students from at least five other high schools, including some from Arab, Druse and Bedouin communities. In building space hardware, the students enjoy specialist help from experienced mentors from the space industry. Duchifat was the first Israeli satellite to be designed, built and constructed by high school students, and the first Israeli CubeSat (see below on CubeSats). It is a 1U CubeSat used for store-and-forward communications, it was launched on July 19, 2014, and is still operating at the time of writing this paper.

The second nano-satellite built by HSL is Hoopooe, a 2U nano-sat with a 2-kg mass that was launched as part of the QB50 multi-satellite mission to study upper atmosphere electricity. HSL is now building its third nano-sat, ABIR (Knight), a 3U nano-sat that will carry an Earth-imaging payload, rather similar to the one described on PISAT-1. ABIR will be three-axis stabilized and it, as do most of the nano-sats constructed or planned, relies heavily on off-the-shelf subsystems now available from a large variety of vendors. Although not operating in the UV, these nano-satellites demonstrate that it is possible to have successful space experiments without extremely high costs and very sophisticated infrastructure.

3. The CubeSat revolution

Space research was strongly dependent since its inception by the fabrication of the platforms used to operate scientific experiments. These were mostly one-of-a-kind constructions, requiring expensive testing to ensure a reasonable degree of success. Yet satellite and spacecraft platforms have a number of common requirements that drive a need for similar properties. The platforms have to be sturdy to survive the rigors of launch and operation in space (i.e., power supply, thermal and attitude control, etc.). In many cases these requirements could be served by standardized components; these could be fabricated in relatively large numbers, reducing the cost-per-unit due to volume production, and if one would be qualified for space flight further products of the same kind would not require the expensive qualification process.

In 1999 the California Polytechnic State University (Cal Poly) and Stanford University developed the CubeSat specifications to ease the design, manufacture, and testing of small satellites intended for low Earth orbit (LEO). The standard CubeSat is a $10\times10\times11.35$ cm unit (1U) that provides $10\times10\times10$ cm clear space (one liter of useful volume) while weighing no more than 1.33 kg. More units can be stacked to offer larger volumes, forming 2U, 3U, 6U or larger platforms. Since many CubeSats are 10×10 cm (regardless of length) they can be launched and deployed using a common deployment system called a Poly-PicoSatellite Orbital Deployer (P-POD), developed and built by Cal Poly. Since the P-PODs and the CubeSats they deploy in orbit are relatively light-weight, they do not require dedicated launchers but can be deployed as secondary payloads whenever a larger and much more massive satellite is orbited. On the other hand, there is almost no control of the orbit, which will be close to that of the primary payload.

The standard 10×10 cm cross-section implies that electronic boards and special sub-system, such as mechanical structure, power distribution, on-board computer, attitude and control systems can be fabricated on standard (PCI-104 form factor) boards and used for many missions. This caused the rise of specialized industries that design, fabricate, test and qualify sub-systems, which are then available to interested experimenters as custom-off-the-shelf (COTS) products. All these measures, and a philosophy of one-string design (foregoing the redundancy requirements) and extensive testing of different models of the experiment (structural, electrical/electronical, qualification, etc.) work together to reduce considerably the cost of a space experiment to as low as a few tens of thousands of US$ for a 1U CubeSat. This has been pointed out clearly by the Committee on Achieving Science Goals with CubeSats; Space Studies Board; Division on Engineering and Physical Sciences; National Academies of Sciences, Engineering, and Medicine (Zurbuchen & Lal, 2017).

Advances in CubeSat design allow now the use of deployable solar panels (more available power and even deployable structures with final dimensions much larger than those of the CubeSat as launched; e.g. the RainCube 6U platform by JPL, which houses a $\sim$50-cm parabolic antenna for a Ka-band (35.75 GHz) radar payload. Enlisting this capability of deploying larger structures from CubeSats for a possible astronomy mission implies the capability of orbiting relatively large collecting optics that would make a CubeSat mission almost equivalent to a "small" sized NASA mission such as GALEX.

4. Segmented optics

Classical telescope optics follow approximately a ratio of 1/10 between the diameter and the primary mirror (PM) thickness. This is the result of the need to maintain the reflecting surface as accurately as possible, at all orientations of the mirror relative to the gravity vector. Thus high-capability optics suffer from a relatively large volume and, given the thickness-to-the-diameter ratio and the density of the materials used to fabricate the mirror, from an associated large mass. All these make the launching of a classical telescope to space a prohibitively expensive undertaking.

There are means of reducing the mass of the PM without affecting its optical performance, such as selectively machining away large fractions of the glass ("light-weighting") while leaving sufficient material to form structural ribs and bosses for securing the finished mirror to its support structure. Extreme light-weighting can reduce the mass of a mirror to 20% or less of its initial, not light-weighted mass. Other means to produce lightweight mirrors require the use of exotic materials, such as beryllium or silicon-impregnated carbon (C-SiC). Also, it is possible to divide the primary mirror into thin segments, saving mass and relying on a support structure to maintain the optical surface. This is the method chosen for the PM of the James Webb Space Telescope (JWST), where a complicated mechanism deploys the PM stack of 18 beryllium segments, each weighting about 20-kg, and aligns them to form the 6.5-m diameter almost diffraction-limited (in the near-infrared at 2 μm) PM.

To reach the required optical quality, the segments of the JWST's PM can be adjusted in space to bring them perfectly in-phase with actuators applying force to the backs of the segments. This allows not only adjusting the tip and tilt of each segment, but also of slightly changing its curvature. It is expected that after JWST reaches is operational orbit at the second Lagrangian point (L2) of the Sun-Earth system, some two months will be spent aligning the optics. The "folding" of the JWST PM also reduces the launched volume, allowing the 6.5-m diameter mirror to fit in the nose cone of the Ariane-5 launcher, which allows a maximum 4.57 meter payload diameter. Segmented mirrors reduce thus both the mass and the volume of the optical systems to be orbited.

5. Segmented optics at the Technion

The Asher Space Research Institute (ASRI) and the Department of Physics at the Technion in Israel run a program to develop segmented mirrors that can be deployed and aligned in space. The preliminary design of such a device has each segment (called here "petal") made of the reflecting surface that has the shape and finish of the final mirror and is supported by a stiff mounting surface that deploys, together with all its attachments, from the main structure. Between the mounting surface and the back of the mirror segment there are a number of nano-actuators that can push or pull the segment relative to the mounting surface. This way, each segment has independent capability to "piston", "tip" or "tilt", thus being able to adjust as required.

The nano-actuators are piezo-electric devices of high reliability and accuracy, thus the motions are well-controlled and repeatable, while not requiring power when not actuated. As with many segmented telescopes, the major issue in forming the final accurate reflecting surface is the phasing of all the segments. As mentioned above, this phase is estimated to require two full months for the JWST. As of now, there is no direct method of measuring the phase of propagating light and the best one can do is to measure intensity. Using this method, laboratory tests with a bench-top system done at ASRI succeeded to phase a four segment mirror system in a few hours by using a hardware "simulated annealing" algorithm that is iterative and uses a feedback loop to correct the phase errors (Paykin et al., 2015). Success is determined by the achievement of the sharpest image, and the method is efficient since the phasing sensor is the same as the imaging sensor of the payload and the source against which the optimization procedure is performed is a star (simulated in the lab by a point source).

6. Putting it all together

With the elements described above, it is possible to propose a revolutionary platform which, with the form factor of a 3U or 4U CubeSat could perform UV science almost at par with what GALEX yielded for a mission cost well below 1 M$, i.e. less than 1% of the total GALEX budget. A generic view of the experiment is shown in Fig.1.

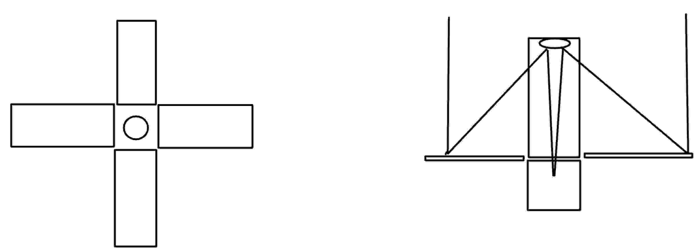

Figure 1. A possible 3U configuration of the proposed spacecraft. The left panel shows a view from the sky with the four petal extended. The right panel shows a side view of the open petals and the secondary assembly. The incident light is focused on the detector located in the bottom unit of the 3U configuration.

As Fig.1 shows, the top two units of the 3U configuration carry the four "petals" of the segmented PM and the secondary mirror assembly. Once in space, the petals deploy and form an unphased PM of some 800 cm^2 unobstructed collecting area (smaller than the $\sim$ 5000 cm^2 of GALEX, but still significant). The phasing is done via the simulated annealing algorithm using the detector, which could be a variant of the one developed for PISAT-UV. The back-sides of the support elements of each petal carry solar panels and are therefore directed sunward after the petal deployment, which puts the telescope itself in an anti-sunward direction.

Between the deployed petals it will be necessary to deploy some thermal blankets. These would ensure that the optics are always in shadow and stay cool during the orbital day. The bottom unit of the 3U configuration would carry all the necessary subsystems for the proper operation of the experiment; if necessary, this can be extended by another unit for a final configuration of 4U. Power is supplied from the solar panels on the bottoms of the petals and on all sides of the bottom unit(s) of the configuration, where the telemetry antennas are also located.

There are numerous science goals that can be achieved with variants of this experiment. To mention just a few, it would be possible to fill-in areas and topics not covered by GALEX such as observing in the FUV, or to monitor transient sources in the UV, or to perform a survey of the 2174Å interstellar extinction feature by adding a grism in the converging beam that would allow measuring the equivalent width of the feature in many stars.

7. Conclusions

We have described a possible mission for the space UV based on the CubeSat architecture, with most components commercially available, and where the science payload is based on work on segmented mirrors and their phasing done at the Technion, and on the detector package for small satellites developed at the IIA. We estimate that such a mission could be realized within two years, would cost less than 1M$, and could provide unique science in the UV. Moreover, if realized such a mission could provide the pathfinder of future missions using essentially the same hardware with minor modification to attack different problems in the field of ultraviolet astronomy.

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