Exploring the UV sky with Small and Affordable Missions

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The exploration of space and, in particular, astrophysics experiments, are now done primarily by missions conducted under the aegis of the major space agencies with a tendency towards "larger and heavier" payloads, driving the cost of missions to hundreds of Millions of dollars or Euros and more. This tendency is exhibited in the latest missions developed by NASA, ESA, ROSCOSMOS, JAXA, and CSA, and prevents the running of experiments or observations on a schedule faster than about a decade.

While this does not seem to be an acute problem for other spectral domains, the astronomy in the ultraviolet is the domain suffering mostly since there is no continuity of missions that would keep the know-how alive. The goal of this short report is to point out possibilities offered by small and cheap missions that could be accomplished for less than about 10 million Euros or US $ and with development time to launch of order two years.

1. Balloons

Traditionally, balloon astronomy focused first on cosmic ray observations starting with the 1912 pioneering flights of Victor Hess that later progressed to observations of Solar System objects, firstly of the Sun. A balloon has the advantage of lifting its payload to altitudes higher than any airplane, but lower than those heights reached by rockets and satellites, and for a fraction of the cost of the latter. Modern stratospheric balloons can reach as high as 150,000 feet or almost 50-km. At such altitudes the sky is dark since there is significantly less atmosphere to scatter sunlight, the atmosphere is much less turbulent since fewer hot air cells are traversing the telescope beam to cause deviations of the light rays, and the atmospheric transparency is exceedingly better than from the best ground-based sites opening up part of the UV range.

Additionally, specially-developed super-pressure balloons can now offer very long duration flights of weeks to months. If performed in the Arctic or Antarctic regions, such flights take advantage of the polar wind vortices; these maintain the balloon and its payload circling the pole which implies that the communication and payload recovery issues are lessened.

The issue of the sky background brightness arises because of the $1/\lambda^4$ dependence of the scattering of light. While one may conclude that UV observations performed at high altitudes and during daylight could be possible because of the minimal atmosphere, calculations performed with optical models of the atmosphere (with e.g. MODTRAN) indicate that the sky is only ~100 times fainter than over Mauna Kea, peaking at ~5000 kR/nm at 400 nm for an altitude of 30-km, and ~300 kR/nm at 50-km. Therefore, in order to observe under really dark background sky levels balloon observations in the UV should be conducted only during the night and even then Moonlight might be a factor.

The reduced atmospheric inhomogeneities at high altitudes imply significantly better seeing than achievable from the ground. In fact, while a ground-based observatory might have a Fried seeing parameter r_0 of 0.2-m, a similar telescope on a balloon at 35-km would have r_0~41-m, i.e., a point spread function with diameter of 0.063 arcsec for a one-meter telescope operating at 250 nm, which means close to diffraction-limited performance.

Finally, the issue of highly enhanced atmospheric transmission in the ultraviolet allows observations impossible to be performed from the ground, even from the highest elevation observatories. While the spectral range shortward of ~310-nm is not accessible from the ground because of Rayleigh scattering and absorption by aerosols and ozone, the situation significantly change for observations performed at high-altitudes. The ozone is mainly concentrated in a layer at about 24-km altitude, thus high-altitude flights above this value would not be affected by the O_3 molecules.

The ozone absorption peaks at about 260 nm; the next contributor to the atmospheric UV absorption is molecular oxygen, O_2, which peaks at about 150-nm. Thus between 150 and 260-nm there is a region in atmospheric transparency with reduced absorption. This region, around 200-nm has been exploited by the SCAP-1000 and FOCA wide-field UV imaging experiments in the 1980s as a collaboration between Observatoire de Geneve and the Laboratoire d'Astrophysique Spatiale. At even shorter wavelengths the atmospheric obscuration is due to other molecules or atoms, such as atomic Oxygen (O) and Nitrogen (N), and molecular Nitrogen (N_2). FOCA had a larger telescope with a 31-cm diameter and fields of view of either 1°.5 or 2°.3, recording the information on film behind a UV converter/intensifier. Some results from these flights were reported by Laget et al. (1991) and others.

Finally, balloon-borne astronomy is a cost-effective way of performing cutting-edge science. Eliot (2012, in Balloon Science) estimated the cost of a long-duration balloon flight at about 4 M$; this would offer about 40 observing nights with HST-like performance and with the possibility of recovering the payload for reflights. In comparison, with FY2012 costs, a similar amount of Keck time would be twice more expensive and would not allow UV observations.

When considering a UV mission to be conducted from a balloon, one should include aspects of electrical power and data communications for long duration flights. The power should be supplied by solar panels, just as used in satellites, with the collected energy stored in on-board batteries for night-time operations. The communication issue, relevant for long-duration flights, should be considered, since the ground station controlling the balloon observatory may be quite distant from flight track of the balloon itself.

The balloon gondola should have the necessary equipment to keep the celestial field of interest centered on the focal plane. This is normally done by having the telescope on an alt-azimuthal mounting with source tracking done by rotating the assembly along the azimuth and changing the elevation as necessary. For wide fields one has to account for the rotation of the field with respect to the detector; this normally requires the addition of a de-rotator mechanism.

In a long-duration circumpolar flight in the Southern Hemisphere, the distance from the South Pole to the nearest Antarctic coast (e.g. McMurdo from where the balloon might be launched) is about 2000-km. The horizon distance for a balloon at 40-km is a bit more than 700-km. This implies that with a control station at the South Pole, the balloon and its transmitter/receiver would be seen below the local horizon thus impossible to communicate with, whereas from McMurdo the balloon would be visible and in communication only part of the time, mostly at low elevation, raising problems such as ground clutter and undesired reflections. To avoid such issues one would probably want to use geo-synchronous communication satellites as relays. This would require the operation on-board the balloon platform of a satellite communication system such as used, e.g., on military UAVs. These offer high bandwidths for command and control and for data downlink, thus allowing real-time operations.

This communication problem would be compounded for flights taking place closer to the equator since not only would the balloon drift eastward taking it away from the continental areas, but also such a flight would overfly major civilian air corridors. On the other hand, such experiments could much easier take advantage of the geosynchronous satellite belt allowing continuous command and control of the experiment.

Finally, any balloon flights have to consider possible interference with aviation, be it either civilian transportation or military activities. These require close monitoring of the balloon and its payload both during the ascent and descent, as well as during the coasting at high-altitudes while maintaining tight communications with the air traffic control. Even though with the balloon being above 30-km altitude it where does not interfere with regular flights, since these are normally relegated to below 50,000 feet altitudes, this can quickly change in case of an accident that causes sudden loss of lift and balloon descent. Thus close contact with the authorities controlling civil and/or military flights, and radar contact with the balloon are a must.

Note here that long duration flights using circumpolar trajectories suffer from contradictory constraints: on the one hand one wants the observations to be done during the night, but on the other during the Arctic or Antarctic nights there is no sunlight to recharge the batteries. For this reason, trans-oceanic long-duration flights are to be preferred for UV astronomy since they will offer both dark night-time for observations and light daytime for battery charging.

2. Rockets

Since the start of the rocket age with the flights of the V2 rockets in the US and continuing with sounding rockets, experiments in the UV astronomy have been conducted from sounding rockets. These can lift reasonably heavy payloads to altitudes much higher than balloons, even thousands of km, allowing observation times of tens of minutes until the payload drops below the interesting altitudes. These much higher altitudes are necessary for the observation of the spectral range shorter than 200 nm and offer a much better transmission than from a balloon. However, one should note that even at these much higher altitudes observations are hampered by atmospheric emissions, such as the resonantly scattered Lyman α line that is visible even at altitudes of tens of 1000s km.

Historically, it was an Aerobee rocket flight which obtained UV spectra of 30 objects in the wavelength range of 160nm to 400nm (Stecher & Miligan, 1962) allowing the discovery of the 217.4-nm extinction “bump”.

Notable also are the far-UV cameras flown on rockets by Carruthers and collaborators in the late-1970s and early-1980s. The information was recorded on film (electronographic) that was later digitized and the images calibrated. The Goddard Space Flight Center also conducted a number of rocket flight for the benefit of UV astronomy. These were described by Bohlin et al. (1982) and Smith & Cornett (1982), with the observations performed with a 31-cm telescope with quite low angular resolution (10-20 arcsec0.

The cost of a sounding rocket flight (in FY2004 US$) is about 3 M$. For this, an experimenter may gather 30-40 minutes of UV data completely outside the atmosphere. While this might be sufficient to test an instrument or to observe a specific object, conducting a survey would require multiple rocket flights making this a less likely project considering the alternatives.

Nowadays most rocket flights seem to be used to investigate phenomena in the higher atmosphere (exosphere) or the interaction between the exosphere and the solar wind. A few missions are still dedicated to astronomy, but we understand that these are used to test and qualify instruments that will be subsequently used on satellite platforms.

3. Nano satellites.

[This part draws partly from the document :Achieving Science with CubeSats: Thinking inside the box", 2016 NAP, Space Studies Board, Division on Engineering and Physical Sciences; hereafter referred to as ASCS]

The trend among commercial and educational entities is now geared towards micro and nano satellites, mostly cubesat based structures. The standard CubeSat structure is composed of standardized units, where a one-unit (1U) is cube of 10x10x10 cm^3). The dedicated satellite might be constructed of as many 1U as necessary, allowing very wide volumes indeed. However, given that part of the volume and mass must be dedicated to housekeeping, power, communications and other vital subsystems, one has to account properly for the volume and mass left for any scientific payload.

Note that many of the subsystems allowing a cubesat-based nano-satellite to operate properly may now be commercially-available saving considerable time and grief from the developers. Such subsystems now also include orientation and position keeping miniature devices, such as a star tracker of less than 100-gr, a three-axis magneto-torquer of less than 200-gr mass, a 90-gr reaction wheel, a 5-gr momentum wheel measuring 23 x 31 x 26 mm, an S-band transmitter massing 75-gr and capable of up to 1 Mbps data rate, etc. Many of these subsystems have been space-qualified and are essentially off-the-shelf items.

Using standardized components frees a potential experimenter from long and tedious development steps, allowing concentration of effort in the developing and qualifying the scientific payload. The relative simplicity of building a satellite from off-the-shelf components allows an investigating team to concentrate mostly on building and testing the science payload.

The NAP publication ASCS analyzes the possibility of performing scientific investigations using cubesat constellations. The authors write that “CubeSats can produce high-value science, as demonstrated by peer-reviewed publications that address decadal survey science goals [p. 7-1]. They qualify the science as “large spacecraft excel at large-scale investigations, when, for example, several instruments need to be collocated. CubeSats excel at simple, focused, or short-duration missions, missions that need to be low cost, or those that require multipoint measurements [p. 7-2]”.

While the possible applications of cubesats in astronomy, listed in chapter 4 of ASCS, do not mention specific UV missions, they make it clear that valuable science CAN be done. The limit in the size of optics, which is of order 10-cm for a 1U design, or for a longer cubesat (2-3U) with the same cross-section, implies a diffraction limit of one arcsec in the optical but 0.5 arcsec in the near-UV (NUV) and close to 0.25 arcsec near Lyman alpha. Such small PSFs, if achieved with a cubesat telescope, require an accuracy in position- keeping and pointing of the same order which will not be easy to achieve .

The science topics specified in ASCS in the domains of planetary science are: distribution of lunar water, in-situ investigation of the chemical and physical properties on planetary surfaces and atmospheres, and measurements of planetary magnetospheres. In the astronomy and astrophysics topics, ASCS mentions the search for exoplanets and the performance of low-frequency radio observations. Cubesats can also provide information on variable sources (stars, transiting planets), swarms of cubesats can be used to form interferometry arrays.

An important aspect of all the small missions mentioned here is their relatively low cost. This allows them to become excellent introduction to space technologies and to train future space engineers and technicians in what does it mean to build, launch and operate a space experiment. It should be mentioned here that high-school pupils (helped and mentored by qualified space engineers from the industry) already built satellites that operate in space for significant periods [e.g. the Duchifat-1 (http://www.madaim.org.il/hsl/php/duchifat1-en.php) which is operating for longer than two years in space].