A Wide-Field Near-UV Moon Observatory

Overview

The Moon provides access to wavelengths not accessible from Earth, making it a unique place from which to study the Universe. In particular, the ultraviolet (UV), at wavelengths shorter than 300 nm, is the best region to study sources such as hot stars, stellar explosions and eruptions, gravitational wave counterparts and tidal disruption events, stellar remnants and accretion disks around stars, white dwarfs, neutron stars and (supermassive) black holes. The Moon provides a unique platform due to its slow rotation, where one revolution takes 27.3 days. This eliminates the need to track a star field by moving the telescope [1]. The Moon provides an eternally dark sky outside of the band traced out by the Sun and the Earth.

These three unique features (UV, slow rotation, continuous dark) are especially important for synoptic astronomy: the study of the Universe in the time-domain to discover and understand explosive and time-variable objects in the Universe. These strengths come together in a Wide-Field Near-UV Moon Observatory: A revolutionary astronomical UV-sensitive wide-field array only possible on the Moon.

Science Opportunities

A wide-field UV telescope array on the Moon enables myriad astrophysical science areas. Here, we outline four topics that could make dramatic progress with suitable instruments on the Moon.

Shock break-outs and young supernova explosions

The deaths of massive stars are one of the most important stages in the life cycle of stars and galaxies where they enrich the Universe with massive elements, including those that are essential to life. Massive stars are the fertilizers of the Universe, enriching a once barren Universe existing of only hydrogen and helium with all the other elements. Which stars end their life in what way is one of the open questions in stellar evolution; it is therefore essential to detect exploding stars as early as possible. The earliest sign of the explosion is the so-called “shock break-out”, when the shock wave of the explosion breaks through the visible surface of the star. Models show these shock-breakouts peak in the UV and last minutes to hours, depending on the size of the star [2-4]. The subsequent UV rise to peak brightness of the young supernova during its shock cooling phase is also essential to determine the radius of the exploding star.

Exoplanets and host stars in the UV

Exoplanet surveys have demonstrated that most stars in the Milky Way host planetary systems. With so many planets now discovered, the next step is the detailed characterization of the physical processes that form and shape these worlds. We now have the opportunity to probe exoplanet atmospheres. By measuring the UV flux received by planetary atmospheres we can model how stellar flux drives atmospheric mass-loss and retention, and ultimately contributes to determining a planet’s habitability (e.g., [5-9]). UV measurements that trace the host star stellar activity, including UV flares, can only be obtained from telescopes placed above the Earth’s atmosphere. These flares last for seconds to hours and peak in the UV. They are the seeds of waves and instabilities in coronal loops with periods of up to a few minutes that allow coronal loop seismology. Understanding the coronal flare activity and UV behavior of stars is an essential ingredient in understanding the possibilities for Earth-like life to emerge.

Kilonova Gravitational wave counterparts

The direct detection of gravitational waves (GW) through laser interferometry has revolutionized our view of the Universe [10]. The detection of a “kilonova” electromagnetic (EM) signal following the LIGO/Virgo discovery of a pair of merging neutron stars began the joint EM-GW study of the Universe [11]. Modeling of the kilonova signal showed that it peaked in the UV during the first few hours of the merger. Detections of UV-bright kilonovae are required to understand the merger process and remnant, the formation of r-process heavy elements such as gold and silver, and the associated opacity, geometry and dynamics of the expanding ejecta cloud [12].

Tidal disruption events

The growth of stellar mass black holes to the supermassive black holes in the centers of galaxies is one of the central questions in both stellar and galaxy evolution. One path is the "gobbling up" of complete stars by a growing black hole. In these "tidal disruption events (TDEs)" the star will be shredded by the tidal forces of the black hole, depending on the mass ratio between the two. TDEs show peak brightnesses in the UV at early stages of the merger event and detecting them early in the UV is therefore tantamount to understanding them [13]. A strong link exists between TDEs, kilonovae and LISA sources, as the kilonova event can be described as a miniature-TDE, and the extreme mass-ratio TDEs are labelled "Extreme Mass Ratio Inspirals (EMRIs)" which are one of the expected classes of LISA sources [14-17].

Strawman Technical Design

The scientific aims outlined above require a UV telescope that combines: (1) a wide field of view to catch rare and often elusive events - a total survey area of >500 sq. deg., (2) high time resolution to catch transient events that last minutes, (3) sufficient sensitivity to probe intrinsically dim events at UV wavelengths - at least 21st magnitude per-exposure in a band 150-300 nm.

The three requirements above can be achieved by taking advantage of the Moon's slow rotation period of 27.3 days and lack of an atmosphere. On Earth, a telescope has to track a source location on the sky, due to the Earth's fast rotation; sources at the celestial equator will move at a rate of 15″/s. On the Moon this equatorial drift rate is at maximum 0.55″/s [18]. Even for observations with spatial resolution at the 1″-2″ level this will allow integration times of 5-10s before trailing distorts the view.

The science described could be achieved with an array of UV telescopes, situated at the lunar (South) Pole, that are configured in a ring, pointing at a selenic celestial declination of δ~60° (i.e. 30° away from the local zenith), and which share a common enclosure to protect them from lunar dust. Each unit telescope could follow a modified Dall-Kirkham design as in MeerLICHT/BlackGEM [19]. This delivers excellent optical quality across a large field-of-view. A 30cm diameter, F/3.5 telescope coupled with a 36 Million pixel UV-sensitive CMOS detector with 10μm pixels will deliver a 2″/pixel spatial sampling and a 3.3° x 3.3° = 11 square degrees instantaneous field-of-view. The crucial element of a "never moving" telescope is the ability to integrate for 10s before image quality degradation occurs. At 60° selenic declination the transfer drift speed is 0.27″/s and in 10s a source moves only 2.7″, i.e. 1.35 pixels. Using an Exposure Time Calculator (ETC) adapted from BlackGEM [19], a 10s exposure will achieve a 5-sigma depth of mAB = 22.4.

References

[1] McGraw, 1994, AdSpRes 14, 105
[2] Huang et al., 2018, MNRAS 475, 3959
[3] Huang et al., 2016, ApJ 832, 139
[4] Gezari et al., 2015, ApJ 804, 28
[5] Eichenreich et al., 2015, Nature 522, 459
[6] Eichenreich & Desert, 2011, A&A 529, 136
[7] Tian, 2015, E&PSL 432, 126
[8] Lammer et al., 2012 EP&S 64, 179
[9] Grießmeier, 2015, ASSL 411, 213
[10] Abbott et al., 2016, PhRvL 116, 1102
[11] Abbott et al., 2017, PhRvL 119, 1101
[12] Arcavi 2018, ApJ 855, L23
[13] Van Velzen et al., 2011, ApJ 741, 73
[14] Stubbe & Quataert, 2009, MNRAS 400, 2070
[15] Guillochon et al., 2014, ApJ 783, 23
[16] Miller, 2015, ApJ 805, 83
[17] Piran et al., 2015, ApJ 806, 164
[18] McGraw, 1994, ASPC 55, 283
[19] Groot, 2019, Nature Astronomy, 3, 1160