CubeSat science instruments

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1 Introduction to CubeSat science instruments

CubeSats are increasingly being referred to as an example of a "disruptive technology" owing to their rapid development cycles and the fact that they are less expensive to develop, launch, and operate compared to large, conventional satellites. The evolving capabilities of CubeSats are leading to a rapid expansion of their application to a wide variety of mission profiles. New, innovative technologies are enabling fundamental science observations, constellations of Earth remote sensing CubeSats, and, more recently, interplanetary CubeSat missions. A variety of evolving technologies, implementing reduced size, weight, and power (SWaP), has led to miniaturized science instruments that are now being used in applications that were once the realm of large, extremely expensive satellite systems.

The pace of development of these technologies is accelerating. SmallSat form factors allow fast-track infusion of technology for space missions, which amounts to a new paradigm in space exploration and utilization. New technologies and new science instruments being developed under the "NewSpace" umbrella are being rolled out at a pace that has the potential to disrupt planetary science exploration as it has begun to do for Earth remote sensing from Low Earth Orbit (LEO) and in astrophysics and heliophysics.

The National Academies of Sciences undertook a study published in 2016 entitled "Achieving Science with CubeSats." The study concluded that CubeSats had already produced high-value science and are particularly well suited to targeted investigations that augment the capabilities of larger, more capable spacecraft and enable new types of science measurements [1]. Technological advances that support these science measurements and the CubeSat revolution in general are considered in other chapters. NASA maintains an online version of the state of the art in SmallSat technology report that documents such technologies in detail. The report provides a comprehensive summary of the current state of SmallSat spacecraft technologies categorized by power, propulsion, guidance navigation and control, structures, materials and mechanisms, thermal control, command and data handling, communications, integration, launch and deployment, ground data systems and operations, and passive deorbit devices [2]. The report provides an excellent reference for CubeSat developers, especially when combined with a companion NASA publication, "CubeSat 101: Basic Concepts and Processes for First-Time CubeSat Developers" [3]. The state of the art in SmallSat

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technology is a comprehensive and valuable resource, which is regularly updated, and provides a far more in-depth look at CubeSat spacecraft technologies than can be considered here. An overview of these technologies with reference to their impact to specific SmallSat mission profiles has been discussed in previous chapters. These advances in spacecraft technologies facilitate CubeSat science missions, which can target specific measurements or observations. The instruments that are used to make these measurements and observations are considered in this chapter.

2 Current and planned CubeSat instruments

For any CubeSat science mission, the point is to make useful, science-grade measurements, whether from Earth orbit or some more exotic destination in the solar system. Consider the latter case, since it is more challenging: not all the instruments needed for deep space exploration can be miniaturized to fit within the constraints of CubeSat or NanoSat volumes. Magnetometers can be made to fit, as seen on INSPIRE [4]; radios can be miniaturized to enable radio science investigations, as seen on both INSPIRE and MarCO; and in situ instruments can, with some effort and ingenuity, be made small and low power enough, as seen in the case of instruments designed for NASA's next Mars rover [5]. Which of these and other instruments can be tailored for CubeSats/NanoSats?

For a first cut at an answer to this question, a survey of Earth observation instruments that was generated in 2012 [6] lends insight. In this study the authors Daniel Selva and David Krejci binned the current state-of-the-art instruments into three categories: feasible, infeasible, and problematic. Their list is summarized and updated for 2020 in Table 1. In the taxonomy used in the 2012 paper, "feasible" meant that a technology or a sensor compatible with the CubeSat standard had already been developed; "infeasible" meant that a technology was seen as clearly incompatible with the CubeSat standard; "problematic" technologies captured instances for which an instrument could be developed to fit the CubeSat standard but at the expense of significantly reduced data quantity and/or quality. This list was recently updated to reflect the progress made by instrument developers by 2019 [7]. It is quite a long list (Table 1) and includes optical/IR cameras; UV/optical spectrometers; IR radiometers and spectrometers, from the Near-IR to Far-IR; microwave radiometers; submillimeter-wave spectrometers; short wavelength radars; GPS radio occultation; and optical communication lasers that can be used for occultation. CubeSat versions of synthetic aperture radars (SARs)—which conventional wisdom has requiring huge apertures and kW's of power to operate from orbit—are under study [8]. Substantial progress has been made in advancing the feasibility of several instrument classes since 2012. In fact, none of the original list from Ref. [6] are now considered infeasible, and only one category (Lidars) can be considered problematic. For planetary science, astronomy, and heliophysics investigations, compact neutron and X-ray spectrometers and mass spectrometers should be added to the list. The NANOSWARM mission concept, for example, proposed to NASA's 2019 Discovery call, included a miniaturized neutron spectrometer and a solar wind ion sensor [9]. Other instruments, such as UV, visible and IR telescopes, and field and particle sensors, are being incorporated into

Table 1 Examples of science-grade instruments designed for CubeSat form factors.

Technology	Examples
Atmospheric chemistry instruments	PICASSO
Atmospheric temperature and humidity sounders	CIRAS, 3D Winds
Cloud profile and rain radars	RainCube, Cloudcube
Earth radiation budget radiometers	RAVAN, CSIM, PREFIRE
Gravity instruments	Drag Free CubeSat
High-resolution optical imagers	Planet
Imaging microwave radars	Ka-Band 12U design
Imaging multispectral radiometers (Vis/SWIR) and hyperspectral imagers	AstroDigital, SWIS , HyperScout, APEX
Imaging multispectral radiometers (IR, microwave, and millimeter wave)	LunarIceCube, TEMPEST, TROPICS, IceCube
Lidars	Lunar Flashlight, TOMCAT, APEX
Lightning imagers	RaioSat
Multiple angle/polarimeter	HARP Polarimeter
Ocean color spectrometer	SeaHawk
Precision orbit	CanX-4&-5; LEDSat
Radar altimeters	SNoOPI
Scatterometers	GNSS refl. (CyGNSS)
Neutron spectrometers	LunaHMap
UV/Vis/IR telescopes	ASTERIA, SPARCs, GUCI
Field and particle sensors	Dellingr, CuSP, Min-XSS, BurstCube
Radio interferometer	SunRISE
Mass spectrometers	APEX

compelling astrophysics and heliophysics science CubeSat missions. The science community has invested significantly in technology development to miniaturize a broad range of instruments, an effort that is now paying off as instrument concepts mature to the point where they can be incorporated into CubeSat/Nanosat missions for exceptional quality science.

The instrument classes summarized in Table 1 are discussed in some detail in the succeeding text, one at a time:

2.1 Remote sensing instruments

Atmospheric chemistry instruments—PICASSO's visible spectral imager for occultation and nightglow (VISION) instrument is designed to obtain vertical profiles of stratospheric ozone via spectral observation of sun occultations in the Chappuis band [10]. Compact for a hyperspectral imager, at less than 1U in size, its spectral range covers the visible and the near-infrared (430–800 nm). Spectral band selection is performed by a tunable Fabry-Perot interferometer, which is well suited for compact realizations. As an ESA-funded mission, PICASSO is scheduled to launch in 2020.

Atmospheric temperature and humidity sounders—The CubeSat IR atmospheric sounder (CIRAS) is a 4U cryo-cooled grating MWIR spectrometer designed primarily for sounding of atmospheric water vapor and temperature but with sufficient spectral coverage and resolution to resolve some atmospheric constituents such as CO and CO_2 [11]. The new technologies embedded in CIRAS are a compact grating spectrometer and a high operating temperature barrier IR detector (HOT-BIRD), operating at 190K. This relatively high operating temperature is critical for use in CubeSats. Lower temperatures require cryogenic cooling that can create significant thermal management challenges, especially in tightly constrained volumes. HOT-BIRD's spectral range spans 4.08–5.13 μm, with spectral resolution of 1.3–2.0 cm^{-1}. CIRAS was funded as a NASA technology development program.

Another atmospheric sounder known as 3D winds has been proposed as a constellation of 12 6U CubeSats, each carrying a passively cooled MWIR hyperspectral FTS sensor, operating in a cross-track scanning mode to cover a 650-km-wide swath at a spatial resolution of ~ 5 km. The spectral range is 5.7–8.2 μm, with spectral resolution 1.26 cm^{-1}. As an IR sounder, each individual 3D wind sensor can retrieve 3D profiles of atmospheric water vapor. In a constellation, measurements separated in time by a few minutes of changes in the water vapor profiles can be combined to estimate atmospheric winds [12].

Cloud profile and rain radars—RainCube proved that a precipitation radar could fit in a CubeSat volume and return high-value science measurements [13]. RainCube's 35.75-GHz radar payload was designed to fit within a 4U volume inside a 6U CubeSat form factor (Fig. 1). RainCube demonstrated miniaturized radar electronics and an innovative, compact deployable antenna within this tiny volume. Funded by NASA'

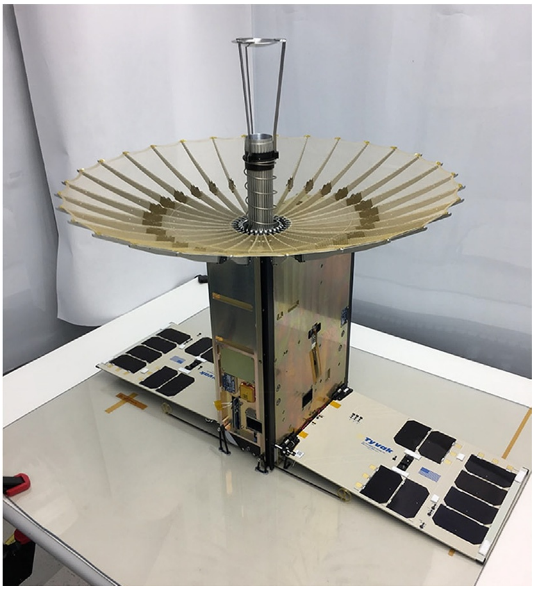

Fig. 1 The 6U RainCube spacecraft in integration and test, with the solar panels and Ka-band radar antenna deployed.
Courtesy NASA/JPL/Caltech.

Earth Science and Technology Office, RainCube was delivered to the ISS on the OA-9 resupply mission and deployed from the Nanoracks dispenser in July 2018. The CloudCube radar concept, currently under development, takes the lessons learned from RainCube and folds in a higher frequency W-band measurement capability for cloud profiling [14].

Earth radiation budget radiometers—The RAVAN mission used a novel approach to a compact radiometer targeting the Earth's radiation budget by capturing all outgoing radiation from the UV (200 nm) to the far-IR (200 μm) with an accuracy of better than $0.3\,\mathrm{W\,m^{-2}}$ absolute [15]. This was achieved by demonstrating two new technologies: vertically aligned carbon nanotubes (VACNTs) that have an extremely flat spectral response over a wide wavelength range to absorb this broadband radiation and a gallium fixed-point blackbody calibration source.

The next CubeSat mission to measure a key part of the Earth's radiation budget will be Polar Radiant Energy in the Far-InfraRed Experiment (PREFIRE)—a miniaturized thermal IR spectrometer operating over the wavelength range 0–45 μm at 0.84-μm spectral resolution [16]. The mission's objective is to quantify a poorly understood component of the Earth's radiation budget: spectrally resolved emissivities over the Arctic at wavelengths >15 μm (Far-IR) that have never before been systematically measured. PREFIRE takes advantage of advances in thermopile detector technology that allow Far-IR measurements in a compact form factor at ambient temperatures without onboard cooling.

Gravity instruments—Clearly marking a path toward CubeSats that can measure gravity field variations, a 3U drag-free CubeSat mission has been proposed to demonstrate the feasibility of a gravitational reference sensor (GRS) with an optical readout. The drag-free CubeSat is designed to shield a 25.4-mm spherical test mass (TM) from external nongravitational forces and to minimize the effect of internal generated disturbances [17]. There is significant potential for gravimetric instruments in Earth remote sensing and planetary exploration.

High-resolution optical imagers—The commercial company Planet has deployed hundreds of its 3U Dove satellites, each carrying a multispectral, optical imager capable of 3–5-m spatial resolution [18]. As a constellation, their flock of Doves yields unprecedented global coverage at this spatial resolution on a daily basis. Since the beginning of operations of the Doves, Planet has produced an archive of >7 petabytes of data. The enabling technology is the camera's use of a line scan technique, which allows for continuous acquisition of high spatial resolution imagery.

Imaging microwave radars—It may seem incredible that a synthetic aperture radar (SAR) might fit in a CubeSat volume, but a concept for a Ka-band SAR has been envisioned that fits in a 12U volume [19]. The shorter Ka-Band wavelength allows a smaller antenna to obtain reasonable swath coverage, SNR, and spatial resolution in such a small package. Additionally, Capella Space, Inc., is building a constellation of six SAR-based microsatellites whose goal is to offer hourly coverage of every point on the Earth rendered in submeter resolution [20].

Imaging multispectral radiometers (Vis/SWIR) and hyperspectral imagers—Another commercial company Astro Digital has developed and flown the LandMapper-BC satellites, a small constellation of 6U CubeSats each carrying a three-band (red, green, and NIR) multispectral imager, capable of 22-m spatial resolution [21]. JPL's Snow and Water Imaging Spectrometer (SWIS) is a compact imaging spectrometer and telescope system designed for integration on a 6U CubeSat platform. It covers the 350–170-nm spectral range with 5.7-nm sampling. The Dyson spectrometer has an innovative single drive onboard calibration system capable of providing radiometric stability and features a new Teledyne CHROMA detector array, optimized for high-temperature operation, with a linear variable antireflection coating to enhance quantum efficiency and minimize backscatter [22]. CoSine's HyperScout visible/near-IR hyperspectral imager is currently flying on ESA's GOMX-4 CubeSat platform [23]. This 1.5U instrument is capable of 70-m spatial resolution over a 200-km swath and 15-nm spectral resolution in the 400–1000-nm range.

Imaging multispectral radiometers (IR, microwave, and millimeter wave)—Lunar IceCube, led by Morehead State University, partnered with the Busek Company, NASA GSFC, the NASA Independent Verification and Validation (IV&V) Center, and JPL, is one of the most challenging CubeSats undertaken to date. In addition to navigating itself into a lunar orbit after its release from the Artemis 1 SLS rocket, using a state-of-the-art RF ion propulsion drive (developed by the Busek space propulsion company), it will carry the first cryo-cooled thermal imaging radiometer flown in space by a CubeSat—the Broadband infrared compact high-resolution exploration spectrometer (BIRCHES). BIRCHES (Fig. 2) will measure solar reflectance around the 3 μm band with 10-nm spectral resolution to separate OH, liquid water, and ice absorption features on the lunar surface at 10-km spatial resolution.

It is a compact 1.5U instrument, with a Teledyne H1RG focal plane array and a linear variable filter (LVF) detector coating. Cooling is achieved by a tactical AIM SX030 microcryocooler with a cold finger to maintain the detector at $\leq$115°K [24]. Lunar IceCube and 12 other Artemis 1 interplanetary CubeSats will be launched on the maiden voyage of NASA's Space Launch System in 2020.

The Temporal Experiment for Storms and Tropical Systems-Demonstration (TEMPEST-D) mission is a 6U CubeSat carrying a cross-track scanning, five-channel passive microwave radiometer with bands in the spectral range 90–200 GHz.

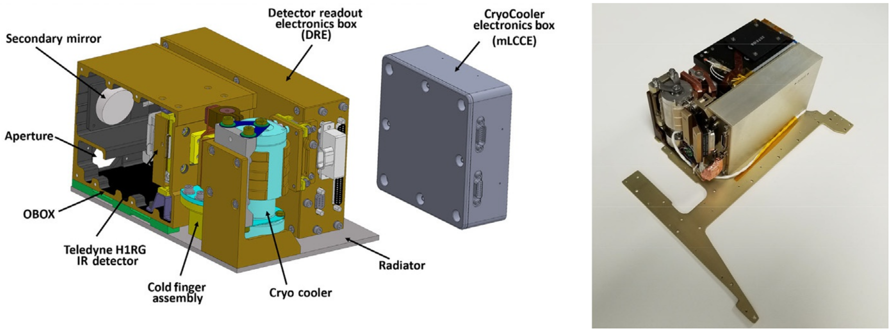

Fig. 2 Lunar IceCube's BIRCHES IR spectrometer (CAD model shown on the left and photograph shown on the right).
Courtesy Morehead State University and NASA Goddard Spaceflight Center.

TEMPEST-D is a collaboration between Colorado State University and JPL. TEMPEST-D was launched in May 2018 and deployed from the ISS in July 2018 at nearly the same time as RainCube [25, 26]. TEMPEST-D resolves the time derivative of the scene brightness temperature, primarily due to atmospheric water vapor variations. The sensor design includes high-quality blackbody calibration sources viewed through the antenna, end to end. Data quality is similar to that of more conventional microwave sounders such as the Advanced Technology Microwave Sounder (ATMS) on the NOAA polar satellites [27].

The TROPICS constellation of six 3U CubeSats is being developed by MIT/Lincoln Labs under a NASA contract to study the development of tropical cyclones through rapid-revisit sampling using a multiband millimeter-wave radiometer instrument [28]. The TROPICS sensor is actually two total power radiometers that measure 12 channels altogether: a "WF-band" radiometer with eight channels from 90 to 119 GHz and a "G-band" radiometer with four channels from 183 to 206 GHz. TROPICS will provide high-revisit microwave nearly global observations of precipitation, temperature, and humidity (Fig. 3).

Another passive radiometer instrument was flown on GSFC's 3U IceCube mission, which carried an 874-GHz submillimeter-wave radiometer for cloud ice observations [29]. At 874 GHz, ice cloud scattering in Earth's atmosphere produces a larger brightness temperature depression than at lower frequencies, which can be used to retrieve vertically integrated cloud ice water path (IWP) and ice particle size. IceCube's compact submillimeter radiometer is based on just one channel of the compact scanning submillimeter wave imaging radiometer, a multiband airborne conical and cross-track imager.

Lidars—The Lunar Flashlight mission, a collaboration between JPL and MSFC, is manifested to launch with NASA's Artemis 1 mission to the Moon, and its 6U CubeSat spacecraft will maneuver into a lunar polar orbit and then use near-infrared

Fig. 3 TROPICS CubeSat.
Courtesy MIT/Lincoln Laboratories.

lasers to reflect off the surface to distinguish water ices from regolith. The lasers will operate in 1 ms train pulses, though they are more of a reflectometer than a true Lidar [30]. McGill and Yorks [31] have proposed a compact Lidar known as TOMCAT for cloud and aerosol profiling.

Lightning imagers—Brazil's RaioSat project [32] is designed to detect intracloud and cloud-to-ground lightning flashes simultaneously, using an optical sensor and a VHF antenna onboard a 3U CubeSat platform. Lightning detections will be validated by comparison with data from existing ground networks. The sensor payload is a VHF passive antenna (frequency range from 50 to 200 MHz) and a spectral imaging camera (spectral range 700–900 nm) using a CCD with resolution of 2048 × 1536 pixels for surface imaging at 80 m/pixel.

Multiple angle/polarimeter—The 3U HARP CubeSat mission, a joint effort by UMBC and Utah State's Space Dynamics Lab (SDL), targets measurements of the microphysical properties of cloud water and ice particles in the atmosphere using a hyperangular imaging polarimeter [33]. The HARP sensor is a wide field of view visible/NIR imager that splits three spatially identical images into three independent polarizers and detector arrays. This technique achieves simultaneous imagery of three polarization states and is the key innovation to achieve high polarimetric accuracy with no moving parts. HARP's hyperangular channel has up to 60 viewing angles per pixel at 670 nm, and three additional channels can provide up to 20 viewing angles per pixel at 440, 550, and 670 nm, with 2.5-km spatial resolution at nadir.

Ocean color spectrometer—The University of North Carolina's Seahawk satellites are 3U CubeSats built by AAC Clyde Space that measure ocean color using eight visible/NIR bands in the same range as SeaWIFS (402–885 nm), at spatial resolutions from 75 to 150 m, with SNR comparable with its predecessor SeaWIFS. The ground swath for each ocean color image frame is 216 × 720 km. The Seahawk instrument is a push-broom design, with four linear array CCDs, each containing three rows of detectors, scanning the field of view as the satellite passes overhead. Saturation is avoided on either the land or clouds using a technique called bilinear gain. Seahawk-1 launched in December 2018 and returned its first ocean color image in March 2019 [34].

Precision orbit—The University of Toronto's CanX-4&5 mission was a dual-nanosatellite formation flying demonstration [35]. The mission achieved its objectives in spectacular fashion by proving that satellite formation flying can be accomplished with submeter tracking error accuracy and low ΔV capability, achieving submeter control of satellite separation and subcentimeter relative position knowledge. Project LEDsat [36] is a collaborative international project designed to improve the identification and orbit determination of CubeSats in LEO. Multiple methods of measuring positions will be flown on the same spacecraft: GPS, optical tracking, satellite laser ranging (SLR), and radio tracking. These satellites will also be equipped with light-emitting diodes (LEDs) for optical tracking while the satellite is in Earth shadow.

Radar altimeters—The NASA-funded SNoOPI 6U CubeSat mission, currently under development, will use reflectometry to exploit UHF (P-Band) signals from geostationary communication satellites to retrieve root-zone soil moisture [37]. The technique cross correlates the direct signal received from GEO with the signal reflected from the ground, using the amplitude and phase of the result to retrieve variations in the reflection coefficient related to subsurface moisture changes. Adding in precision orbit determination to fix the location of the receiver CubeSat allows similar measurements to be used for altimetry, though shorter wavelengths (e.g., Ka-band) are preferred for this type of measurement [38].

Scatterometers—Building on a technique first demonstrated using a much larger instrument, the L-band SIR-C radar [39], the Cyclone Global Navigation Satellite System (CyGNSS) mission [40] is the first science mission utilizing a bistatic radar scatterometer to characterize surface ocean winds through GPS reflections, especially under tropical cyclones. CyGNSS was implemented as a partnership between the University of Michigan and the Southwest Research Institute (SwRI). CyGNSS measures the shape and power of the delay-Doppler map in the GPS signals reflected from the ocean surface, which are modulated by roughness induced by near-surface winds [41]. The CyGNSS science team has been very creative in finding broader applications for CyGNSS measurements over land, indicating great promise for future measurements of soil moisture, for example, which compare favorably with those from NASA's much larger (and costlier) SMAP mission [42]. Each CyGNSS spacecraft in the eight-satellite constellation carries a pair of GPS antennas, mounted on the bottom and facing Earthward, providing high revisit rate observations between ±35-degree latitude. The CyGNSS spacecraft are properly designated as SmallSats, but their GPS reflections instrument could be sized to fit on a 12U CubeSat.

Neutron spectrometers—Arizona State University's Lunar Polar Hydrogen Mapper (LunaH-Map) is another Artemis 1 mission, a 6U CubeSat that will propel itself into a polar orbit around the moon with a low altitude (5–12 km) perilune centered on the lunar South Pole, near the Shackleton crater. LunaH-Map, illustrated in Fig. 4, will carry two neutron spectrometers that can map neutron emissions from near-surface hydrogen (H) at spatial scales of ~7.5 km/pixel. This is made possible by an innovative new scintillator technology called an elpasolite, specifically Cs2YLiCl6:Ce (CLYC), with high neutron detection efficiency across a wide energy range [43].

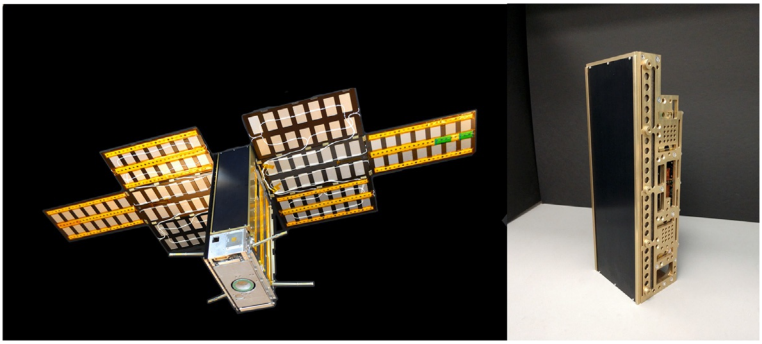

Fig. 4 LunaH-Map's Neutron Spectrometer (Mini-NS) left and spacecraft right. Images courtesy Arizona State University.

2.2 Instruments for astronomy and heliophysics

Thus far, this chapter has focused on instruments used for remote sensing of planetary surfaces and atmospheres, particularly for Earth. In the following, CubeSat instruments used for astronomy and heliophysics are addressed in the context of the missions on which they are flown.

UV/Vis/IR telescopes—ASTERIA was a compact, visible/near-IR (500–900-nm wavelength range) telescope mounted on a 6U CubeSat platform (Fig. 5) and flown in LEO. In a collaboration between MIT, JPL, and Morehead State University, the mission's objectives were to demonstrate fine pointing and thermal control of the detector array while staring at distant stars to look for exoplanet transits using the technique of precision photometry. The ASTERIA team was successful in achieving all of the mission objectives: demonstrating 0.5 arcsecond pointing by tracking a set of guide stars on the CMOS detector and moving a piezoelectric stage to compensate for residual pointing errors; 0.01 K temperature stability over an observing period of 20 min; and detection of the transit of exoplanet 55 Cancri e across the face of its parent star in 2018 [44]. During operations, Morehead State University tracked the spacecraft, providing the telemetry and control services to the Mission Operations team at JPL, while MIT performed target selection and analysis of stellar photometry data from ASTERIA.

In a collaboration between Arizona State University and JPL, the Star-Planet Activity Research CubeSat (SPARCS) spacecraft will carry a UV telescope (162- and 280-nm wavelength bands) in a LEO orbit to observe time-domain variability in low-mass stars and assess the habitability of those that harbor planetary systems. The enabling technology for SPARCS is the highly sensitive delta-doped

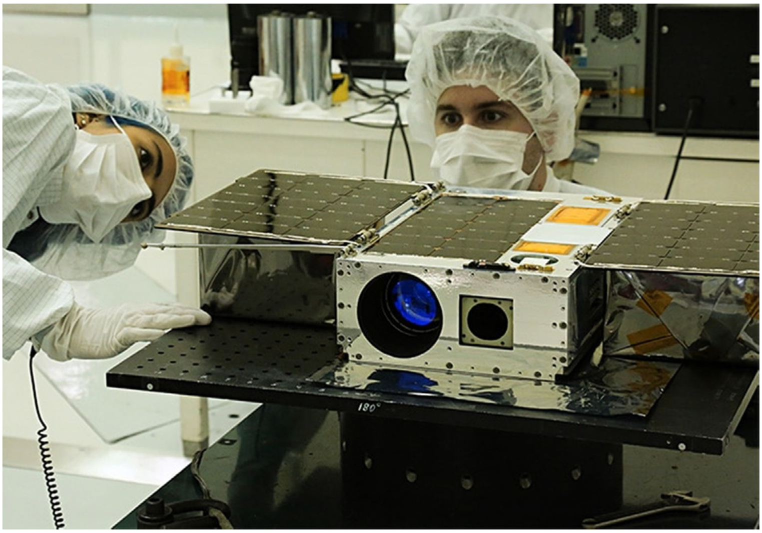

Fig. 5 The ASTERIA spacecraft in integration and test in JPL's CubeSat Development Lab. Courtesy NASA/JPL/Caltech.

detectors it uses [45]. This example of time-domain astronomy is a unique use of CubeSats, which can stare at a single bright star for extended periods—unlike larger telescopes that are generally tasked to observe multiple objectives in different locations in the sky.

The Gravitational-wave Ultraviolet Counterpart Imager (GUCI) Mission, led by NASA GSFC, is a time-domain observatory under consideration for flight within the Small Explorer program. GUCI consists of two 12U CubeSats in LEO orbits, each instrumented with a wide-field (50 square degrees) dual-band UV (190–220 and 260–290 nm) imager. The concept of operations for GUCI is to uplink occurrences of binary neutron star mergers detected by ground-based gravitational wave observatories and then scan the sky to localize them via their UV signature within an average of 1 h. Localization of such transient events then allows ground-based telescopes to observe their time-varying signatures at longer wavelengths, as they cool. While not tracking down neutron star mergers, GUCI will study other energetic, transient phenomena, such as accretion around supermassive black holes, and core collapses in supernovae, by conducting a first synoptic survey of the UV transient sky, imaging 1500 square degrees every 3 h to a depth of 19.0 mag (AB) [46].

Another time-domain astronomy mission, GSFC's 6U BurstCube, will detect long gamma ray bursts (GRBs), attributed to the collapse of massive stars and short GRBs (sGRBs), resulting from binary neutron star mergers while monitoring other gamma ray transients in the energy range 10–1000 keV. Models of binary star mergers predict that short GRBs are generated alongside gravitational waves that can now be detected by ground-based observatories such as LIGO. BurstCube will enhance the likelihood of coincident detection and the number of short GRBs that can be correlated with gravitational wave signals. The BurstCube gamma ray detector contains four CsI scintillators coupled with arrays of compact low-power silicon photomultipliers (SiPMs) on a 6U CubeSat. This first BurstCube can be seen as a pathfinder for a future Gamma Ray Observatory—a constellation of up to 10 BurstCubes providing all-sky, time-domain observations for GRBs and localization of their point of origin [47].

Fields and particles—NASA and other space agencies fly many space missions to study heliophysics, particularly the interaction of the solar wind with the Earth's magnetosphere and upper atmosphere. The instruments these missions carry measure strong electromagnetic fields and the properties of energetic particles. The intensity of the signals these instruments are designed to observe means that miniaturized versions can still be very effective, even when making measurements over relatively short timescales.

NASA's first science CubeSat was Min-XSS, launched in 2016 and operated for almost a year [48]. In a collaboration between the University of Colorado, Southwest Research Institute, NASA GSFC, and NCAR, this 3U CubeSat was a heliophysics mission, studying soft X-rays generated by the sun and their interaction with Earth's atmosphere, using a miniature solar X-ray spectrometer instrument. Miniaturized silicon drift detectors that can operate in the 0.5-keV (25 Å) to 30-keV (0.4 Å) range with ~0.15-keV FWHM spectral resolution were the enabling technology for Min-XSS measurements.

Another notable heliophysics science mission is NASA GSFC's first 6U CubeSat, Dellingr [49]. The measurement made by Dellingr's instrument suite of a gated ion/neutral mass spectrometer, and three fluxgate magnetometers are used to study coupling of the solar wind with the magnetosphere and its effects on Earth's ionosphere.

The CubeSat mission to study Solar Particles (CuSP) is a 6U CubeSat manifested on the Artemis 1 launch of the SLS planned for 2021. CuSP carries three small but capable instruments: the Suprathermal Ion Spectrograph (SIS) from SWRI to detect and characterize low-energy solar energetic particles; GSFC's miniaturized Electron and Proton Telescope (MERiT), which will return counts of high-energy solar energetic particles; and JPL's vector helium magnetometer (VHM). From its vantage point in interplanetary space (away from the influence of Earth's magnetosphere), CuSP will measure variability in the solar wind and solar magnetic fields, as a kind of space weather "sentinel" [50].

Radio interferometer—Recently selected for flight by NASA, SunRISE will be the first radio interferometer flown in space. In a collaboration between the University of Michigan and JPL, the SunRISE instrument is a "science swarm" of 6U CubeSats that together form a high-frequency (HF) radio interferometer to observe coronal mass ejections from our sun. This constellation of six CubeSats will fly in a loose formation at separations from 1 to 10 km in a GEO "graveyard" orbit (just above GEO) as a synthetic aperture radio telescope to study a critical problem in solar physics: how solar energetic particles are accelerated and released into interplanetary space [51]. They will be delivered to their orbit as a hosted payload on a Maxar communication satellite via Maxar's Payload Orbital Delivery System (PODS). Once on orbit, each CubeSat is pointed toward the sun and uses an HF receiver (Fig. 6) to measure radio emissions

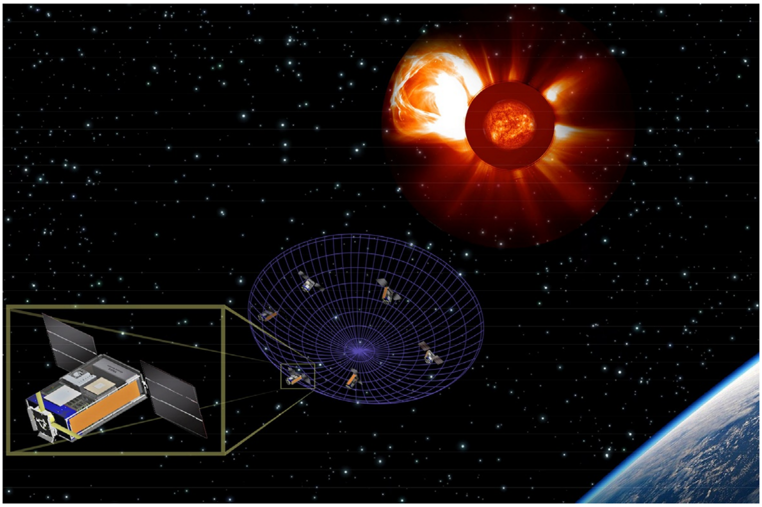

Fig. 6 The SunRISE mission concept—a constellation of CubeSats that combine to form the first HF radio interferometer in space, studying coronal mass ejections (CMEs) through their radio emissions.
Courtesy NASA/JPL/Caltech.

from 0.1 to 25 MHz—a frequency range not observable from the Earth's surface due to the ionosphere. Signals collected by the synthetic array will be combined on the ground. Radio frequency emissions generated by coronal mass ejections will be tracked and localized.

3 The future of CubeSat instruments

The range of instruments being proven to be viable for the CubeSat form factor, as can be seen from this discussion, is ever increasing. The sensitivity of these instruments, in some cases, approaches that of instruments designed for larger, monolithic spacecraft. Instrument designers have found creative ways to calibrate CubeSat instruments, so the quality of the data they collect can be favorably compared to data acquired by larger, more expensive instruments. As the on-orbit success rate of these instruments trends ever upward, so too will the efforts to further evolve these measurements and to miniaturize other types of instruments, advancing the technological evolution of CubeSat missions.

The enabling technologies described in previous chapters and the miniaturized instruments described herein have ushered in the first generation of science-grade CubeSats for Earth observation and will soon enable true interconnected constellations of MicroSats and CubeSats. Earth observation missions will ultimately also be revolutionized through the implementation of constellations of SmallSats with highly capable, miniaturized instruments. Heliophysics is undergoing a similar revolution. Time-domain astronomy, observing time-varying or transient phenomena such as stellar flares, seems to be a very fruitful niche for CubeSats in astronomy. In the very near future, the Artemis 1 fleet of CubeSats will demonstrate that science quality measurements can be achieved with interplanetary CubeSats. It seems clear that, despite the "tyranny of the rocket equation," planetary science missions in the future will build on this foundation to go further than they do today, touch more objects in our solar system, return far more information, and be implemented for budgets and schedules that can only be dreamed of today.

In the future, it may be common practice to incorporate CubeSat/NanoSat ride-alongs on Flagship missions to enable science measurements at close range and in environments that would be considered too risky for the primary spacecraft. This future is already on the verge of being realized by the selection of the Italian Space Agency's LICIAcube CubeSat as a ride along for NASA's Double Asteroid Redirect Test (DART) mission [52] and the Asteroid Prospection Explorer (APEX) and Juventas CubeSat ride along for ESA's Hera mission [53]. The science yield of both the DART and Hera primary missions, planned to launch in the early 2020s toward their destination—the Didymos binary asteroid pair—will be significantly enhanced by their CubeSat companions. LICIACube will carry a camera to observe the larger DART spacecraft as it impacts the smaller of the two Didymos asteroids. The Juventas CubeSat plans to carry a low-frequency radar to probe the interior of the smaller asteroid. The planned payload for APEX is ambitious for a 6U CubeSat: an imaging spectrometer, a magnetometer, a compact mass spectrometer, and a Lidar. As we have seen in this chapter, ambition is not particularly bounded, given the ingenuity of the CubeSat community.

Projecting a little farther into the future, small landers with instruments demonstrated on CubeSat missions will allow us to explore the surface and even the subsurface of planetary bodies. Science results from these smaller, subsidiary missions may often have a higher profile than results from the primary mission and likely will attract much greater public attention—as Philae did on Rosetta. Recent trends also suggest launch costs/kg will continue to decline and spacecraft capabilities will continue to expand. In all, new eras of space exploration and Earth observation from the high ground of space are being ushered in by CubeSat and SmallSat technologies, particularly science instruments. The space paradigm of the future will no doubt incorporate CubeSats and NanoSats as a central element of the new exploration architecture.

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