The CubeSat Revolution

Peter Kretschmar & Michael Küppers, with inputs by Roger Walker and others
What are we talking about?

- Small satellites of standardised external cubic unit dimensions launched inside a container.
- Small, cheap, fast to develop. In reach of universities and of countries without major space sector.

1 unit = 1 L = 10x10x10 cm

1 unit
1 kg

2-unit
2-3 kg

3-unit
3-6 kg

6-unit
6-12 kg

12-unit
12-24 kg

16-unit
16-32 kg

27-unit
27-54 kg
CubeSats are **really** small
CubeSats are really small
But there are a lot now (approaching 1000)

https://sites.google.com/a/slu.edu/swartwout/home/cubesat-database
Their average size is increasing

https://sites.google.com/a/slu.edu/swartwout/home/cubesat-database
But reliability could still be improved
Geographical distributions, builders & launchers

**CubeSats by Nationality of the Builder (non-constellation)**

- **Asia**: 6.9%
- **China**: 4%
- **Japan**: 7.3%
- **Europe**: 20.3%
- **USA**: 53.7%

**CubeSats by Nationality of Launch Vehicle (No Constellations)**

- **ISS**: 18.1%
- **India**: 13.9%
- **China**: 4.6%
- **Russia**: 17%
- **USA**: 41.4%
- **Europe**: 2.4%
- **Japan**: 2.6%
IOD CubeSat mission implementation in GSTP

>16 MEuro in ESA GSTP FLY Element since 2013 for 12 IOD CubeSat missions

- **Netherlands:** Star tracker devt & TFO, S-band radio devt (ISISpace), HyperScout TFO (Cosine)
- **Sweden:** GOMX-4B Propulsion (Gomspace SE)
- **Finland:** PICASSO Multi-spectral imager (VTT), Solar X-ray Flux Monitor IOD mission (Reaktor Space)
- **Switzerland:** RACE viscam (MICOS) & docking mech. (Almatech), Austria: OPS-SAT IOD Mission (TU Graz tech lead/SE, Magna Steyr), PRETTY IOD Mission (RAUG, TU Graz, Seibersdorf)
- **Hungary:** RadCube IOD mission (C3S/MTA EK)
- **Denmark:** GOMX-3, GOMX-4B, GOMX-5, RACE IOD Missions
- **Romania:** RACE GNC testing
- **Poland:** OPS-SAT (GMV OBSW, SRC/CreoTech TMTC), RACE GNC (GMV), RADCUBE mag boom (Astronika)
- **Belgium:** QARMAN (VKI), PICASSO (BISA), SIMBA (RMIB, KUL), PROBA V Companion (Aerospacelabs)
- **United Kingdom:** PICASSO p/f (Clyde Space), QARMAN s/w (Bright Ascension), RADCUBE magnetometer (ICL)
- **Italy:** CubeSat dispenser
Qarman (3U) studying atmosphere re-entry
GOMX-3 (3U) demonstrating new platform technologies
GOMX-4b (6U) demonstrating constellation technologies
PICASSO (3U) studying the atmosphere
SIMBA (3U) monitoring climate variables
PRETTY (3U) demonstrating GNSS reflectometry
RACE (2x6U) demonstrating rendezvous and docking
RadCube (3U) measuring space radiation and magnetic field
XFM Cube (2U) measuring X-Ray fluxes
M-ARGO (12U) demonstrating asteroid rendezvous and identifying in-situ resources
HERA CUBESATS (2x6U) observing asteroid deflection assessment
Lunar CubeSats for Exploration studying Moon’s surface and its environment
→ ESA’S TECHNOLOGY CUBESAT FLEET
GSTP-funded Technologies Enabling New Missions

Ongoing Developments

Solar Array Drive Assembly (IMT Italy)
- High power generation (120 W)

Reflectarray Flat Antenna (TICRA/Gomspace Denmark)
- High RF gain (29 dBi)

Cold Gas RCS (Gomspace Sweden)
- Reaction control in deep space
GSTP-funded Technologies Enabling New Missions

Planned Near-term Developments

- **Nanosat X-band TT&C transponder EM**
- **High specific impulsion electric propulsion system**
  - **Deep space communication & ranging** (10 kbps @ 1AU)
  - **LEO re-/de-orbiting**
    - **Deep space manoeuvres** (3750 m/s @ Isp 3000s)
A handful of small satellite astronomy missions are working or on their way.

Covering radio to X-/gamma-rays.
On the verge of an astronomy CubeSat revolution

Evgeny L. Shkolnik

CubeSats are small satellites built in standard sizes and form factors, which have been growing in popularity but have thus far been largely ignored within the field of astronomy. When deployed as space-based telescopes, they enable science experiments not possible with existing or planned large space missions, filling several key gaps in astronomical research. Unlike expensive and highly sought after space telescopes such as the Hubble Space Telescope, whose time must be shared among many instruments and science programs, CubeSats can monitor sources for weeks or months at a time, and at wavelengths not accessible from the ground such as the ultraviolet, far-infrared and low-frequency radio. Science cases for CubeSats being developed now include a wide variety of astrophysical experiments, including coelophases, stars, black holes and radio transients. Achieving high-impact astronomical research with CubeSats is becoming increasingly feasible with advances in technologies such as precision pointing, compact sensitive detectors and the miniaturization of propulsion systems. CubeSats may also pair with the large space- and ground-based telescopes to provide complementary data to better explain the physical processes observed.

- A handful of small satellite astronomy missions are working or on their way.
- Covering radio to X-/gamma-rays.
BRITE (BRIght Target Explorer) Constellation

- Network of five working nanosatellites (Austria, Poland, Canada).
- Stellar variability of bright stars followed by high precision long-term photometry in two colours (red and blue).

<table>
<thead>
<tr>
<th>Organisation</th>
<th>Consortium</th>
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<tbody>
<tr>
<td>Deployed</td>
<td>2013–2014</td>
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<tr>
<td>Size Factor</td>
<td>2×2 U</td>
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<tr>
<td>Status</td>
<td>Working</td>
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Graph showing referred and non-referred publications from 2013 to 2018.
ASTERIA (Arcsecond Space Telescope Enabling Research in Astrophysics)

- Technology demonstration and opportunistic science mission.
- Demonstrated pointing stability better than 0.5 arcsec RMS over 20 minutes and pointing repeatability of 1 milliarcsec RMS from orbit-to-orbit. Thermal stability of +/-0.01 K
- Optics: f/1.4 85 mm Zeiss lens 28.6-deg FOV.
- In extended mission to search for new exoplanet transits around nearby, bright stars.

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PicSat: (Not) unravelling the Beta Pictoris system

- Try to observe the transit of the young exoplanet Beta Pictoris b in front of its bright and equally young star Beta Pictoris. Secondary goal: transits of smaller bodies.
- Payload designed for main goal: 5 cm telescope coupled to a single-pixel avalanche photodiode by a single-mode optical fiber (fits in 1U).

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<tr>
<th>Organisation</th>
<th>Paris Obs.</th>
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<tr>
<td>Launched</td>
<td>Jan 2018</td>
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<td>Fell silent</td>
<td>Mar 2018</td>
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<td>Size Factor</td>
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<td>Status</td>
<td>Failed</td>
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HaloSat

- Study hot halo of Galaxy in soft X-rays (0.4–2 keV). Map OVII and OVIII line emission in ~200 fields of ~10 deg diameter each → distribution of halo.
- Addresses “missing baryon problem”, implications for cosmology.
- Planned 1-year mission, results some months later.

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Kaaret, HaloSat Overview, 2016
HaloSat

- Study hot halo of Galaxy in soft X-rays (0.4–2 keV). Map O\textsc{vii} and O\textsc{viii} line emission in ~200 fields of ~10 deg diameter each → distribution of halo.
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Kaaret, HaloSat Overview, 2016
Educational Irish Research Satellite (EIRSAT) 1

- Includes Gamma-ray Module (GMOD) with new silicon photomultiplier technology, novel attitude control system (Wave-Based Control, WBC), and test of protective coatings used for Solar Orbiter.
- Expected to detect ~20 GRBs per year.

Organisation: UCD & ESA Edu. Office
Deployed: 2020 (TBC)
Size Factor: 2U
Status: Develop

Murphy et al., Proc. SSEA 2018
Colorado Ultraviolet Transit Experiment (CUTE)

- Characterize the composition and mass-loss rates of exoplanet (hot Jupiter) atmospheres during transits.
- Near-ultraviolet (NUV) transmission spectroscopy from 255 to 330 nanometers (nm). Spectrally resolved lightcurves.
- Nominal mission: 7 months.
- *Not to be confused with other CUTE CubeSats* ...

**Organisation** | Univ. Colorado & NASA
**Deployed**    | 2020 (TBC)
**Size Factor** | 6U (3×2)
**Status**      | Develop

*Fleming et al. 2018, JATIS 4(1), 014004*
Star-Planet Activity Research CubeSat (SPARCS)

- High-energy radiation environment of exoplanets.
- FUV (153–171 nm) and NUV (258–308 nm) monitoring of low-mass stars (0.2–0.6 M_{\odot}).
- Each star observed for at least one stellar rotation (4–45 days). 25 M stars in 2 years.
- Stellar UV activity impacts atmospheric loss, composition and habitability.

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<th>Organisation</th>
<th>Arizona State Univ. &amp; NASA</th>
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<td>Develop</td>
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BurstCube

- Detect gamma ray transients, possibly GW event counterparts, in the 10–1,000 keV energy range.
- Detectors similar to Fermi-GBM.
- Rapid localization distribution via GCN.
- Ultimate goal: fleet of 10 BurstCubes for full all-sky coverage.

Organisation: GSFC
Deployed: 2021 (TBC)
Size Factor: 6U (3 × 2)
Status: Develop

Racusin et al., POS (ICRC2017) 760
A subjective selection of further ideas

- **CubeSpec** [Belgium]: 6U CubeSat for near-UV/optical/near-IR spectroscopy.
- **BlackCAT** [USA]: 6U CubeSat for GRB prompt and afterglow emission and detection of electromagnetic counterparts of gravitational waves in soft X-rays.
- **CAMELOT** [Hungary, Czech Republic, Japan]: Fleet of at least nine 3U CubeSats for all-sky monitoring and localisation of soft gamma-ray transients.
- **Sharjah-Sat-1** [UAE, Turkey]: Hard X-ray (25–200 keV) CubeSat based on detector first flown in Turkish BeEagleSat (not accepting commands).
- **HERMES** [Italy, Germany]: Constellation of up to hundreds of 1U CubeSats covering few keV to 2 MeV.
- **COMPOL** [France]: 3U CubeSats dedicated to the spectral/timing/polarization study of bright X-ray/γ-ray sources in the 20–200 keV energy range. Each CubeSat focusing on one source (20 Msec / year). 


Current state and outlook

- **Gamma-ray**
- **X-Ray**
- **UV**
- **Optical**
- **Infrared**
- **Radio**

**2013**  |  **2015**  |  **2017**  |  **2019**  |  **2021**

- BRITE (4U)
- HaloSat (6U)
- ASTERIA (6U)
- **PicSat (3U)**
- SPARCS (6U)
- CUTE (6U)
- **BurstCube (6U)**
- **EIRSAT-1 (2U)**

**Satellites**
- **Sharjah-Sat-1**
- COMPOL
- CAMELOT
- HERMES
- **BlackCAT**
- **CubeSpec**
Cubesats in Interplanetary Space

- First interplanetary cubesats just arrived at Mars
- All missions in the next few years are piggyback opportunities
  - Propulsion and Communications are the main challenges for stand-alone cubesats beyond earth orbit

MARs Cube One
Terminology

• In what follows, we limit ourselves to cubesats (smallsats that follow the cubesat form factor, made of 10 x 10 x 10 cm$^3$ boxes)
• There are other smallsats (e.g. Minerva rovers carried to Ryugu on Hayabusa 2)

18 x 7 cm
< 2U
~1kg
First cubesats on a planetary mission

- MARs Cube One (MARCO) cubesats launched with Insight
- Separated shortly after launch
- Flew by Mars and served as communications relay for Insight during descent and landing
- 18.5 M$ mission cost, 2 x 6U

Image of Mars from 7600 km (Marco-B)

EXPLORATION MISSION-1

The first crewed, integrated flight test of NASA’s Orion spacecraft and Space Launch System rocket, launching from a modernized Kennedy Space Center

1 LAUNCH
SLS and Orion liftoff from pad 39B at Kennedy Space Center

2 JETTISON ROCKET BOOSTERS
Solid rocket boosters separate

3 JETTISON LAUNCH ABORT SYSTEM & CORE STAGE SEPARATION
The LAS is no longer needed, Orion could safely abort at anytime; core stage separation and engine shut down

4 ENTER EARTH ORBIT
Perform the perigee raise maneuver

5 FINAL RETURN TRAJECTORY CORRECTION (RTC)
Precision targeting for Earth entry

6 OUTBOUND TRANSIT
Requires several attitude maneuvers and Optical Navigation Checkout

7 CUBESATS DEPLOY
ICPS deploys 13 CubeSats total

8 RETURN TRAJECTORY BURN
Precision Trajectory Burn aiming for Earth’s atmosphere

9 OUTBOUND TRAJECTORY CORRECTION (OTC)
As necessary adjust trajectory for Lunar insertion to DRO

10 OUTBOUND POWERED FLY-BY
Results in DRO insertion; 62 miles from the Moon

11 DISTANT RETROGRADE ORBIT (DRO)
Burn maneuver and solar panel adjustment; 37,000 miles from the surface of the Moon

12 ORBIT INSERTION
Enter Distant Retrograde Orbit for next 6-10 days

13 RETURN TRANSIT
Return Trajectory Correction burn prep; travel time 6-10 days

14 RETURN POWER FLY-BY (RPF)
RPF burn prep and return coast to Earth initiated

15 FINAL RETURN TRAJECTORY CORRECTION (RTC)
Precision targeting for Earth entry

16 RE-ENTRY INTERFACE
Enter Earth’s atmosphere

17 SPLASHDOWN
Pacific Ocean landing within view of the U.S. Navy recovery ships

Total distance traveled: 1.3 million miles – Mission duration: 25.5 days – Re-entry speed: 24,500 mph (Mach 32) – 13 CubeSats deployed
13 Cubesats on Exploration Mission 1

Lunar Flashlight
- Lunar polar orbit
- IR spectrometer to search for water ice deposits

Near-Earth Asteroid Scout
- Close flyby of a near-earth asteroid using a solar sail

Cislunar Explorers
- Demonstrate water propulsion and optical telecommunications
Asteroid Impact Deflection Assessment (AIDA)
AIDA mission overview

06/10 - 08/22
DART IMPACT

HERA CRUISING TO DIDYMOS

AUTONOMOUS PROXIMITY OPERATIONS DEMONSTRATION

ASTEROID RESOURCES DEMONSTRATION INVESTIGATION

LANDING ON DIDYMOS MAIN MISSION ENDS

DIDYMOS

MULTI-POINT ASTEROID INVESTIGATION

DETAILED CRATER SHAPE INVESTIGATION

DETAILED SUBSURFACE CRATER INVESTIGATION

DETAILED CHARACTERISATION PHASE
Measuring surface and interior properties

CUBESATS RELEASE

ADDITIONAL ASTEROID FLYBY

EARLY CHARACTERISATION PHASE
Measuring mass and dynamics

DIDYMOS
Cubesats on AIDA: 1 LICIA (Light Italian Cubesat for Imaging of Asteroids) on DART

- Imager: Based on Argomoon cubesat on Exploration mission 1
- Will be deployed from DART before impact and flyby the asteroid
- Imaging of impact ejecta
- Imaging of impact crater?
Cubesats on AIDA: 2 APEX on Hera

Apex

Payload:
• Fabry-Perot imaging spectrometer (vis. + near-IR)
• Secondary ion mass analyser
• Magnetometer

End of Life Operations (EOL) – includes landing on Asteroid(s)

Inner System Science Operations (ISSO)

Outer System Science Operations (OSSO)

CubeSat Advantage
Greater agility
Higher risk tolerance: allowing the spacecraft to operate in locations and take measurements where Hera cannot.
Provide complementary observations from a close distance

European Space Agency
Cubesats on AIDA: 3 Juventas on Hera

30 x 20 x 10 cm³!
The Future

• NASA considers to send cubesats regularly on future planetary mission (e.g. on Psyche and Lucy)

• Stand-alone cubesat missions are in sight
Miniatuised Asteroid Remote Geophysical Observer (M-ARGO)

Objectives:
- Demonstrate critical technologies & operations for stand-alone deep space CubeSats in the relevant environment
- Rendezvous with a Near Earth Object (NEO)
- Physical characterisation of NEO with a small payload suite for in-situ resource exploration purposes

Mission concept:
- 12U CubeSat
- piggyback launch to Sun-Earth L2 transfer or lunar swing-by
- parking in L2 halo orbit
- 1-2 year low-thrust interplanetary transfer
- 6-month close proximity ops at NEO target
- 83 different NEO targets accessible

Status: Phase A
ITT in Q4 2018
Launch 2022

M-ARGO will lower the entry-level cost of deep space exploration by over an order of magnitude, leading to fleets of nano-probes for e.g. in-situ resource exploration of NEOs
Perspective of missions like M-Argo

• A single cubesat mission to an asteroid costs a few 10s of M€

• For the price of one M-class mission 10s of cubesats could be launched to different asteroids

• Consideration for ESAC (and ESOC): Is there a way to do operations differently/at lower price?
Finally: Cubesats as a business

- Planet Labs images the earth daily at a resolution of ~3 m
- ~300 cubesats launched
  - About 150 active
- Little detail available about the specifications of their systems
So how will the future be?
So how will the future be?
So how will the future be?