Lab to Launch

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2- Department of Electrical Engineering, Stanford University, USA

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3- The University of Auckland, New Zealand

VASSCAA-9, 2018, Sydney, August 12-16, Australia
Space and laboratory plasmas:

Except for scaling, parameter ranges of both coronal plasma and plasma arcs/jets can be achieved in the laboratory and tailored to suit many applications.
Scaling and expansion of the plasma

From capillary to very large
Pressure regime and coupling modes will be derived from given size: atm, high, medium, low pressure, pressure gradient
Crucial to the microelectronics industry
Chemical and electric propulsion

Credit: SpaceX

Credit: NASA

From Sputnik to the ISS

1957: Sputnik, 1\textsuperscript{st} satellite, 83kg
1960: Titos, 1\textsuperscript{st} Meteorology Sat.
1962: Telstart 1, 1\textsuperscript{st} Telecom Sat.
1998: International Space Station (ISS), 400 tons, >$100 billions

1999: Nano-satellites (CubeSat), 1-10 kg, $100 000

\[ T = \frac{d(mv_{ex})}{dt} \]
\[ I_{sp} = \frac{T}{(dW/dt)} = \frac{v_{ex}(dm/dt)}{g(dm/dt)} = \frac{v_{ex}}{g} \]
60 years of space use = space junk

- 29,000 objects >10 cm
- 750,000 objects from 1 cm to 10 cm
- 166 million objects from 1 mm to 1 cm

Placement of large telecom satellites on graveyard orbit, Hydrazine (new regulations)
Low-power low-cost ‘green’ thruster for small satellites, Long-term interplanetary travel
SP3_ANU rf thrusters

HDLT (Helicon Double Layer Thruster) – 2002, electrodeless radiofrequency (rf) plasma thruster
Astrium (AIRBUS) 2006-2013

DS4G (Dual Stage Four Grid thruster) – 2005-2006, ion gridded rf thruster
European Space Agency (ESA)

PR (Pocket Rocket Thruster) – 2010, electrothermal rf plasma micro-thruster
Lockheed Martin US 2013-2015

Miniaturisation
Helicon source: low pressure expanding magnetized plasma

- Double saddle field antenna
- GLASS PLATE
- Solenoids
- RF
- Gas
- Energy analyser (RFEA)
- Langmuir probe
- Current-free Double Layer

March 1999

- 13.56 MHz
- ~ 1 mTorr
- ~ 120 G diverging

Plasma potential (V) vs. Distance (cm)

- Vacuum chamber
- Pump

- Double-layer (axial)
- 90° (radial)
- 0° (axial)
Ion beam accelerated by double layer in a magnetic nozzle

Electrostatic and Electromagnetic plasma acceleration

50 eV ion beam: supersonic (≥ 10 km.s⁻¹)
Low beam divergence
$A_{\text{beam}} \sim 150$ cm²

Local downstream plasma potential

Ion beam accelerated by double layer in a magnetic nozzle

Electrostatic and Electromagnetic plasma acceleration
Inductive/wave heated radiofrequency plasma source

No neutraliser needed --> simple and low cost
No electrodes --> no erosion, extended lifetime
No moving parts --> safe and reliable
Choice of propellants (Xe, Ar, O₂, H₂, CH₄, NH₃, CO₂, N₂...)

Scalable in power (10 W-100 kW) and in geometry

The Australian Plasma Thruster
(~10 cm diam)

Helicon Double Layer Thruster: HDLT

Measurements in CO₂ plasma
HDLT Gen I Testing Campaign
at European Space Agency

April - May 2005

Xenon
1 kW
0-500 G
80 sccm
HDLT Gen II: direct thrust measurements

Surrey Space Centre UK, VIPAC, ANU (2009)
Collaboration: Iwate Uni (2011), Japan
Tohoku University Sendai (2013), Japan

Diagnostics:
- Thrust balance
- Langmuir Probe
- Energy analyser

Takahashi et al, APL 2011
Lafleur et al, APL 2011
Charles et al, APL 2012
Plasma thrust components for HDLT

Worldwide collaborations (Japan, Israel, UK, France…)
Zhang et al, PRL 106 (2016)

Momentum equation in expanding magnetised plasma

\[
T_{\text{total}}(z) = 2\pi \int_0^{r_s} rp_e(r, z_0) dr \\
- 2\pi \int_{z_0}^{z} \int_0^{r_p(z)} r \frac{B_r}{B_z} \frac{\partial p_e}{\partial r} dr dz \\
- 2\pi \int_{z_0}^{z} \int_0^{r_p(z)} \frac{\partial}{\partial r} (r m n u_r u_z) dr dz,
\]

100 W \sim 1\text{mN}
AITC: Advanced Instrumentation Technology Centre

Mount Stromlo, Canberra, Australia


APT project funded by the Australian Space Research Program

Space (e.g. thruster qualification) & Astronomy center (e.g. Giant Magellan Telescope)
Small satellites & space payloads & astronomical instrumentation Testing
Sept 4, 2013: WOMBAT XL arrives at Stromlo

WOMBAT XL
Diameter 3 m, Length 5 m
Pumping speed ~140 000 ls⁻¹
-190 to +150 °C

Large Thermal Vacuum Chamber
The largest space simulation facility in the Southern hemisphere

Dual purpose national facility:
Thermal test configuration and Thruster test configuration
Australian thermal-vac chamber: Wombat XL

develop expertise using HDLT
key technological challenges:
thrust balance for radiofrequency thrusters with $B_{\text{field}}$

HDLT Gen II++

Propulsion module
From space qualification to flight heritage

‘Premium’ access to space:
Expensive, Largely government funded, Fierce competition
Collaboration with major partners outside Australia

‘Cheaper’ access to space:
Piggy back method for cheaper access: CubeSats or arrays of CubeSats
Alternate form of funding (e.g. Kickstarter, groups of universities)

SP3 status:
Plasma physics expertise (momentum imparted by a plasma)
Engineering expertise (rf in vacuum, thrust balance), Industry portfolio

AITC status:
Open to national and international users (officially opened on July 15, 2014)
Large TV chamber, satellite shaker, clean room, anechoic chamber, labs and workshops
Emergence of small satellites

- Cheaper access to space
  - Less heavy
  - Launch in multiples
  - Piggyback on other missions
- Doing what larger satellites can’t
  - Constellations for low data rate communications
  - Multi-point measurements
  - In-orbit inspection of larger satellites
- Education
- Test/qualification of space hardware
- Growing commercial space

“Large satellites” >1000kg
(Hubble ~ 11 tons)

Small satellites (broadly) <500 kg

Image credits: NASA

NASA ST5

CubeSat
CubeSats

- Multiples of 10x10x10cm (1U) configurations
- Standardised format developed in late 90s at Cal Poly and Stanford
- Allows for multiples launched, deployment from ISS etc.
- Missions involving Earth observation, communications and science payloads
- MarCO CubeSats the first to leave Earth orbit on their way to Mars (May 2018)
- Over 800 launched as of April 2018
- Systems miniaturisation critical
Micro-satellite propulsion systems

- Chemical thrusters, Small gridded thrusters, Hall effect thrusters
- Cold Gas Thruster: No heating, low $I_{sp}$
- Arcjet: Arc heating, erosion issues, kW, part chemical
- Resistojet: Wall heating, $10^2 - 10^3$ W
- Hollow Cathode Thruster (HCT_SSTL)
- Pulsed Plasma Thruster (STRaND-1_SSTL)
- Electrospray thruster

$$T = \frac{d(mv)}{dt}$$

Cold Gas Thruster
(Courtesy of moog.com)

Pocket Rocket rf plasma thruster

SSTL Hollow Cathode Thruster

SSTL Pulsed Plasma Thruster

Busek BIT-3 RF thruster

Astrium’s hydrazine system

Busek 1mN

Electrospray: S-iEPS MIT 8 MEMS (0.1 μN)
Pocket Rocket rf micro-thruster: PR

Low-power (0.5-50 W) capacitive radiofrequency plasma source at \(~\) a few Torr

Electrothermal micro-thruster (1.5 mm diameter, 2 cm long)

Thrust from hot neutrals (ion-neutral charge exchange collisions) \(~\) 0.1-1 mN

Safe, low-cost ‘green’ propellants (Ar, Xe), best with atomic gases

rf power subsystem and gas propellant subsystem not commercially available

2010

C. Charles, and R.W. Boswell, PSST 2012
Pocket Rocket thrust in Wombat vacuum

C. Charles et al, JPP 30 (2014)
C. Charles et al, Front Phys (2016)

Mounted on thrust balance
Immersed in vacuum
Gas and rf line connected
0.1-2 mN

Partner: Lockheed Martin

Source of Power loss
Cold gas and plasma thrust component (Xe)

\[ F_{\text{total}} = F_{\text{plasma}} + F_{\text{cold gas}} \]

\[ F_{\text{cold gas}} = \dot{m}c_s \]

\[ I_{sp\text{ cold gas}} = \frac{c_s}{g_0} \]

\[ G = \frac{F_{\text{plasma}}}{F_{\text{cold gas}}} \]

Use Xe to facilitate measurement, Large loss in PCB match
Plasma thrust gain about a factor of two
(increases for decreasing flowrate)
Prototype and subsystems need optimising

C. Charles et al, Front Phys (2016)
Ion Density ($n_{\text{ion}}$)

Plasma simulation: propellant heating modelling and optimisation

T.S. Ho, C. Charles, and R.W. Boswell,
Physics of Plasmas 24, 084501 (2017)

A. Greig, C. Charles, and R.W. Boswell,
Frontiers in Physics 2, 80 (2015)
European Union QB50 CubeSat project

Multiple Scientific Instruments for the Analysis of the Lower Thermosphere

- INMS (Ion/Neutral Mass Spectrometer)
- FIPEX (Flux Probe Experiment)
- mNLP (multi Needle Langmuir Probe)

Constellation of 50 Cubesats from 27 countries: Dec 30, 2016 launch to ISS
Jan 2017 release from ISS, 1-2 year orbit, ‘open source’ www.qb50.eu

1- Lower thermosphere, ionosphere of the Earth
2- ‘plasma & gas’ sensors INMS (MSSL), mNLP (Oslo), FIPEX (Dresden)
• Originally assigned to University of Sydney

• Became a collaboration between ANU, UNSW and USyd

• Multi-Needle Langmuir Probe

• Built in Sydney based off the design of AU02 (UNSW-ECO)

• Tested in thermal vacuum chamber and vibration table (Stromlo)
Nano-satellites: a path towards flight heritage

University project: from TRL 6 to 9?

- **TRL 9**
  - Actual system "flight proven" through successful mission operations

- **TRL 8**
  - Actual system completed and "flight qualified" through test and demonstration (ground or space)

- **TRL 7**
  - System prototype demonstration in a space environment

- **TRL 6**
  - System/subsystem model or prototype demonstration in a relevant environment (ground or space)

- **TRL 5**
  - Component and/or breadboard validation in relevant environment

- **TRL 4**
  - Component and/or breadboard validation in laboratory environment

- **TRL 3**
  - Analytical and experimental critical function and/or characteristic proof-of-concept

- **TRL 2**
  - Technology concept and/or application formulated

- **TRL 1**
  - Basic principles observed and reported

Miniaturisation
Low cost
Innovation

Baseline

INSPIRE-2: a 2 U qb50 CubeSat
http://sydney.edu.au/inspire-cubesat/
QB50 Australian final Testing in Wombat XL

http://sydney.edu.au/inspire-cubesat/

INSPIRE-2: 30th September 2015, Wrapped and shipped to Europe
Flight-ready on 19th August 2016
6 months wait, launched May 2017

Disruptive technology & Need of propulsion unit
Launch to the ISS: 19 April 2017
(rescheduled from ... 30 December 2016 .... 9, 22, 24, 27 March 2017, ... 18 April 2017...)

ROCKET LAUNCH: UNITED LAUNCH ALLIANCE ATLAS V CYGNUS OA-7/ CRS-7

With AU01, AU02, AU03, Biarri-Point ➔ 4 Australian CubeSats
Wait some more before deployment in to orbit by Nanoracks
QB50: two space launches

28 CUBESATS LAUNCHED FROM THE INTERNATIONAL SPACE STATION

- **QB50-ISS**
  - 28 CubeSats
  - Altitude: 415 km
  - Inclination: 51.6 deg
  - Launched on 18th April 2017
  - Atlas-V Rocket from Cape Canaveral (USA)
  - Deployed from the ISS in May 2017

8 CUBESATS LAUNCHED ON THE PSLV INDIAN ROCKET

- **QB50-PL**
  - 8 CubeSats
  - Altitude: 500 km
  - Sun Synchronous Orbit: 97.1 deg
  - Part of the Science Campaign
  - Launched on 23rd June 2017
  - PSLV Rocket from Satish Dhawan Space Centre
• Access: Give opportunities for space access to small companies and universities
• Education: Help facilitate student involvement in space systems engineering
• Science: In-situ measurement of the thermosphere using m-NLP and INMS

Image credits: QB50, MIT
QB50 INMS testing in ANU ChiKung plasma wind tunnel experiment

Collab with Dhiren Kataria

UCL INMS sensor (12QB50s)

QB50 Flight prototype (UK)

Immobile ions & satellite at ~8 km/s

Ion analyser (RFEA) & baffle:

Fast ions & neutrals (~10 km/s) & immobile satellite

Ground-based low ion beam energy calibration <100 eV / physics (PHOENIX)
The need for ground stations

• Typical orbit altitudes for LEO are ~410-500km

• Expected lifetime of 1-1.5 yrs if starting at 400km (no onboard propulsion)

• Orbital velocity ~8km/s

• Results in two or three ~10 min passes per day for a given location (inclination dependent)

• Need many ground stations around the world to make the most of your CubeSat

Image credits: scienceabc.com
“Blue Wren” ground station (ANU)

Azimuth and elevation control

GOMspace TNC

ANU Cubesat Ground Station

VHF antenna: M2 2WCP14

Yaesu GS-232B computer-rotator interface box

Yaesu G-5500 Control box

Radio

PC

Dimitris

GOMspace TNC
• One of the only QB50 CubeSats still functional

• Built by a team of students from Cheng Kung University (Taiwan)

• Instruments:
  • INMS
  • Thermistors
  • Solar EUV sensors

• Ongoing communications with ANU ground station
  • Schedule data broadcast
  • Automated ground station

Image source: space.skyrocket.de, QB50
• Non QB50 CubeSat from LESIA Laboratory (Paris Observatory)

• Point camera at known location of young exoplanet of young star Beta Pictoris

• Excellent engagement with amateur radio community

• Radio amateurs contribute to data download

• Silence from 20 March 2018 😞
Pocket Rocket $\frac{1}{2}$ U propulsion for `CubeSat'

- **MiniPR thruster**
- **RF subsystem**
- **Argon gas subsystem**
  - Cold gas
  - Plasma

Argon, 1-10 W, $T=0.1-1$ mN, $I_{sp}<100$ s,
Flight heritage (TRL9 is the objective)
Propellant sub-system: 1/3U

Ar propellant (not N₂ due to vibrational states at low power)
Bulk plasma heating (µs) by pulsing
COTS parts for propellant sub-system (gas canisters, 3D printed tubing)

N₂, A. Greig et al, APL (2014)
Propellant sub-system: <1/2U

Ashley Ellis, Honours Thesis (2016)
Thomas Charoy, 6 months visit (2016)
Alex Stuchbery, Honours Thesis (2017)
Class Φ2 inverter: allows the use of lower voltage FETs by introducing a component of second harmonic into the amplifier and thereby reducing the peak height. Low weight, small, robust and efficient system power supply.
Stanford-ANU test campaign March 2016:

RF sub-system prototype initial testing in vacuum

Complete system in WOMBAT showing (from right) battery box, DDS, rf amplifier and 2 stage match connected to Pocket Rocket (~10 shots).
Power sub-system: current prototype status

Stanford-ANU test campaign March 2017:

Wei Liang, PhD Thesis (2017)
W. Liang et al, COMPEL 2017

>100 plasma tests (~2.4 W nominal) in vacuum with no parasitic discharges
Stanford-ANU test campaign March 2017:

Footprint suitable for CubeSats

Wei Liang, PhD Thesis (2017)
Combined subsystems testing (not in vacuum)
1U CubeSat integration

Latest prototype: battery-powered with wireless remote control
Vacuum testing of in Wombat (Sept 2017)

1- Demonstration of ignition and tuning with no parasitic discharge
2- Option of wireless control for future thrust balance measurements
Vacuum testing of all subsystems in Wombat

1- Demonstration of Pocket Rocket propulsion system for nano-satellites
2- Future possible options:
   - nozzle optimisation
   - 3 axis Pocket Rocket
   - satellite docking
Vacuum testing of Pocket Rocket in Wombat

1-Argon 1-60sccm (nominal 20 sccm), 1-100 W (nominal 5 W)
2-TRL 7 demonstration for <1/2 U CubeSat assembly (~ 500g)
Lab to Launch

SP3
http://sp3.anu.edu.au
Space Plasma, Power & Propulsion

PhD: Dimitris

Stanford University
PhD: Weston

PhD: Félicien

The University of Auckland
Te Whare Wānanga o Tamaki Makaurau
New Zealand
New Zealand Space Agency since 2016
The Auckland Programme for Space Systems

Open to all undergraduate students from across the University

Competition to choose best CubeSat mission each year

First mission, APSS-1 will be Q1 2019 with Rocket Lab USA
Ionosphere electron density measurements
Peter Beck and Rocketlab (New Zealand)

1- Launch site from Mahia Peninsula in New Zealand
2- Second flight delivered 4 spacecrafts into orbit
Find partner or $$ for
-getting 2U Engineering Model to work on interfacing Pocket Rocket with COTS
-thrust testing of complete satellite (TRL 8), mission opportunities to reach TRL 9
Lab to Launch: 2 steps to space

Australian Space Agency?