BIRDY: an interplanetary CubeSat to collect radiation data on the way to Mars and back to prepare the future manned missions

Boris Segret (1)(boris.segret@obspm.fr), Jordan Vannitsen (2), Marco Agnan (2), Audrey Porquet (4,5,6), Oussema Sleimi (2), Florent Deleflie (4,5,6), Jiun-Jih Miau (2), Jyh-Ching Juang (3), Kaiti Wang (7)

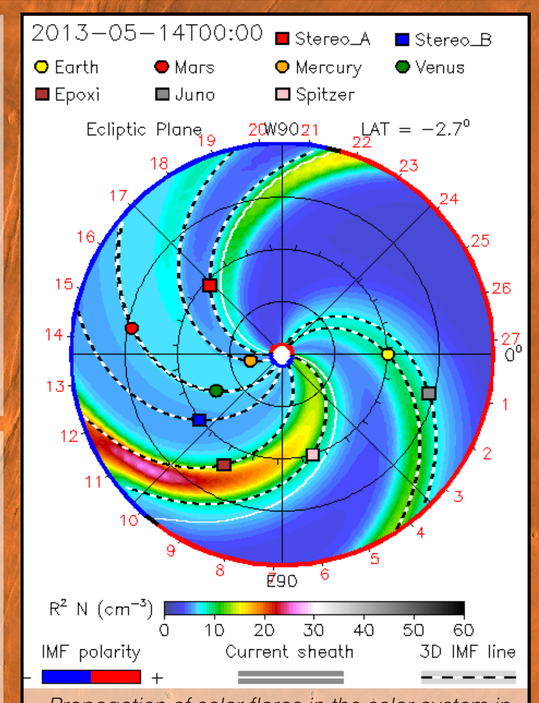
(1) Laboratoire d'Etudes Spatiales et d'Instrumentation en Astrophysique, (LESIA), Observatoire de Paris, Meudon, France. (2) National Cheng Kung University, Department of Aeronautics and Astronautics, Tainan, Taiwan. (3) National Cheng Kung University, Department of Electrical Engineering, Tainan, Taiwan. (4) Institut de Mecanique Celeste et de Calcul des Ephemerides (IMCCE) Observatoire de Paris, Paris, France. (5) Centre National de la Recherche Scientifique (CNRS), France. (6) Université Pierre et Marie Curie, Paris, France. (7) National Cheng Kung University, Institute of Space and Plasma Sciences, Tainan, Taiwan.

Space weather in interplanetary medium

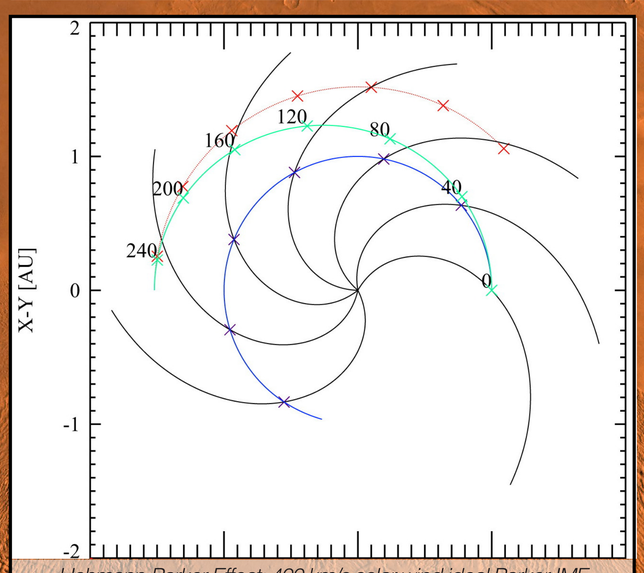
Simultaneous measurements from multiple locations in the solar system are mandatory to improve the knowledge in space weather.
BIRDY (*Bleeping Interplanetary Radiations Determination Yo-yo*), a specialized 3-Unit CubeSat (10x10x30 cm3, 4kg), is a smart and cheap solution to take part in this global effort.

The science case is to take advantage of an Earth-Mars-Earth journey to participate in the space weather understanding by gathering observational data useful to improve the current models of radiations due to the solar wind, the GCR (Galactic Cosmic Rays) and their mutual interactions. BIRDY would demonstrate the possibility of doing interplanetary space science with a single miniaturized instrument payload onboard a CubeSat platform.

BIRDY scientific and engineering objectives are:
1. to characterize the energetic particle spectrum in the energy range from 10 MeV/nucleon to 1 GeV/nucleon in interplanetary medium between Earth's and Mars' orbits, and Venus' orbit eventually;
2. to probe the arrival directions in and out of the ecliptic plane, and to measure the arrival directions and velocities of the energetic particles of interest;
3. if arbitration must be done in the design, to put a priority on the potentially hazardous radiations for a future manned mission to Mars;
4. to collect and keep the data for a duration as long as an Earth-Mars-Earth free-return trajectory, and to upload these data to a Martian orbiter and to ground stations when back nearby the Earth;
5. to autonomously estimate its own position with a Planet Tracker and to adapt its trajectory with an on-board small electric propulsion to allow a free return to Earth.



Propagation of solar flares in the solar system in 2013 (NASA Goddard Space Weather Center).



Hohmann-Parker Effect: 400 km/s solar wind ideal Parker IMF lines (black). Earth (blue), Mars (Red) spacecraft on a Hohmann trajectory (Green) and the Sun in the center (A. Posner et al., 2013).

BIRDY Radiations Payload

In 2011-2012, during the Earth-Mars cruise of the MSL (Mars Science Laboratory)-Curiosity mission, the instrument RAD (Radiation Assessment Detector, PI D. Hassler) provided the first radiation observational data on an Earth-Mars trajectory. But RAD was optimized for measures on the Martian surface, not from the interplanetary space. For BIRDY, the RAD (~25x10x10 cm^3 and 1.6 kg) is considered as a technical inspiration for a **new, miniaturized and specialized instrument** (~15x10x10 cm^3 and max. 1.5 kg) to fit into the CubeSat.

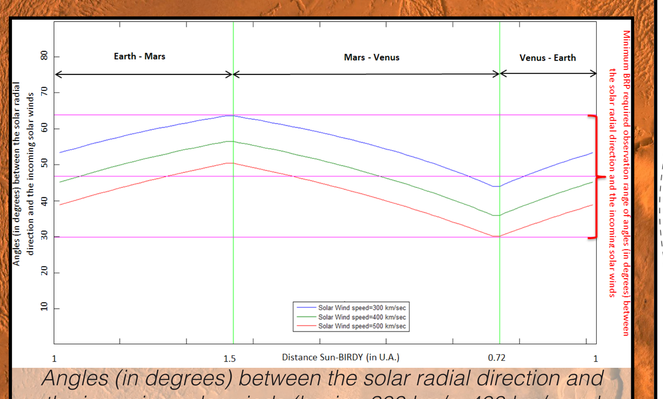
BIRDY will focus on radiations due to **GCR and SPE** (Solar Particle Events). The SPE particles get through interplanetary medium along the IMF (Interplanetary Magnetic Field). The typical angle between the IMF lines and Sun's direction is the scientific factor driving the observation attitude requirement for the payload. Preliminary studies show that BIRDY will be able to accurately observe incoming particles of the solar wind with velocities comprised between 300 km/sec and 500 km/sec. BIRDY could verify the **Hohmann-Parker effect**, which defines that a spacecraft traveling on an Earth-Mars Hohmann trajectory is magnetically connected by the same IMF line either coming from Earth, or going to Mars. If so, the same SPE flux detected by a space probe could be also detected a few hours earlier nearby the Earth and/or or later nearby Mars by other probes. Such a confirmation with BIRDY would be a bonus to contribute in space weather awareness. The secondary particles produced due to the CubeSat structure or detector may be mistakenly counted as primary particles with a lower energy than the actual primary particles. It would result in some confusion and this issue is still under investigation.

An **international call of opportunity** will offer a collaboration to a research laboratory for this payload.

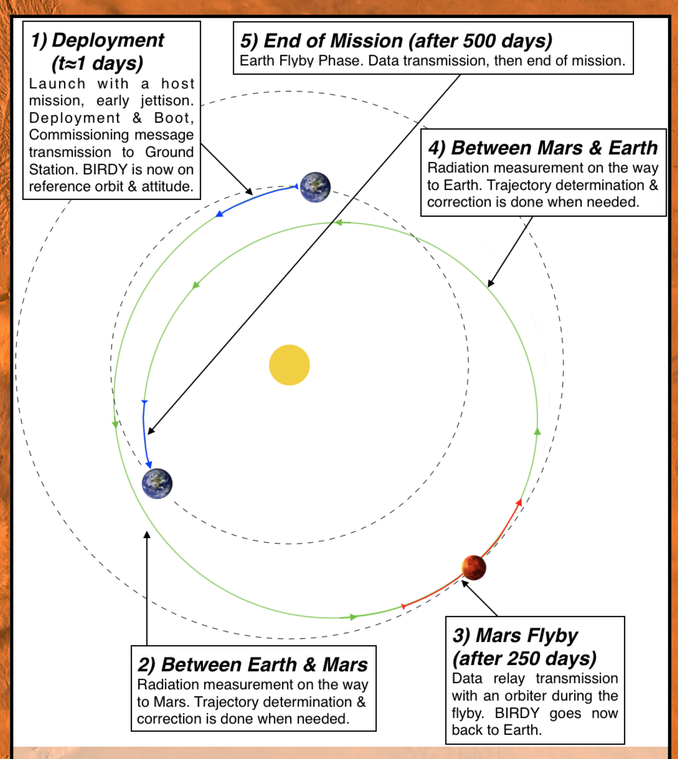
Communication (TT&C)

BIRDY is not able to do interplanetary communications. The scientific and housekeeping data recorded on the way to Mars have to be sent to an orbiter in Mars' vicinity used as a data relay to the Earth. The data rate depends mainly on the distance to the orbiter. The figure below shows preliminary analysis done on data transmission in Mars' vicinity. Further studies are needed to refine all the assumptions and to specify technical solutions (Software Defined Radio could be an option). On the way back to the Earth, BIRDY will transmit data to ground stations when arriving nearby.

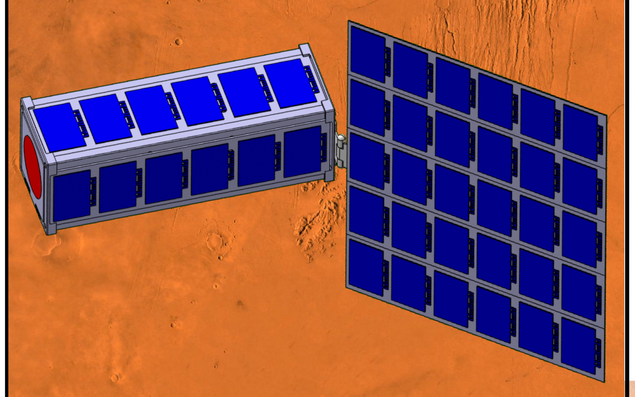
The beacon will be monitored by the Very Large Baseline Interferometer (VLBI) for BIRDY's tracking and basic house keeping data.



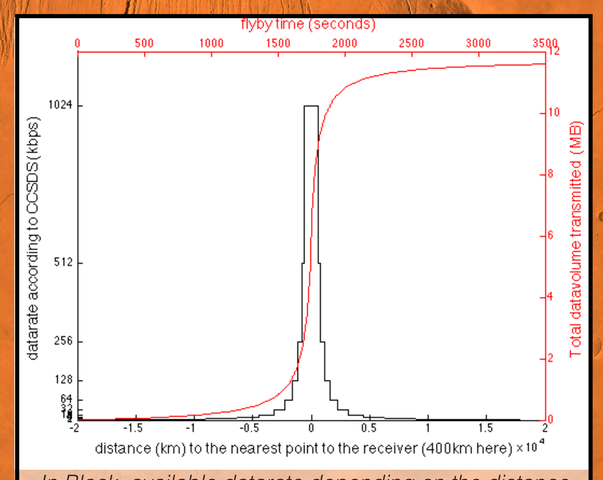
Angles (in degrees) between the solar radial direction and the incoming solar winds (having 300 km/s, 400 km/s and 500 km/s velocities) function of the Sun-BIRDY distance during the mission.



Trajectory / Timeline of the BIRDY mission.



BIRDY preliminary design version.



In Black, available datarate depending on the distance to the receiver, according to the CCSDS protocol. In red, transmissible data volume (preliminary result: 11.5 MB) depending on the maximum flyby time.

Navigation

After jettisoning from the host mission, the CubeSat is fully autonomous. An optical system provides the location of the planets in front of the sky by determining their coordinates (longitude Li, latitude li) and comparing them with the preloaded ones (L0i, l0i). The "planet tracker" consists in estimating the CubeSat's position close to a previously computed reference trajectory, by comparing the angular distances between planets and stars with the expected ones that are stored in the CubeSat's memory to calculate the needed attitude and trajectory corrections.

For those corrections, an electrical propulsion system is integrated in BIRDY, a system of liquid micro-pulsed plasma thrusters that is close to space qualification (L-µPPT, http://www.liquidppt.eu, funded by Europe's FP7 program and member of BIRDY consortium).

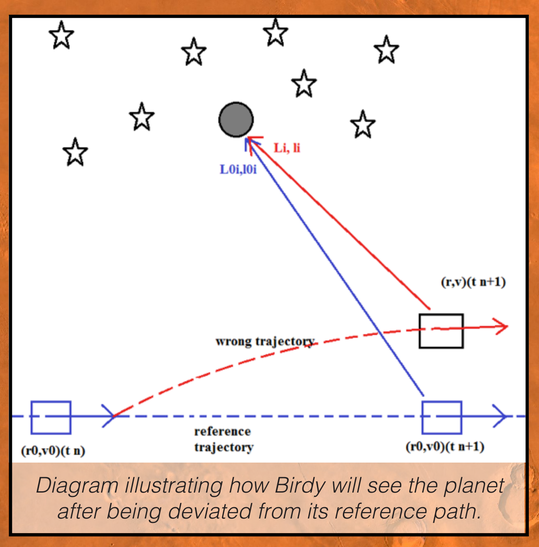


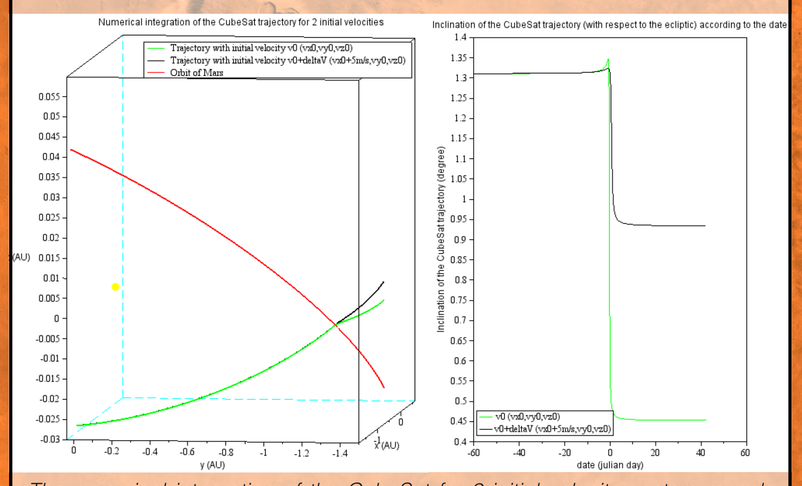
Diagram illustrating how Birdy will see the planet after being deviated from its reference path.

Reference Trajectory

A reference trajectory of BIRDY is planned according to the trajectory of the host mission going to Mars. The reference trajectory aims at a Mars flyby which modifies the inclination of the orbital plane in order to ensure a coming back to the Earth, indeed each inclination corresponds to a different date at which the CubeSat will cross the Earth orbital plane.

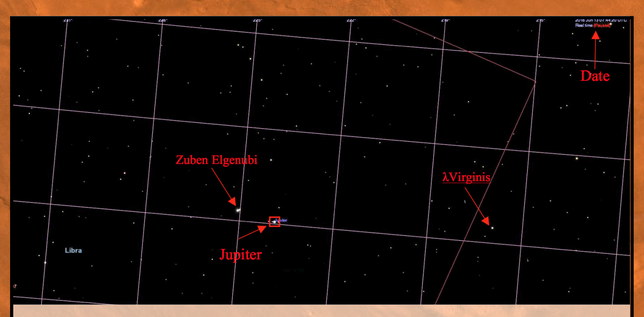
Several hypothesis must be taken into account during the CubeSat's flight because the movement is not just Keplerian between the CubeSat and a central body. In the numerical integration, the J2 (non-sphericity parameter of the Earth, Mars and the Sun) should be considered but also the radiation pressure and the influence of external bodies. The mission preparation tool belongs to the ground segment and should be available early enough to quickly assess any launch opportunity to Mars as a piggyback for BIRDY (ExoMars 2018, MSL2020, Dennis Tito 2018, …) and prepare the data which will have to be stored in the flight navigation software.

Mars Flyby

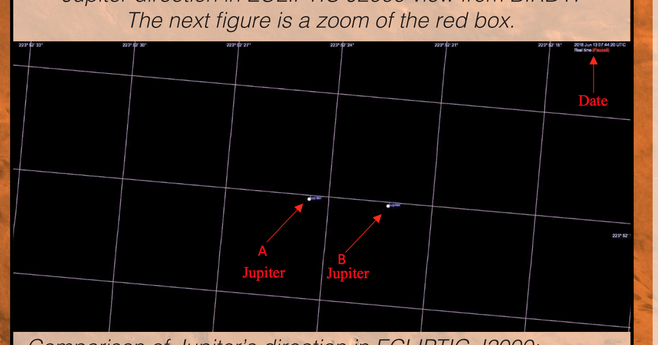


The numerical integration of the CubeSat for 2 initial velocity vectors reveals that a small ΔV applied on the trajectory of the CubeSat can have an important impact in the change of inclination of the orbital plane, close to the minimum distance to Mars: a ΔV of 5m/s only (applied at11000 km from the center of the Earth) changed the inclination from 0.95° to 0.45°.

On the right, the orbital plan inclination without ΔV (in black) and with ΔV (in green) the flyby depending on time (in days) before and after the flyby. This inclination will be decisive for a possible return of the CubeSat to the Earth. Moreover, the non-sphericity of Mars has to be taken into account for the numerical integration.



Jupiter direction in ECLIPTIC J2000 view from BIRDY. The next figure is a zoom of the red box.



Comparison of Jupiter's direction in ECLIPTIC J2000:
- expected (A: 0°04'14.5'', 223°52'25'')
- observed (B: 0°04'14.5'', 223°52'22'').

The BIRDY-Jupiter distance is 4.18 AU (6.3x10^8 km) and BIRDY's displacement between both pictures is about 10.000km (corresponding to a 3" shift for the optical system).

Development Plan

BIRDY as a "project" will set up a new approach in engineering that is inspired from the **AGILE principles** practiced in the software industry and specifically adapted to the development of CubeSats. Four phases have been planned to demonstrate the progress of the project: **Set up Phase (SuP), Short Term Phase (STP), Middle Term Phase (MTP), Long Term Phase (LTP)**. This approach is preferred instead of a typical space project approach (phases 0/A, B, C, D, E).

• SuP: (2013/02 - 2014/08): **Mission pre-sizing and feasibility**, science advisory group set-up, STM (Structural and Thermal Model) student team hired, specification of needs of the scientific payload, internships at NCKU, IMCCE and LESIA.

• STP: (2014/09 – 2015/12): At the end of this phase the BIRDY preliminary conception is achieved and a PDR (Preliminary Definition Review) will take place. This phase will target the manufacturing and tests of the **BIRDY STM** (Structural and Thermal Model).

• MTP: (2016/01- 2018/12): During this phase the **BIRDY PTM** (proto-flight model) is achieved and ready to participate to a precursor flight with the following scenario: the CubeSat is launched as a piggyback of a geostationary host mission, released at the beginning of the GTO (Geostationary Transfer Orbit) and then go back nearby the Earth at the end of its elliptical trajectory, eventually after several pseudo-GTO orbits depending on the electrical propulsion performances.

• LTP: (2019/01-2020/12, TBC): During this phase the **BIRDY FM** (flight model) will be manufactured according to the lessons learned from the precursor flight and will be launched towards Mars with a host mission but released soon after injecting in the interplanetary transfer orbit.

Overall project: valuable technologies and technics for deep-space CubeSats (autonomous navigation, complex on-board processing, inter-satellites communication, electric propulsion) and new engineering methods will be acquired for CubeSats in a new educational and international context.

(Involved Institutions)
1.Association Planète Mars, 2.Mars Society Switzerland, 3.Observatoire de Paris, 4.Laboratoire d'Etudes Spatiales et d'Instrumentation en Astrophysique, 5.Laboratoire Atmosphères, Milieux, Observations Spatiales, 6.Centre National de la Recherche Scientifique, 7.Institut de Mécanique Céleste et de Calcul des Ephémérides, 8.National Cheng Kung University, 9.LabEx Exploration Spatiale des Environnements Planétaires, 10.Centre d'Etudiant pour la Recherche et l'Exploration Spatiale, 11.Research University Paris Sciences Lettres, 12.Pierre and Marie Curie University, 13.Université Lille 1 Sciences et Technologies, 14.Institut Polytechnique des Sciences Avancées, 15.École d'Ingénierie des Sciences Aérospatiales, 16.Consortium Liquid Micro Pulsed Plasma Thruster, 17.KopooS Consulting Ind., 18.Ecole Centrale Lille, 19.Joint Institute for VLBI in Europe

(Involved actors in chronological order, number in brackets indicates the institution)
Students: J.Vannitsen(8), A.Ansart(15,8), Q.Tahan(15,8), M.Agnan(10,8), J.Velardo(10,3), A.Deligny(10,3), G.Quinsac(10,3), A.Porquet(10,3,7), A.Lassissi(10,3), N.Gerbal(15), O.Sleimi(14,8), S.Durand(10,3,4), R.Klajzyngier(18), J.Diby(18), T.Mallet(18), J.Foissaud(18), L.Orsatto(18), E.Colin(18), N.Heim(18), J.Lin(8), A.Tsai(8), A.Chen(8), J.Tsai(8), T.Chang(8), D.Boisseau(15,8)
Supervisors: B.Segret(4,9,3,1), B.Mosser(4,10,11), K.Wang(8), J.C.Juang(8), J.J.Miau(8), J.Daniel(1), Y.Desplanques(18), D.LaPiPart(18), F.Deleflie(7,3,6,12,13)
Sc.Adv.Gp: J.Vannitsen(8), B.Segret(4,9,3,1), J.J.Miau(8), J.C.Juang(8), K.Wang(8), M.Cabane(5,12), M.Dudeck(12), K.L.Klein(4), N.Vilmer(4), R.Heidmann(1)Sponsors: M.Cabane(5,12), P.Brisson(1,2), D.Coscia(5), C.Koppel(15,17), G.Clima(19)

ESEP

l'Observatoire de Paris — LESIA

Laboratoire d'Études Spatiales et d'Instrumentation en Astrophysique

NATIONAL CHENG KUNG UNIVERSITY 1931

INVESTISSEMENTS D'AVENIR