

White Paper to the Decadal Survey on Biological and Physical Sciences (BPS) Research in Space 2023-2032 (BPS2023), Conducted by The National Academies of Sciences, Engineering and Medicine

A Topical Campaign to Investigate Emission of Particles by Spacecraft Through a Combination of New On-ground and In-space (CubeSat) Experiments, and First-principles Predictive Models

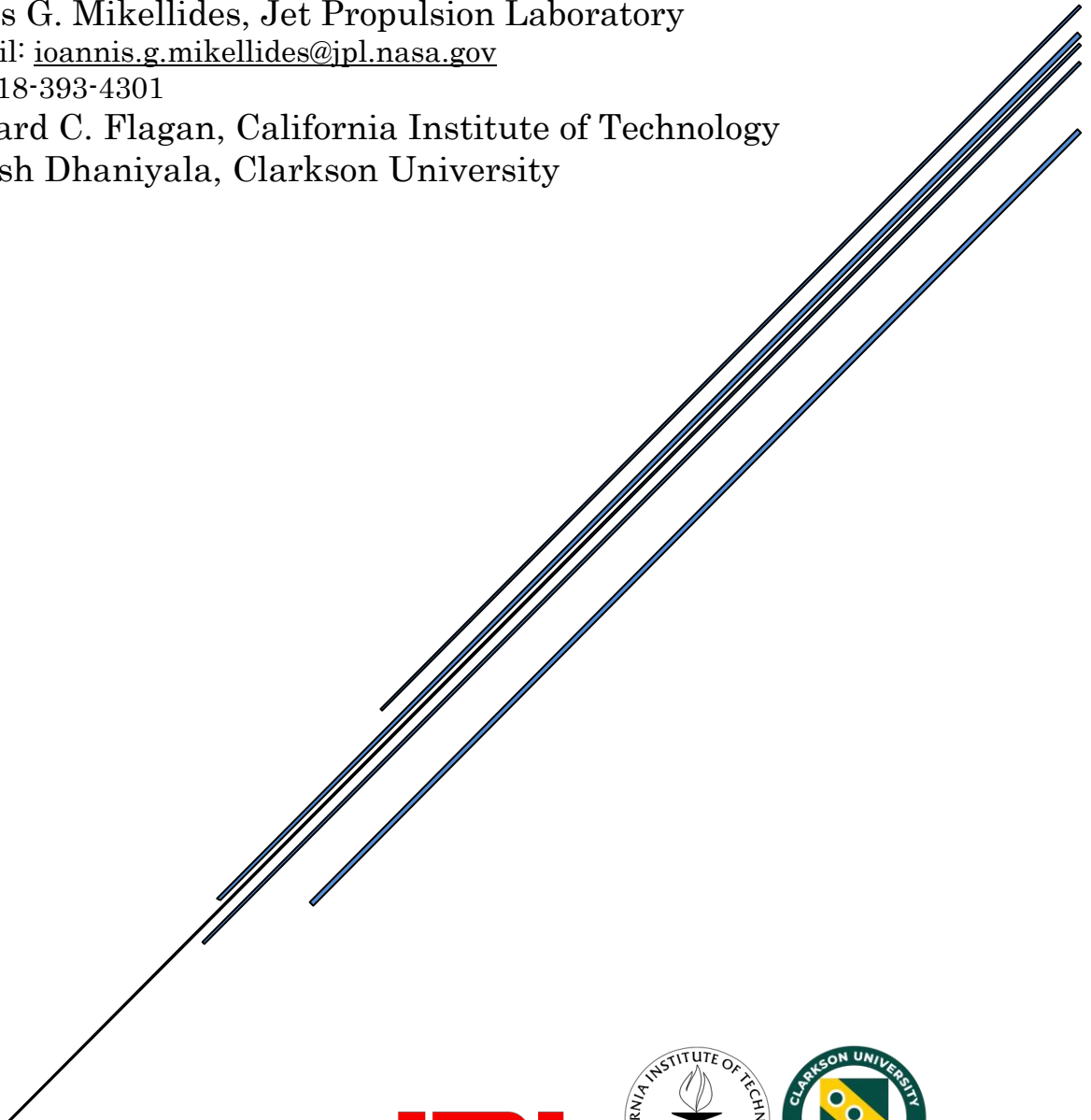
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What we propose: The Jet Propulsion Laboratory (JPL) in collaboration with the California Institute of Technology and Clarkson University proposes a systematic 5-year experimental and physics-based modeling investigation of the well-observed but poorly understood emission of particles from spacecraft, in the size range of sub-microns to hundreds of microns. The main experimental effort will consist of controlled laboratory investigations in vacuum facilities and will culminate with experiments in space using a constellation of miniature satellites (“CubeSats”). The goals of the on-ground laboratory studies will be to, (1) isolate and study in a space-like and well-controlled environment, sources of particle emission that have been hypothesized to act on large spacecraft based on previous in-space observations, (2) develop and demonstrate the diagnostics that will be used onboard the CubeSat space experiments and, (3) develop first-principles predictive models of particle emission in space using the laboratory findings. The models will be combined in a computational platform that can be used by the biological and physical sciences (BPS) community to assess either the time-dependent abundance of these particles on a given spacecraft throughout its mission, or guide the design of spacecraft to allow for control of the rate of release of these particles based on the mission requirements. Since prior to launch, spacecraft can be contaminated with both inert dust but also with elements that carry microbiological signatures, our investigations will pursue both biological and a-biological particles. The effort will conclude with a series of low-cost space experiments that will employ CubeSats to validate the methods and physics models developed during our on-ground investigations. The successful deployment from the International Space Station of the first JPL-built CubeSat in 2017 called ASTERIA [1] (Arcsecond Space Telescope Enabling Research in Astrophysics) demonstrated the Laboratory’s expertise in the development and flight of such miniature spacecraft, which we will most certainly utilize in this effort. Unlike large spacecraft, the inherent simplicity of CubeSats can enable well-controlled experiments in space and therefore easily interpretable measurements. For example, each CubeSat can be propelled to a specific orbit (e.g. LEO, GEO or other), depending on the space environment under investigation, and built using well-characterized materials. The CubeSats can be designed to seed particles on its surfaces while in space and be fitted with sensors to detect their emissions. Critical to these miniature space experiments is the orbit insertion, maintenance and maneuvering of the micro-satellite, which can now be readily provided by a wide range of demonstrated electric and non-electric propulsion technologies [2], at low cost. Indeed, miniature spacecraft are becoming so inexpensive that large commercial satellite manufacturers, capable of committing >\$100M for typical spacecraft, are no longer as dominant in the satellite market. By way of comparison, the total budget for flight nano- and micro-satellites begins at \$1M, with the starting cost of building a functional commsat estimated to be as low as \$0.025M [3]. The cost of our 5-yr effort for JPL and the two universities, including the development and instrumentation of the CubeSats, is not expected to exceed \$10 M.

Why we propose: The release of particles from spacecraft in near-Earth orbit has been well-observed for many decades and can cause a variety of problems during a mission. For example, by scattering light and emitting radiation into the fields of view of detectors it can introduce spurious signals, which can result in the loss of valuable scientific information [4-6]. Naturally, this can be particularly troublesome on missions that employ sunward-facing star trackers [7]. Interference with scientific instruments and other sensitive spacecraft systems is, of course, an old and well-known problem. New problems are also emerging however as a consequence of this phenomenon.

For example, there is now a valid concern that the growing numbers of rocket launches driven by a demand for space tourism could pollute the upper layers of the Earth's atmosphere and

contribute to climate change [8]. Some of these rocket motors burn hydrocarbon fuels and generate soot, while others (like solid motors) can release aluminum oxide particles and hydrochloric acid, all of which have a deleterious effect on the atmosphere. Our ability to measure the abundance of these harmful particles in the vicinity of the spacecraft with on-board instruments, will most definitely depend on our ability to detect and exclude those particles that were originally on the spacecraft at launch but pose no threat to the atmosphere.

There are new implications beyond near-Earth orbit as well. As we pursue missions that aim to bring back to Earth samples from other planets, moons or asteroids, assessments of the risk of contaminating the Earth's biosphere with biologically hazardous material from these foreign bodies depends critically on our ability to predict the fate and transport of particles emitted from the returning spacecraft. A most current and highly visible example is the Mars Sample Return [9], a joint NASA/ESA campaign that aims to return to Earth in the 2030s' samples of Mars material, currently being collected by the Perseverance rover. Since the return spacecraft can potentially be contaminated by Mars dust, it is critical for planetary protection risk assessments to have the ability to predict how such dust, which may contain hazardous material(s), is emitted in space and at what rate prior to arrival in near-Earth orbit.

There have been several near-Earth missions during which particle emission was observed. The most well-known examples were the early Space Transportation System (STS) missions in the 1980s (e.g. [4, 10] and references therein). Similar observations have been made in deep-space missions as well however, like Dawn [7]. Perhaps a less-known but far more illuminating mission regarding this phenomenon was the Midcourse Space Experiment (MSX) flown in the late 1990s. MSX had a suite of instruments dedicated to contamination measurements and, by contrast to the STS missions, flew at a high-enough (near sun-synchronous) orbit that the released particles were not quickly accelerated away from the field of view of the instruments by atmospheric drag. As such, MSX provided an extremely valuable collection of particle emission measurements [11-16]. It was observed that particles were released during umbra exits (but not entry), spacecraft maneuvering (slews) and mechanical activities (such as instrument door openings), as well as by micro-meteoroid (MMD)/space debris impacts. Spacecraft charging was not found to be a major source of particle release in this mission but it certainly can be in other space environments where the flux and energy of electrons is high enough to cause charging, like in GEO.

It is, of course, not surprising that the spacecraft position relative to the sun, its geometry, thermal design, onboard materials, maneuvers and mechanical operations in space, as well as the ambient particle environment (MMD/debris/energetic charged particles), can all play a role in the release of particles in space. But our understanding of how exactly these events and environments lead to such emission never reached a rigorous enough level to allow for the development of predictive, first-principles models. Research on the characterization of particle emissions from surfaces is voluminous but it has been primarily motivated by their impact on indoor contamination control [17], human health [18], and the environment [19, 20], all of which are directly linked to terrestrial atmospheric conditions, not space vacuum. Physics-based models developed for these applications have already shown a strong dependency on the knowledge of particle-surface properties, particle deposition characteristics, and the exact resuspension forces relevant to each problem [21, 22]. For spacecraft, considering the complexity of material properties of their surfaces, uniqueness of deposition and resuspension forces acting on particles, and the extreme nature of operating conditions of pressure, temperature, and relative humidity, the relevance and accuracy of the existing models are, therefore, highly uncertain.

Approach: Our investigations bring together diverse research backgrounds and capabilities (see also **Biographical** section), and will follow a methodical approach that will: (1) deconvolute the complexity of spacecraft (geometry, materials, etc.), (2) isolate in a well-controlled manner, individual processes suspected to cause particle emission in space, first in the laboratory and ultimately in space, and, (3) produce a suite of first-principles models that will be guided and ultimately validated by the above experiments. These models can then be combined to predict particle emission from real spacecraft given their geometry, materials, space environment and planned mission activities. We believe such a large-scale predictive capability is well-needed by the BPS community but, to the best of our knowledge, does not exist. Specifically, we will interrogate, independently, each of the following effects on the emission of particles from surfaces:

- (1) electrostatic effects associated with the presence of space-charge sheaths along electrically conducting or insulating surfaces immersed in a low density plasma,
- (2) effects of constant and transient solar illumination,
- (3) transient thermal effects through direct application of thermal pulses,
- (4) mechanical stresses produced by typical spacecraft operations in near-Earth space,
- (5) effects of molecular outgassing on particle liberation, especially of water vapor.

The above list is only a representative set of known emission sources but others could be included as well in our 5-yr investigations, if deemed necessary.

We will use existing vacuum chambers at JPL that are regularly used to test plasma sources like electric propulsion and hollow cathodes (in extremely low background pressure), and will employ such sources to produce plasma environments that emulate specific space conditions. We have produced such environments several times in the past in previous tests at NASA [23-25]. In these investigations we will examine electrostatic effects per (1) above. In another set of experiments, we will investigate the effects of solar illumination and surface heating on the release of particles (2-3 above), followed by application of mechanical loads (4). Finally, in a controlled setup where water vapor (or other molecular constituents of interest) on a coupon will be carefully characterized, and for which the outgassing rates can be predicted quite accurately, we will interrogate how such outgassing can promote particle release in vacuum per (5) above. To ensure unambiguous results in our investigations, we will use in our laboratory experiments rectangular coupons made of a single material. Properties of these materials known to affect particle adhesion will be well-characterized *a priori*. The properties of particles present in spacecraft clean rooms are also well known, both in terms of material properties and size distributions (e.g. see [26]). In some clean rooms the biological content has also been measured [27]. In our experiments we will begin with idealized spherical particles but eventually use simulants of particles expected on spacecraft prior to launch. Our previous experience suggests that most relevant forces on spacecraft particles are stronger than the gravitational force. Nevertheless, we will perform our terrestrial experiments in multiple directions relative to the gravity vector to quantify the significance of this force on our emission rate measurements. Of course, ultimately, the most unambiguous validation of our findings on the effects of gravity will be provided by our CubeSat experiments in space. For this phase of the program the JPL-Caltech-Clarkson team will be augmented by highly experienced spacecraft and contamination control engineering personnel at JPL to support the development of the flight hardware.

A range of particle diagnostics and methods will be developed and tested at Caltech and Clarkson University prior to employing them in our vacuum chambers at JPL, based on a combined experience by our academic team members of more than five decades in the field of particle resuspension and adhesion physics. Using controlled aerodynamics experiments [28-30], Prof.

Flagan's group at Caltech has developed a wide range of laboratory techniques to measure the emission of particles from surfaces that can form the basis of our diagnostics development for our investigations in vacuum. Experiments performed using a thin (200 μm) laminar flow tunnel (which now resides at JPL) probed aerodynamic removal on time scales of minutes. Translating impinging jets have also been used at Caltech to measure removal of particles exposed to shear stresses for a few seconds to a few milliseconds [28, 30]. Impinging shock waves probed removal when forces are applied for microseconds [31]. In the Caltech experiments, the removal was directly observed by dark-field imaging of uniformly-sized particles on a substrate, counting particles before and after exposures in the impinging jet and shock wave experiments, and during exposure in the laminar flow channel experiments. The relatively large ($> 6\text{-}\mu\text{m}$ diameter) particles used in these experiments were produced with a vibrating orifice aerosol generator, and included fluorescent polystyrene particles of wide molecular weights to explore the effects of material properties. The same system has been used to develop calibration standard particles for detection of explosives on surfaces, uniformly sized, spherical, mineral-laden carbon particles with controlled porosity for studies of ash formation and vaporization mechanisms in coal combustion and pharmaceutical agents for drug delivery studies. It is presently being employed to measure the kinetics of bubble nucleation in liquids, using optical resonances to detect incipient bubbles too small to be imaged. The Flagan lab has also generated smaller particles with a wide range of compositions, e.g., 200 nm yttria particles by electrospray atomization and pyrolysis of precursor solutions [32], and 4 nm silica-coated silicon nano-particles by gas-phase reactions [33]. Thus, a variety of techniques are available to produce test particles of known size and properties for our experiments. Furthermore, the Caltech laboratory is equipped with state-of-the-art aerosol instruments for real-time measurement of particle size distribution measurements over the size range from 1 nm to 20 μm .

At Clarkson University, Prof. Dhaniyala's group have been theoretically and experimentally studying particle resuspension of biological particles [21, 22, 34, 35]. Given the small size ($\sim 1\ \mu\text{m}$), non-ideal shape, complex surface properties, and uncertain charge state of biological particles, resuspension studies of these particles have required experiments under a range of extreme flow conditions (speeds exceeding 100 m/s in 3 mm tunnels) and the use of advanced in-situ sensing approaches [26]. With minor modifications, the Clarkson resuspension tunnel can be used for initial characterization of particle adhesion as a function of mechanical impact, operating pressure, substrate properties, and particle characteristics. Experimental results from such studies will validate and guide development of not only theoretical models but also the diagnostics that will be used in the JPL vacuum facilities and ultimately onboard the CubeSats in space.

Upon the completion of our terrestrial experiments a parallel effort will commence to develop: (1) the diagnostics for the CubeSat experiments and, (2) a suite of physics-based models that can predict the emission of particles from geometrically simple surfaces. The models will be developed to receive as input the relevant properties of these particles and the surface(s) on which they reside, and the conditions of the space environment in which emission is to be determined. By modeling, first, simple configurations like the CubeSats that will be flown in our space experiments, model validation can be achieved with reduced uncertainty and ambiguity. After such validation is completed the modeling capability can be advanced to handle more complicated spacecraft geometries. A computational platform that has been used successfully to provide analyses of terrestrial particle resuspension and transport in the presence of flows for our Mars 2020 mission already exists at JPL (36, 37). This platform and the data used to validate its models [38] will be used as a guide in the proposed model development effort.

Biographical



Dr. Ioannis (Yiangos) G. Mikellides is a Principal Engineer with the Electric Propulsion (EP) Group at JPL and a Fellow of the American Institute of Aeronautics and Astronautics (AIAA). He received his Ph.D. in Aeronautical and Astronautical Engineering with concentration in applied plasma physics. As a member of the EP Group for the last two decades he has investigated a broad range of laboratory and space plasma applications using numerical simulations, and was the architect of magnetic shielding in Hall thrusters. For the last several years he has been the Plasma Modeling Lead Engineer of a joint NASA-industry program tasked to develop HERMeS, the first flight Hall thruster with magnetic shielding. More than a decade ago, while continuing his work in EP, he began his participation in JPL's Mars Program by leading the aerodynamic design of the Wind and Thermal Shield for the InSight mission. He has also served as the principal analyst for all matters related to the transport of biological and inert particles to the return samples for NASA's Mars 2020 mission, and led the design and testing of the viscous Fluid Mechanical Particle Barriers employed on Perseverance to protect the samples from terrestrial contamination. Dr. Mikellides is now the Technical Lead Engineer of the Particle Analyses and Control Team for the joint NASA/ESA Mars Sample Return Campaign. He has authored close to 60 peer-reviewed articles in aerospace engineering, applied physics, planetary/space sciences and astrophysics journals.



Dr. Richard C. Flagan is the Irma and Ross McCollum-William H. Corcoran Professor of Chemical Engineering and Environmental Science and Engineering at the California Institute of Technology. He received his PhD from MIT in Mechanical Engineering. He is a leader in the broad field of aerosol science whose research focuses on atmospheric aerosols and their impacts on climate, air quality, and human health, and on the development of methods for measurement of aerosol particles from many micrometers to 1 nm in size. He has invented a number of instruments and experimental methods for measuring fine airborne particles, including one, the Scanning Mobility Particle Sizer (SMPS), that has become the primary instrument worldwide for the measurement aerosol particles smaller than 1 μm . His research has contributed substantially to present understanding of smog and the links between fine aerosol particles and clouds. Prof. Flagan has published over 440 papers, one textbook which has been downloaded over 260,000 times, and holds 28 patents. He has previously served as Executive Officer for Chemical Engineering and as Chair of the Faculty at Caltech. He is a past president of the American Association for Aerosol Research, and has served as Editor-in-Chief of its journal, *Aerosol Science and Technology*. He is a member of the Board of Directors of the California Council for Science and Technology, an organization that provides scientific and technical support to the state legislature, administrative agencies, and governor of California. Among other awards, Prof. Flagan's many contributions to aerosol and atmospheric science have been recognized with election to the National Academy of Engineering (2010) and the Fuchs Award (2006), the highest award in the field of aerosol science.



Dr. Suresh Dhaniyala is the Bayard D. Clarkson Distinguished Professor of Mechanical & Aeronautical Engineering and the Co-Director of the Center for Air and Aquatic Resources Engineering and Sciences (CAARES) at Clarkson University. He received his Ph.D. in Mechanical Engineering from the University of Minnesota, Minneapolis in 1998 and was a post-doctoral scholar in Chemical Engineering at California Institute of Technology before joining the faculty at Clarkson University in 2002. Dr. Dhaniyala's technical expertise is in fundamental aerosol science, with a particular focus on the aerosol fate and transport modeling, design and development of novel air quality and bioaerosol sensors, and atmospheric aerosol characterization. Dr. Dhaniyala has published over 70 peer-reviewed articles, 3 book chapters, 5 patents, and delivered more than 40 invited presentations. He serves on the Editorial Board of *Aerosol Science and Technology* (AST) and on the UN committee for safety of Mars sample return.

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