

CENTAUR ENVIRONMENT AND SURFACE ACTIVITY MEASUREMENT EXPERIMENT (CESAME).

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Introduction: CESAME is a top-level space exploration concept study for a NASA medium-class mission that will rendezvous with 29P/Schwassmann-Wachmann, an active Centaur. We propose a payload (and a potential small companion payload) that will conduct four science investigations: imaging, radar sounding/gravity measurement, mass spectroscopy, and an impact experiment. Our study addresses the following science goals by exploring how a Centaur experiences outgassing, evolves geologically, and stores and loses volatiles.

Science goals: We define the following science goals: 1. Characterize the physical, geological, and chemical processes of a Centaur to give insights into how outer solar system objects have been altered to comets; 2. Investigate how volatiles have been delivered from reservoirs in the outer solar system to the inner solar system; and, 3. Connect the formation and evolution processes of outer solar system objects with the accretion processes of planets and small bodies in the solar nebula.

Targeting Centaur 29P/Schwassmann-Wachmann: 29P has a nucleus radius of 27 ± 5 km [e.g., 1] and orbits the sun in a surprisingly circular orbit beyond Jupiter (an eccentricity of ~ 0.04 and a semi-major axis of 6 AU). 29P has shown consistent outgassing activities with no trend related to the heliocentric distance. The rotational period has not been determined [e.g., 2].

Science objectives (SOs): The traceability of the science goals to the following science objectives are studied in this concept study. These objectives can be achieved by using four mature, low-risk instruments: (1) imaging, (2) impact experiments, (3) radar sounding/gravity measurement, and (4) mass spectroscopy.

SO.1: Constrain the gas distribution evolution and thermal emission: Outgassing driven by sublimation is the main mechanism through which small bodies change their shapes, sizes, and rotation due to mass loss driven by sublimation and outbursts [3]. There are several theories to explain how Centaurs are active far from the Sun: exothermic crystallization of amorphous ice [4]; sublimation of supervolatiles [5]; reactions of unstable radicals created by prolonged cosmic-ray bombardment [6]; exothermic processes of solutions [7];

polymerization reaction [8]; impact bombardment [9]; mass wasting events [10].

A hyperspectral Infrared (IR) imager is used to map the rotational-vibrational emission of coma volatiles, H₂O, CO₂, and CO, and the thermal emission over the duration of the encounter. Monitoring the distribution evolution of outgassing will provide crucial information for the outgassing mechanism.

SO.2: Identify the geomorphological features on the nucleus' surface: Centaurs are likely to be a direct link between Kuiper Belt Objects (KBOs) and Scattered Disk Objects (SDOs). Because 29P is too far from the Sun for effective sublimation of H₂O ice, its surface condition should be very different from those of regular comets [11]. While outgassing erodes the surface condition, reaccumulation of dust and volatiles may overlay old surfaces [12]. We anticipate that regions with steep slopes may be likely to be activity sources [13].

CESAME will include a high spatial resolution visible (VIS) imager to observe such features on 29P from an altitude of one radius from the nucleus' surface (~ 27 km). We consider a strawman instrument based on the Visible Camera (VisCAM), which was proposed by the Primitive Volatile Explore (ProVE) mission concept for observations of Oort Cloud Comets (OCCs) [14]. VisCAM was designed by the ProVE team in partnership with Malin Space Science Systems (MSSS).

Impact experiments are planned to generate artificial craters and excavate internal structures that have not experienced significant activities in the past. We analyze a strawman impactor system that extends the impactor system designed by Honeybee Robotics [15].

SO.3: Measuring the internal structure: We analyze radar sounding and gravity measurement techniques for looking through the interior of 29P's nucleus to give insights into the structure of cometary nuclei.

To investigate the feasibility of radar sounding, we evaluate whether a monostatic method (a system having both a transmitter and a receiver) [e.g., 16] or a bistatic method (a transmitter and a receiver are separated) [17] fits our mission concept. The bistatic mode can also provide tomography mapping, which may allow for measuring deep interior.

We assess a gravity measurement technique for finding the global mass distribution, which constrains the structural heterogeneity of the nucleus of 29P. Gravity measurement is based on spacecraft navigation.

SO4. Measuring the isotope ratios of gas species:

The isotope ratios of chemical species are key parameters that may indicate the thermal history that objects have experienced. We consider a strawman mass spectrometer based on MAVEN's NGIMS mass spectrometer, which is a quadrupole mass analyzer developed with the heritage of Cassini's INMS at NASA/GSFC [18], to determine whether water isotopes, HD^{16}O and H_2^{16}O , can be measured to compute the D/H ratio in water ice.

Mission operations: The present mission concept is for a spacecraft to rendezvous with the nucleus of 29P.

Interplanetary Trajectory: There are multiple reasonable trajectories using a Jupiter flyby gravity assist with Chemical Propulsion (CP) or Solar Electric Propulsion (SEP) systems. For both cases, the departure is on January 23, 2030, and the launch C_3 , which is defined as twice the kinetic energy to escape the Earth gravity, is $81.9 \text{ km}^2/\text{sec}^2$. For the CP case, the spacecraft arrives at 29P on March 4, 2039 with a velocity change at Jupiter of 0.23 km/sec and that at 29P of 3.02 km/sec . For the SEP case, the spacecraft arrives at 29P of Sep 23, 2039. This trajectory can be achieved with a thrust of 10 mN with a specific impulse (Isp) of 1900 sec . For another launch opportunity, the departure is on Aug 29 in 2035, and the arrival is on Nov 4 in 2045. The velocity change at Jupiter is 0.10 km/sec , while that at the arrival is 2.71 km/sec . The launch C_3 is $87.0 \text{ km}^2/\text{sec}^2$.

Proximity operation: Operation consists of four phases: 1. Conduct global mapping at low resolution to determine the mass, rotation, and shape, as well as the safety conditions; 2. Perform global mapping at high resolution to characterize the geomorphological features and the outgassing elements; 3. Conduct impact experiment and avoid hypervelocity collisions with impact ejecta but capture an ejecta plume; and 4. Observe an artificially developed crater to identify young layers and primordial structures.

Launch system: Given the C_3 requirements, it is necessary to use a high-energy launch system. Launch systems capable of achieving the derived C_3 include Delta IV, which can deliver a payload with a wet mass of ~ 2 tons, and Space Launch Systems Block 1B, which will be able to carry it with a wet mass of ~ 8 tons. NASA's Parker Solar Probe used Delta IV to satisfy its C_3 ($154 \text{ km}^2/\text{sec}^2$). Other systems such as Falcon Heavy, Vulcan, and Atlas V may also be possible.

Thrust vectoring system: The velocity change at the arrival may not be significantly reduced because it depends on the locations of Jupiter and 29P. The CP case requires more fuel but can reduce complexity in orbital

and attitude controls during the proximity operations. NASA/Juno spacecraft's Leros 1b main engine with a specific impulse (Isp) of 318 sec and a thrust of 635 N may be feasible for the current mission concept. The SEP case requires more power but can significantly reduce the total mass. The NEXT-C thruster can give thrust of 17 mN with an Isp of $4,190 \text{ sec}$ under a power of $\sim 500 \text{ W}$ and is a candidate of our thruster.

Power management: Both a radioisotope power system (RPS) and a solar array system (SAS) are a candidate of power generation. The Juno spacecraft is designed to use a power of 435 W for its science operation at Jupiter. If we only use the RPS, the planned concept requires multiple units (for eMMRTG, at least three units; for Next Gen, at least 2 units) to support such power. This case eliminates the option of using the SEP. If we only use the SAS, high-efficient triple-junction Gallium-Arsenide cells, which were used to demonstrate their high efficiency ($>27\%$) in the Dawn mission [19], are a viable option.

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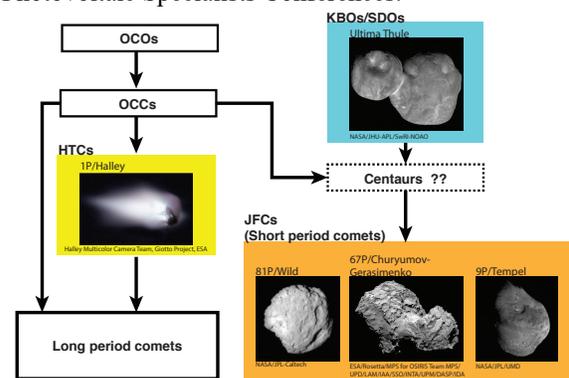


Figure 1. Links in comets and out solar system objects.