AAS 86-233

RESULTS FROM A SERIES OF US/JAPAN TETHERED ROCKET EXPERIMENTS

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Tethered rocket experiments have been carried out four times during a US-Japan joint space program in progress since 1980. The goal of the rocket program has been to perform a new type of active experiment by ejecting an electron beam from the tethered mother-daughter payload system. In the third and fourth rocket flights, the conductive tether wire was deployed more than 400 m. It was found that the tether wire acted as an antenna and its antenna impedance decreased with the extension of the wire both in HF and VLF bands. The vehicle charging due to the beam emission up to 80 mA was repeatedly measured in the series of the experiments. During the 80 mA emission, a clear evidence for the ignition of a beam plasma discharge was obtained by the plasma probe, photometers and wave receivers.

INTRODUCTION

A tethered payload system in which two separate payloads in space are connected with an insulated conductive wire has been proposed to conduct a new type of active experiment combined with electron beam emission (Shuttle Electrodynamic Tether System, SETS)(Ref.1). By applying a high voltage between the two payloads connected with a conductive wire, we can study the response of ionospheric plasma to large

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potential differences between the collector and the plasma. With electron beam emission at one end, we can control the tether current. By modulating the beam current, low frequency radio waves with long wave length, such as whistler and Alfvén modes, will be excited in a well-controlled manner.

In this paper we report the results of four tethered rocket experiments conducted as part of a US-Japan joint program underway since 1980 (Tethered Payload Experiment; TPE series)(Ref.2,3). The major purpose of the experiments has been to obtain technical and scientific data supporting the future electrodynamic tethered subsatellite experiments by the Space Shuttle, currently scheduled for 1989 as part of the Tethered Satellite System-1 mission. The first two experiments reported here were done under collaboration of the Institute of Space and Astronautical Science (ISAS) and the Center for Atmospheric and Space Science of Utah State University (USU) by Japanese sounding rockets K-9M-69 and S-520-2 (Ref.4,5). In these, a tether wire was deployed to length of 38 m and 65 m, respectively, although total deployments of 400 m were planned. In the last two experiments, under collaboration of USU, ISAS, Stanford University and the University of Michigan using NASA Black Brant V rocket, the wire was successfully deployed more than 400 m, as planned. In the first three experiments, the beam was not injected after mother-daughter separation on account of a failure of the payload battery pack supplies. In the last experiment, an electron beam up to 1 kV and 80 mA was injected during the wire deployment.

EXPERIMENT

The payload instruments are basically the same in the four experiments. The onboard instruments in the series of the experiments are listed in Table 1. The tether deployment system was installed on the mother rocket in the first two experiments, while it was installed on the daughter rocket in the last two experiments. Figure 1 shows the configuration of the payloads in the last experiment.

The mother payload was composed of an electron gun, a floating/Langmuir probe array, a thermal electron energy detector, photometers, cameras, an electrostatic electron energy analyzer, a charge probe and a tether voltage/current monitor. The electron gun (Fast Pulse Electron Gun; FPEG) generated a narrow electron beam of 1 kV, 80 mA (peak current) in DC and multi-pulse modes (2,8,32,256 μsec). The floating/Langmuir probe array (PLP) consisted of 4 cylindrical probes installed on a rod every 25 cm which was deployed after despin. Two 35 mm cameras with high sensitivity color film (ASA 400) were also installed. One was operated synchronized with the beam firings to observe

	TPE-1	TPE-2	TPE-3,4(CHARGE-1,2)
Rocket	K-9M-69	S-520-2	Black Brant V
Launch Date	Jan.16 1980	Jan.29 1981	Aug.8 1983/Dec.14 1985
Launch Site	Kagoshima Space Center	Kagoshima Space Center	White Sands Missile Range
Mother Payload	Electron Gun(1kV30mA max)	Electron Gun(1kV30mA)	Electron Gun(1kV80mA max)
	Langmuir/Floating Probe	Return Current Monitor	Langmuir/Floating Probe Array
	Charge Probe	Charge Prove	Charge Probe
	Electron Energy Analyzer	Electron Energy Analyzer	Electrostatic Analyzer
	Optical Detector Array	CCD Camera	Still Camera(2)
	Tether Deployment System	Tether Deployment System	Photometer(2)
	Flashing Lamp	Tether V/I Monitor	Flashing Lamp
	Tether V/I Monitor		Tether V/I Monitor
Daughter Payload	VLF Receiver	VLF Receiver	VLF Receiver
	HF Receiver	HF Receiver	HF Receiver
	Langmuir/Floating Probe	Langmuir/Floating Probe Array	Tether Deployment System
	Charge Probe	Charge Probe	Charge Probe
	Impedance Probe		

Table 1 TPE payload instruments

the beam trajectory. Another was synchronized with flashing of a strobe light to illuminate the reflective tape attached to the daughter rocket. Two photometers filtered at 3914 Å were used to detect the light emission from the interaction of the electron beam with the atmosphere and from the charge sheath around the rocket surface skin. The charge probe, a DC/DC converter to apply a high voltage up to 500 V between the two payloads, and the tether voltage/current monitor were assembled in one unit (MCP). A wire tension monitor and a mechanism to cut the wire at the re-entry to the atmosphere were installed at the end of the tether wire. The operation of FPEG, cameras, photometers, MCP and fast data handling unit were controlled by a microprocessor.

The daughter payload consisted of the Tether Deployment System (TDS), HF/VLF wave receivers, and a charge probe (DCP). TDS contained 426 m of wire and a deployment monitoring system with 0.1 m resolution. The wire was stainless steel, 0.66 mm in diameter, coated with teflon. Two sets of 2.4 m-dipole antennas (tip-tip) were used for the wave detection. HF wave signals from 0.2 MHz to 10 MHz were analyzed as a frequency spectrum every 250 msec. VLF wave signals in a broad band from 0.4 to 30 kHz were directly transmitted to ground via an S-band telemetry link.

K-9M-69 was launched at 12:00 JST on January 16, 1980 with an elevation angle of 77 degrees from Kagoshima Space Center at Uchinoura. It reached a maximum altitude of 328 km at 292 sec after launch. The electron beam of 0.5 kV 22 mA and 1 kV

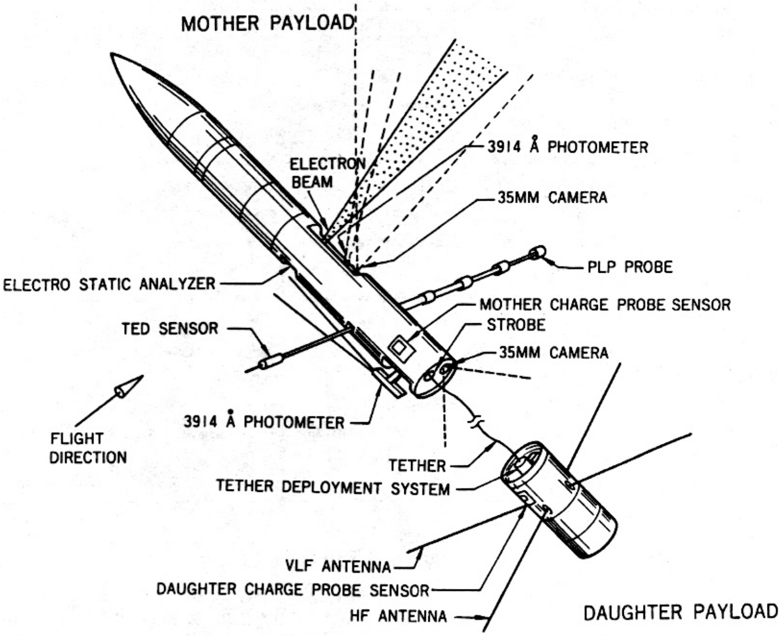

Fig.1 Payload configuration of the fourth TPE experiment (CHARGE-2)

30 mA was injected from 90 sec to 106 sec (150 km-180 km). The mother-daughter rocket was separated at 106 sec (180 km). The wire was deployed to a distance of 38 m. The second flight, S-520-2 was launched at 16:00 JST on January 29, 1981 with an elevation angle of 80 degrees from Kagoshima Space Center. It reached a maximum altitude of 322 km at 337 sec. The beam of 1 kV 30 mA was injected around the height of 200 km. The rocket was separated at 134 sec (220 km). The tether wire was deployed with an extension of 65 m. The third experiment was carried out by Black Brant V, launched at 00:00 MDT on August 8, 1983 from White Sands Missile Range, New Mexico. It reached a maximum altitude of 218 km. An electron beam of up to 1 kV 80 mA was injected parallel to the magnetic field from 117 sec to 144 sec (142-169 km). The rocket was separated at 153 sec (175 km). The tether wire was deployed to a length of 418 m during 283 sec. The fourth experiment was carried out by Black Brant VB, launched at 00:16 MDT on December 14, 1985 from White Sands Missile Range. It reached a maximum altitude of 262 km. The rocket was separated at 116 sec (161 km). The wire was deployed to a length of 426 m during 290 sec. An electron beam of up to 1 kV 80 mA was injected at various pitch angles before and after the rocket separation.

EXPERIMENTAL RESULTS

Tether Wire Deployment and Dynamics

The tether wire started to deploy at the mother-daughter separation by a multiple spring system. The separation speed was set at 0.5, 1.0, 1.5 and 1.05 m/sec in the first, second, third and fourth experiments, respectively. In the first two experiments, the deployment speed gradually decreased with time and finally stopped abruptly at 38 m and at 65 m, respectively, due to a frictional force in the tether deployment system. In the last two experiments, an improved deployment system with less friction was flown, and a Reaction Control System (RCS) on board the daughter rocket was operated every 40 sec to compensate for the friction. Figure 2 shows the deployment velocity in the last experiment. At the bottom, the thrustering of RCS is designated. Figure 3 shows the daughter payload and tether wire observed by the still camera onboard the mother payload after separation in the last experiment. The wire was observed to be slightly twisting during the deployment.

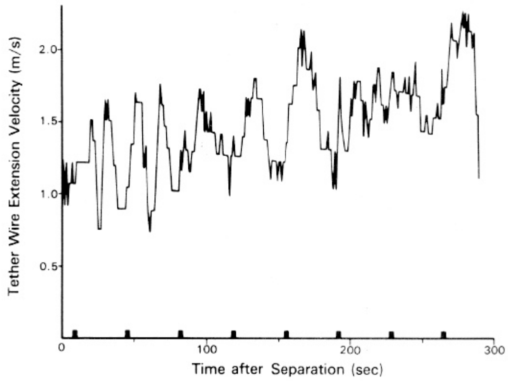

Fig.2 Wire deployment velocity (fourth experiment)

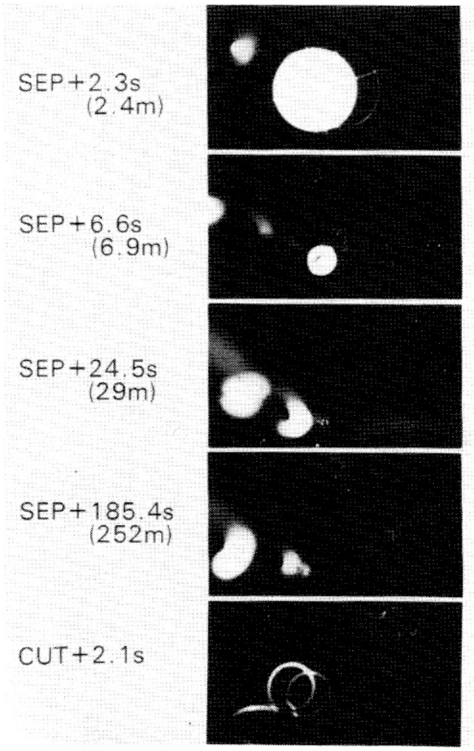

Fig.3 Daughter payload and tether wire

VxB Potential Generation

The potential difference between the two payloads was measured by MCP onboard the mother payload. Figure 4 shows the potential difference while the tether wire was deploying in the last experiment. Since the rocket was launched almost upwards and the daughter payload was separated towards east, the daughter payload was biased positively during upleg and negatively during downleg. The measurements in the first half agree with the model calculation. The cause of the large deviation in the latter half will be explained by the high impedance between the surrounding plasma and daughter payload which was negatively biased during downleg. The measurements became zero after the wire was cut at 443 sec.

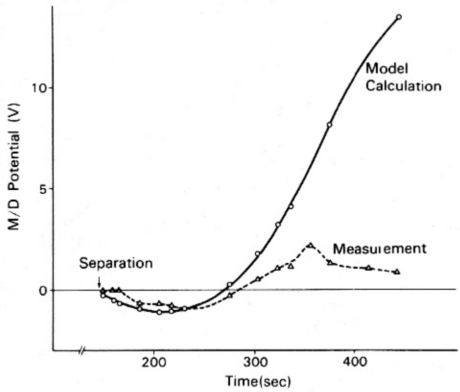

Fig.4 VxB potential

Wave Enhancement when Tether Wire Extended

Figure 5 shows the variation of the integrated wave intensity from 1 to 30 kHz with time in the third experiment. The integrated intensity increased after the start of the wire deployment. It abruptly decreased at 454 sec when the wire was cut near the daughter payload. No remarkable change was detected when the tether wire was cut at the mother payload at 436 sec. This indicates that the tether wire acted as a VLF antenna. Note that the tether wire was not connected to the receiver input, just connected to the ground of the daughter payload. The background VLF noise is presumed almost constant near the apogee (altitude from 200 km to 218 km). In this region (ascending and decending), the wire was deployed from 60 m to 270 m (6.5 dB in length) during 135 sec. During that period, the detected wave intensity increased by about 8 dB. This means that the antenna impedance of the tether wire decreased almost in inverse proportion to the wire length. Waves in the HF range at 0.6-1.6, 5, 6, 9.5 MHz were detected almost all flight time after the antenna extension even after the re-entry. Their source must be located on ground. The wave intensity of 0.6-1.6 MHz (wave length 500-188 m) was remarkably changed with the deployment of the tether wire as shown in Fig.6 (third experiment). The measured wave intensity decreased abruptly at 454 sec when the tether wire was cut near the daughter payload. This means that the wire

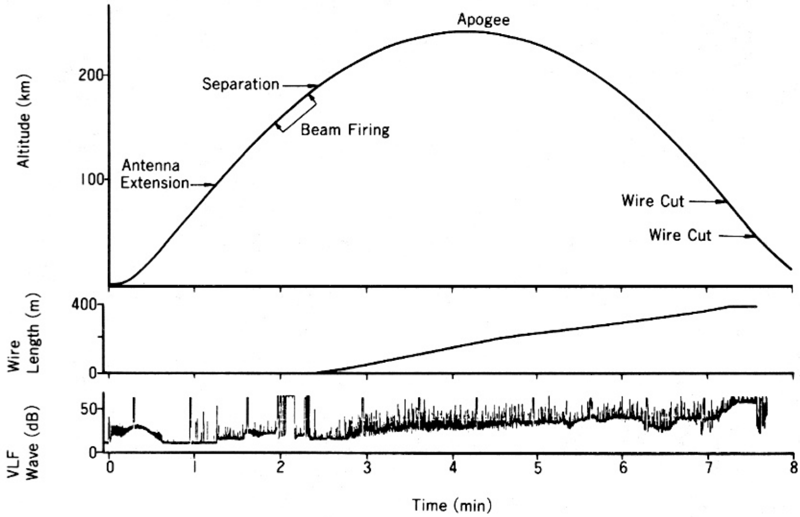

Fig.5 VLF wave intensity during tether wire deployment

acted as an HF antenna in this band, although it was not connected to the HF wave receiver. At low frequencies less than 0.75 MHz (wave length longer than 400 m), the average intensity increased monotonically with the wire length. At 0.95 MHz (wave length 315m), the intensity has a peak around 300 m. At 1.2 MHz (wave length 250m), the intensity was maximum around 200 m. At 1.3 MHz (wave length 230m), the intensity was strongly modulated by the spin motion of the daughter payload. Above 1.6 MHz (wave length less than 190m), the intensity did not change remarkably. The antenna impedance of the tether wire decreased with the wire length for the

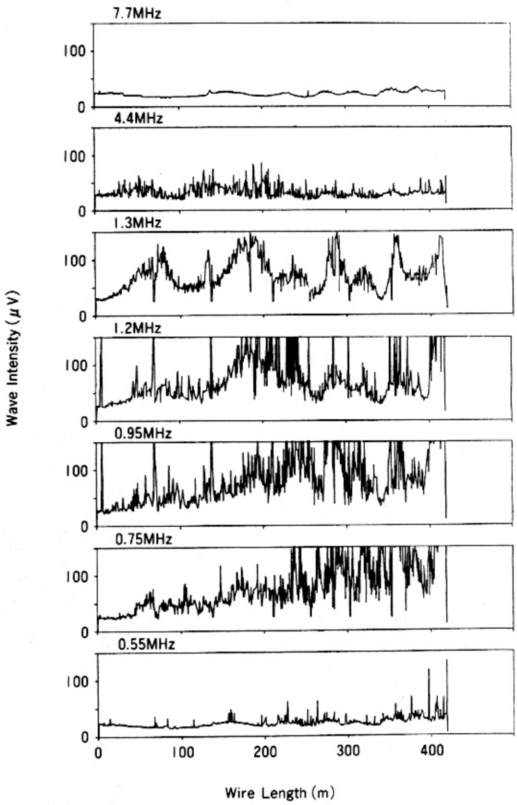

Fig.6 HF wave intensity during tether wire deployment

radio waves below 1.6 MHz, but did not clearly change above 1.6 MHz. This cannot be explained by the theory of simple dipole antenna. It will be investigated elsewhere related to the theory of antenna impedance in space plasma.

Potential Measurement during Beam Emission

Two sets of floating probes and Langmuir probes close to the rocket skin were used in the first experiment. In the last three experiments, a floating probe array composed of four probes was extended up to 1-1.2 m from the rocket skin. This array was also used as a Langmuir probe by time-sharing of the bias, which was swept from -10 V to 10 V in 125 msec. In the last experiment, the potential of mother payload emitting an electron beam was also measured from the daughter payload which was located far away from the mother payload. Table 2 summarizes the potential rise due to the stationary beam injection measured in the first three experiments. In the last experiment, the potential rise was much larger than those of the first three experiments, but the final calibration has not been done yet.

Experiment	TPE-1		TPE-2		TPE-3		
Local Time	12:00 Jan.16		16:00Jan.29		00:00 Aug.8		
Altitude	150 ~ 180km		200km		140 ~ 170km		
Beam Energy	0.5kV	1kV	1kV	1kV	1kV	1kV	1kV
Beam Current	22mA	30mA	30mA	5mA	10mA	40mA	80mA
Potental Rise	6.3-9.3V	6.0-10.2V	5-10V	0.1-0.8V	≲ 1V	≲ 1V	1.0-2.4V

Table 2 Summary of rocket charging due to beam emission

Beam Plasma Discharge

The last two experiments were carried out in night time during new moon to make optical observations using a still camera and two photometers filtered at 3914 Å. Figure 7 shows the beam trajectory observed by the still camera. Photometer A, installed on the same side of the rocket as the electron gun, looked at the beam path and photometer B installed on the opposite side to the gun detected the light

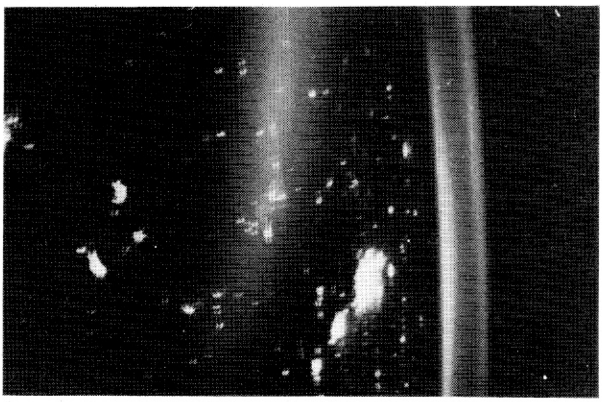

Fig.7 Beam trajectory observed by still camera. Airglow and city lights are also seen.

emission in the sheath near the rocket skin. Figure 8 shows the light intensity detected by the two photometers and the beam appearance observed by the still camera in the third experiment. The photon production rate per unit volume is proportional to the beam current density and N_2 density. The light intensity for the first two steps (5,10 mA) detected by photometer A increased linearly with the beam current. The light intensity increased remarkably by almost one order of magnitude when the beam current increased from 40 mA to 80 mA. This cannot be explained by the beam-background gas impact excitation alone. The anomalously-enhanced light emission during the beam injection at 80 mA evidently indicates the ignition of the beam plasma discharge in space.

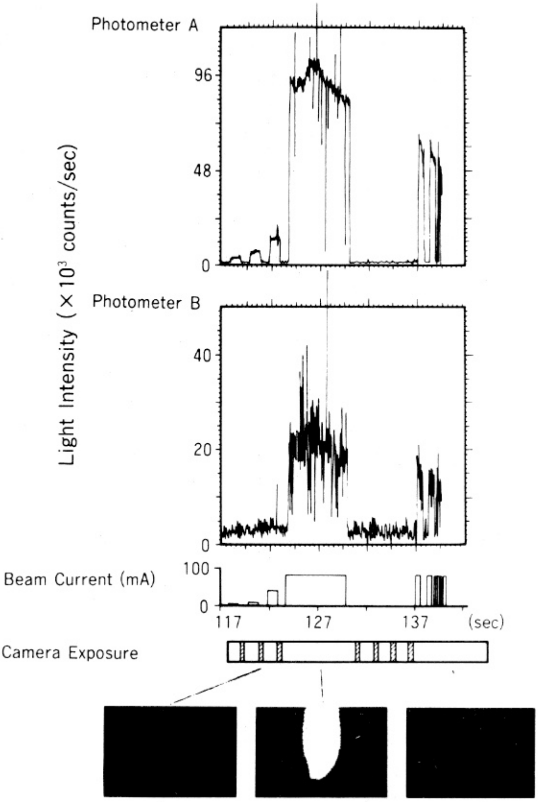

Fig.8 Light intensity observed by two photometers

The general features of wave excitation during the beam injection are shown in Fig.9. Waves with a discrete spectrum around 6 and 9.5 MHz result from ground transmitters. The same applies to the broad band background spectrum from 0.6 to 1.6 MHz. At 5 mA, an emission with a sharp spectrum at 0.9 MHz was detected, which corresponds to the plasma frequency of the background ionospheric plasma ($10^4/cm^3$). At 10 mA, peaks at 0.9 MHz and 1.3 MHz were detected. At 40 mA, the discrete emissions disappeared and broad band emission decreasing with frequency appeared in whistler mode range below 0.5 MHz. At 80 mA, the wave intensity was increased by more than 15 dB on average, and the broad band emission up to the third cyclotron harmonic was detected. From previous work, the appearance of the continuous broad band emission is an important evidence for the ignition of the beam plasma discharge (Ref.6).

CONCLUSION

The dynamics of tether wire and the effect of the wire deployment on the wave measurements have been studied. It has been found that the tether wire acted as a wave antenna and the antenna impedance decreased with the tether length in both the VLF and HF bands up to 1.6 MHz. This suggests that a tether wire system can act as an effective wave transmitter with low impedance. The evidence for the ignition of the beam plasma discharge during 80 mA injection at around 150 km has been clearly obtained by light and wave measurements. The light emission at 3914 Å was greatly enhanced and continuous broad band radio emission extending beyond the cyclotron frequency was detected. These features coincide with the experimental results on the beam plasma discharge in the ground laboratory experiments.

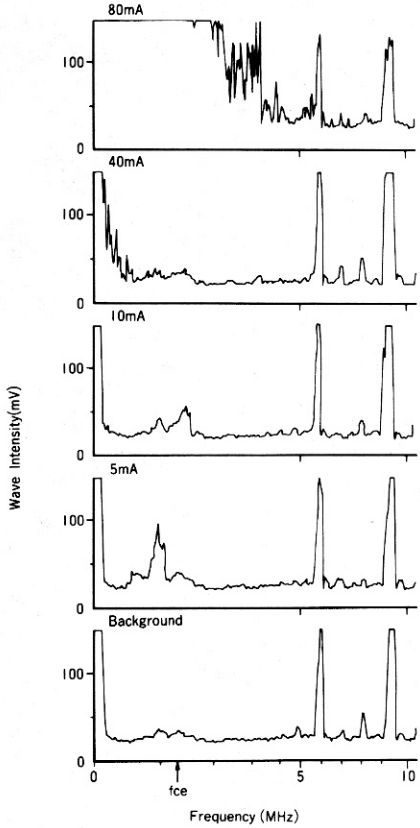

Fig.9 HF wave emission during beam injection

ACKNOWLEDGEMENT

A portion of this work was funded through NASA grant NAGW-235 at Stanford University.

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