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Introduction to the North Star Active Plasma-Jet Space Experiment

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THE North Star Active Plasma Experiment mission was designed to investigate the dynamics and interactions of high-speed plasma jets in the high-latitude ionosphere. The artificial high-speed plasma jets produced during the North Star mission are relevant to plasma jets produced by electric propulsion thrusters, to electrodynamics associated with spacecraft tethers, and to advance spacecraft charging technologies. In addition, this experiment is relevant to the study of basic plasma physics problems such as momentum coupling between different plasma populations and how this coupling relates to the propagation of Alfven waves and electron acceleration. Specifically, the goals of the North Star mission were to address issues relating to the propagation of high-speed plasma jets across magnetic field lines, investigate the role of the neutral atmosphere in secondary jet ionization processes, and assess the Critical Ionization Velocity hypothesis.

The North Star mission[1] was launched on 22 January 1999 at 1358:03 UT using a Black Brant XII sounding rocket from Poker Flat, Alaska (Fig. 1). The experiment occurred just after an auroral breakup. The trajectory of the rocket crossed auroral arcs on its ascent prior to the execution of the two active plasma-jet experiments. The plasma jets were produced using a device known as an explosive-type generator (ETG) and resulted in the generation of a high-speed jet of both neutral and ionized aluminum. The neutral aluminum is formed from the rapid recombination of aluminum ions formed at the time of the initial jet initiation. The jets were directed perpendicular to the magnetic field toward instrumented subpayloads located 200–1500 m from the source. The plasma-jet experiments occurred at altitudes of 360 km (ETG-1) and 280 km (ETG-2). A canister of compressed air was released prior to ETG-1 injection to simulate the neutral density at a 150-km altitude in the vicinity of the payload.

The North Star plasma-jet papers reviewed in this introduction address diverse topics, such as plasma-jet electrodynamics, plasma-jet magnetic field perturbations, plasma-jet propagation and neutralization, optical signatures of the plasma jet, and the Critical Ionization Velocity (CIV) theory.

Erlandson et al.[1] present an overview of the North Star mission and a review of the findings, and they discuss the high-speed optical measurements of the high-speed aluminum plasma-jet injection. The emissions were dominated by line emissions caused by neutral aluminum and a continuum thought to be from hot (1500–2000 K), micron-sized debris. The timing from detectors viewing the jet and looking away from the jet confirms an average jet speed of 20–25 km/s during the first tens of milliseconds. This is consistent with the in situ measurements that indicate similar speeds associated with the core of the jet.

Lynch et al.[2] present charged particle measurements associated with the aluminum ion plasma jet created by the ETGs. Ions with velocities up to 36 km/s were observed just prior to the arrival of the diamagnetic cavity associated with the jet. Three distinct enhancements, separated by the gyroperiod of aluminum, were observed as the jet moved past the payload. The ion properties are compared with those predicted by the CIV process. Lynch et al. discuss these jet properties in the context of the CIV theory, finding that the peak ion fluxes are observed only when the jet velocity exceeds the CIV critical velocity, namely, $v_{\text{jet}} > V_{\text{crit}}(\text{O}^+)$.

The plasma jet produced complex electric field perturbations and the generation of plasma waves. Pfaff et al.[3] present results from double-probe electric field measurements acquired at frequencies from 0–10 MHz. The ETG-1 plasma jet, which was injected through an artificial air cloud, produced a diamagnetic cavity. The dc electric field was essentially zero inside the cavity. Large dc electric fields and parallel electric fields were observed on the edges of the cavity. In addition, waves and turbulence were observed prior to the arrival of the jet, within the jet, and after the jet passed the payload. The effects were considerably weaker during the ETG-2 plasma-jet injection.

Gavrilov et al.[4] investigate the magnetic field perturbations associated with the jet and compare these cavities with the observed plasma density. The density of the ETG-1 plasma jet exceeded the density of the ETG-2 plasma jet by two orders of magnitude in spite of the jet generators' being identical. Gavrilov et al. discuss the effect of the air cloud on the jet ionization and attribute these differences in number densities to the presence of the air cloud during the ETG-1 injection. They suggest that high-speed aluminum neutrals from the ETG are ionized as they move through the neutral air cloud. In addition, Gavrilov et al. suggests that the high-speed aluminum neutrals provide inertia acts to maintain the speed of the ionized component of the jet.

Gatsonis et al.[5] model the ETG-1 plasma jet, the air cloud, and background plasma using a three-dimensional, single-fluid, unsteady, viscous, compressible magnetohydrodynamic formulation. In their simulation the initial conditions for the air cloud at the time of the jet injection are obtained from a free-molecular expansion model, and the aluminum plasma jet is initialized as meter-sized axisymmetric density distribution with characteristics that correspond to laboratory data. The simulation shows the deceleration of the ETG-1 jet, the induced motion in the background plasma, the formation of a diamagnetic cavity, and the formation of a complex structure of magnetohydrodynamic waves. Comparisons with the plasma density and magnetic induction data taken onboard the plasma density payload located at about 468 m from the injection point show good overall qualitative and quantitative agreement. The simulation predicts the formation of a diamagnetic cavity with a 30,000-nT depletion of the ambient value. The magnetic induction components show the presence of a small perturbation in the direction perpendicular to the ambient induction and large perturbations

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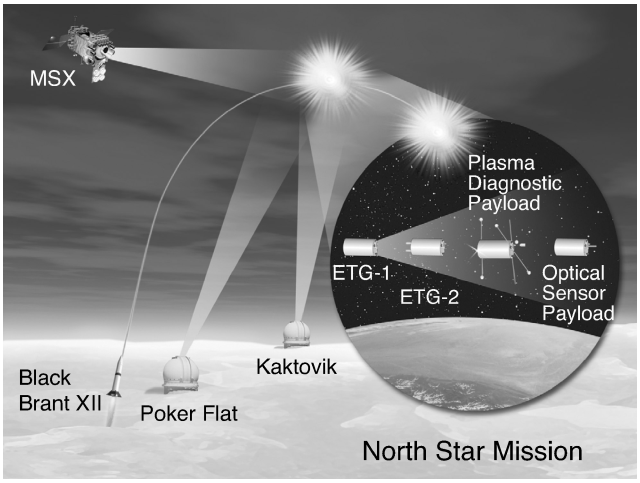

Fig. 1 Schematic of the North Star experiment. The circular cutout shows the locations of the subpayloads relative to the two explosive-type generators (ETG-1 and ETG-2).

on the plane of the ambient induction. Gatsonis et al. discuss the current closure patterns consistent with the single fluid and attribute the deceleration of the jet to momentum imparted to the background plasma. The three-dimensional simulations also show the sensitivity of instruments to the orientation of the jet.

Delamere et al.[6] model the ETG-1 plasma jet using a three-dimensional hybrid simulation method, and they investigate the coupling of the plasma jet with the ambient plasma. The current system is composed of Alfvén currents and diamagnetic currents caused by density gradients. The propagation of the jet is consistent with a polarized plasma jet drifting at the $\boldsymbol{E} \times \boldsymbol{B}$ drift velocity, which decreases in magnitude as a result of momentum transfer to the ambient. Because of the quasi-neutral assumption of the model, the polarization electric field results from the differences in gyromotion of ions and electrons and not from the development of space charges. The simulation is able to reproduce the basic features of the cavity in terms of plasma density, magnetic fields, and electric fields, including the relationship of these quantities to each other. Delamere et al. conclude that the plasma jet is fully coupled to the ambient plasma at a distance of $\sim$500 m [plasma diagnostic payload (PDP) location]. However, the exact nature of the momentum coupling of the jet to the ambient plasma at distances beyond the PDP payload is not known.

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