**A localized and surprising source of energetic particles in the Uranian magnetosphere near Ariel.** I. J. Cohen[1], D. L. Turner[1], P. Kollmann[1], G. B. Clark[1], M. E. Hill[1], L. H. Regoli[1], and D. J. Gershman[2], [1]The Johns Hopkins University Applied Physics Laboratory (11100 Johns Hopkins Road, MS 200-E254, Laurel, MD 20723; Ian.Cohen@jhuapl.edu); [2]NASA Goddard Space Flight Center

**Introduction:** In situ exploration of Uranus has been limited to a single flyby encounter by the Voyager 2 spacecraft in 1986. The system boasts a range of outstanding mysteries regarding its magnetospheric structure and dynamics [1-2]. In particular, the mystery surrounding Voyager 2's discovery of unexpectedly strong radiation belts at Uranus motivated a revisiting of measurements from the Low Energy Charged Particle (LECP) instrument [3]. This fresh survey revealed a previously underappreciated signature in the energetic particle observations from. Specifically, LECP observed a significant (several orders of magnitude) discrepancy between the intensity of energetic particles (both ions and electrons) observed during the outbound leg of the Uranus flyby encounter in the region between Miranda and Ariel compared to the inbound leg.

**Confirming and Characterizing the Source:** Of particular interest are the pitch angle distributions (PADs) —i.e., the angle of the charged particle velocity vector relative to the background planetary magnetic field vector—measured by LECP [4], which display extremely steep gradients (Fig. 2). The nature of these pitch angle ($\alpha$) distributions is curious. The $\sin^n(\alpha)$ fits (dashed lines) show that the $n$ values of the fits get extremely large, very rapidly at higher energies. Such a steep gradient in pitch angle is difficult to maintain since any waves—ranging in frequency from ultra-low frequency (ULF) to electromagnetic ion cyclotron (EMIC)—would act to scatter the particles and isotropize the distribution. This would require a significant and relatively constant source of energetic particles, specifically for those at near-90° pitch angles, at rates that can balance or even overcome any loss/scattering processes from waves. Incidentally, this region between the orbits of Ariel and Miranda was also exactly where Voyager 2 observed intense whistler-mode wave emissions [5]. Maintaining such a steep PAD would require a significant and relatively constant source of energetic particles, specifically for those at near-90° pitch angles, at rates that can balance or even overcome any loss/scattering processes from waves.

To illustrate this point, a one-dimensional pitch angle diffusion model was developed to simulate the expected evolution of the 1.45-MeV ion (assuming protons) pitch angle distribution observed by LECP at L=6. These simulations showed that simple pitch angle diffusion would isotropize the PAD within a few hours without the presence of an intense localized, near-90° particle source.

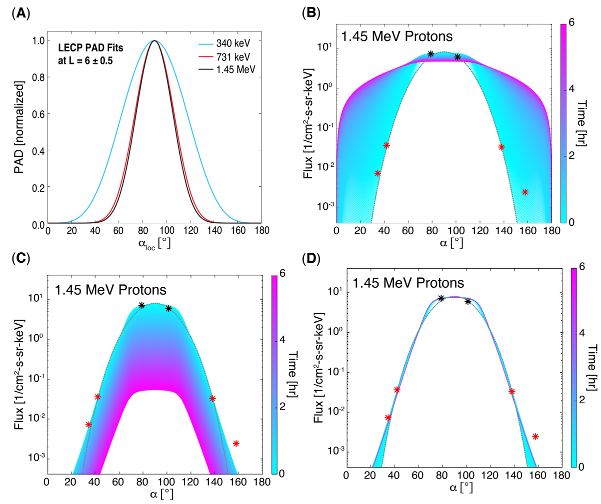


**Figure 1.** Simple one-dimensional pitch angle diffusion modeling suggests that an energetic particle source is required to sustain the steep pitch angle gradients observed by LECP. (A) Comparison of $\sin^n(\alpha)$ fit for the average PADs at three different >300 keV ion energy channels. (B) The expected evolution of the LECP 1.5-MeV ion (assuming protons) PAD assuming a pitch angle diffusion coefficient ($D_{\alpha\alpha}$) with a loss time constant ($\tau$) of 36 hr. (C) The same scenario but adding losses to the moons at all local pitch angles <80° on a 10-min loss timescale. (D) Adding a Gaussian pitch angle source centered at $\alpha$ = 90° with σ =1.5° and an amplitude of $S_0 = 1.26\times10^{11}$ cm$^{-2}$-s$^{-1}$-sr$^{-1}$-MeV$^{-1}$/s.

To assess whether such an energetic particle source is in fact present in the Uranian system, measurements of the phase space density (PSD) profiles of the ions versus L-shell as a function of the first adiabatic invariant ($\mu$) were investigated (Fig. 2) [6]. The clear maximum between Miranda and Ariel at L~7 clearly suggests a source of energetic ions in this region. The clear maximum between Miranda and Ariel at L~7 clearly suggests a source of energetic ions in this region. It should be noted that a similar peak in phase space density (i.e., energetic particle source) was revealed in Voyager 2/LECP observations at Saturn in the region just inward of Enceladus [7], which the orbital Cassini mission later revealed to be an actively outgassing ocean world [8].

**Discussion of Potential Origins**: It is challenging to definitively determine the source of these energetic particles given the limited—in range, duration, and system coverage—in-situ measurements of the Uranian magnetosphere. In particular, composition measurements of ion species—both mass and charge state—in the suprathermal (10s to 100s keV) energy range are lacking, which could help identify particle sources and acceleration processes. Likewise, field measurements at the relevant frequencies required to assess ion-mode wave processes are missing. However, even the limited measurements obtained at Uranus can be combined with understanding informed by more comprehensive observations in other planetary magnetospheres to assess the feasibility of several sources based on whether they could explain different aspects of the LECP observations—specifically 1) the >300 keV energies, 2) the substantial particle intensities, and 3) the strongly peaked near 90° PADs.

Potential energetic particle sources include particle injections, cosmic ray albedo neutron decay (CRAND), and an active moon (i.e., a candidate ocean world). Particle injections are believed be unlikely because the LECP electron observations display neither any energy dispersion nor any evidence of drift echoes as might be expected. CRAND is likewise believed to be an unlikely source as the planet itself is believed to be the primary source in the system and therefore would result in a radial profile very different than that observed by LECP.

However, an active moon source is potentially plausible. First, the narrow pitch angle source required to obtain the results in Fig. 1d matches that expected from newly created pickup ions [9]. Since the 1986 Voyager 2 flyby of Uranus, several moons throughout the solar system have been revealed to be geologically active. often cryo-volcanic, ocean worlds. The location of the maximum in the PSD profiles at L~6 (Fig. 2) suggests Ariel to be the most likely potential source moon, since such PSD values usually fall off closer to the planet; however, Miranda cannot be discounted as a potential additional source. Other Voyager 2 observations also provide potential additional evidence to support an active moon source. Unfortunately, at Uranus, the LECP instrument could not measure ion composition below ~500 keV/nuc [4]—e.g., 2 MeV for helium, 8 MeV for oxygen; thus, it is unsurprising that LECP did not see any non-proton populations that may have been sourced by an active Uranian moon as it was unlikely that these species were easily energized to such extreme energies; however, evidence exists that such heavy ions can be accelerated to suprathermal energies by EMIC waves [10]. Additional measurements from the Plasma Experiment (PLS) [11] suggest that there are

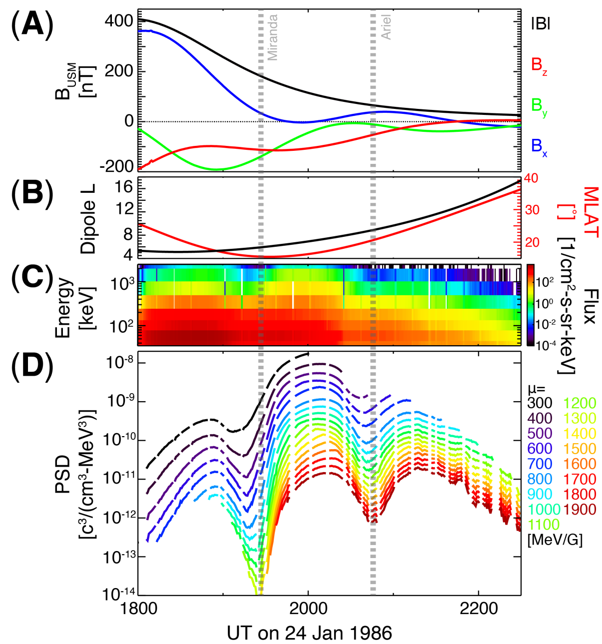


**Figure 2.** Revisiting Voyager 2 observations (A-C), revealed a very clear maximum between Miranda and Ariel at L~7 in the ion phase space density (D), which indicates a source of energetic ions in this region.

heavier ions in the region between Miranda and Ariel [12]. Similarly, the aforementioned PLS signatures of anomalous spacecraft charging could possibly be a result of flying through a dense torus or cloud of ionized particles, including salts.

**Conclusions**: Ultimately, further investigation of this mysterious energetic particle source will require additional observations from the Uranian system, preferably from an orbiter mission that is equipped with instruments to measure the thermal plasma properties and composition, suprathermal (tens to hundreds of keV) ion composition, with both mass and charge-state, and wave activity extending into the ion-cyclotron modes (i.e., EMIC waves).

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