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# Asymmetry in Uranus' High Energy Proton Radiation Belt

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**Key Points:**

- Asymmetry in Uranus' magnetic field causes variations in the azimuthal drift component which is most significant for high energy protons
- This drift velocity profile results in regions where there can be a surplus or depletion of protons
- Voyager 2's measurement of weak proton radiation belts at Uranus could be partially explained by this phenomenon

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## Abstract

Uranus is one of the least explored planets in our solar system, it exhibits a unique magnetic field structure which was observed by NASA's Voyager 2 mission nearly 50 years ago. Notably, Uranus displays extreme magnetic field asymmetry, a feature exclusive to the icy giants. We use the Boris algorithm to investigate how high energy protons behave within this unusual magnetic field, which is motivated by Voyager 2's observation of lower-than-expected high energy proton radiation belt intensities at Uranus. When considering full drift motions of high energy protons around Uranus, the azimuthal drift velocity can vary by as much as 15% around the planet. This results in areas around Uranus where particles will be more depleted (faster drift) and other regions where there is a surplus of particles (slower drift). This could provide a partial explanation for the “weak” proton radiation belts observed by Voyager 2.

## Plain Language Summary

In 1986, Voyager 2 made history as the first spacecraft to fly by Uranus, offering humanity unprecedented insights into the distant icy giant. This mission revealed to us the unique magnetic field of the planet. Typically, planets with strong magnetic fields can capture high energy charged particles from space and trap them around the planet. While being trapped within the magnetic field, the particles will slowly drift around the planet, forming what are known as “radiation belts”. The radiation belts of Uranus are of particular interest to us as the Voyager 2 flyby indicated that they were much weaker than expected despite the strong magnetic field presence. We suggest that this could be explained by the unique magnetic field structure causing variations in the speed at which particles drift around the planet. This would create regions where particles are packed closer together and other regions where they are more spread-out; we show Voyager 2 flew past a region where particles were more spread-out. At the time of writing, a new mission to Uranus is being planned, and so this new idea could be one of many that will be tested by a future mission to the outer planets.

## 1. Introduction

In 1986, Voyager 2 became the first human made object to pass by Uranus. Another 3 years later, it would be the first to pass by Neptune as well, making it the only man-made satellite to visit the icy giant planets to this day (Evans, 2022; Stone & Miner, 1986). These flybys allowed us to glimpse into their local environments, enabling us to measure their magnetic field, plasma properties and upper atmosphere structure (Desch et al., 1986), as well as discover their rings and several moons. From this data, we saw that these planets have magnetic fields like no other in the solar system; both exhibit extreme asymmetry in their field structure. For comparison, most planetary field structures can be well approximated by a simple dipole field; to model the field at Uranus, the higher order “quadrupole” field must be implemented to simulate this asymmetry (Connerney, 1993). This makes the icy giants prime candidates for investigating new magnetospheric phenomena that cannot be observed at closer planets. At the time of writing, a Uranus flagship is being prioritized by NASA (Origins, Worlds, and Life, 2023), with magnetospheric dynamics at the forefront of the mission objectives and so highlighting what we do and do not know about the system will help lay the groundwork for identifying key mission objectives in the future (Fletcher et al., 2020; Kollmann et al., 2020).

This paper will focus on one intriguing phenomenon observed by Voyager 2 at Uranus, the relatively weak proton radiation belts (almost 100 times lower intensity than the Kennel-Petschek (KP) limit) (Kennel & Petschek, 1966; Mauk, 2014). Radiation belts typically form within the inner magnetosphere of magnetized bodies where charged particles can become trapped, gyrating along the field lines of the planet with gyro-radius,

$$R_{\text{gyro}} = \frac{mv_{\perp}}{qB} \quad (1)$$

where $v_\perp$ is the component of velocity perpendicular to the magnetic field at the position of the particle (which determines the pitch angle of the particle), $m$ is the mass, $q$ is the charge and $B$ is the magnitude of the magnetic field. We do not include the relativistic Lorentz factor as protons at the energy we are considering do not experience significant relativistic effects. These particles then bounce between the magnetic poles of the planet, where the field is strongest. Gradients in the magnetic field strength along the field line and the curvature of the field structure itself cause an azimuthal force to act on the particle, resulting in these trapped particles slowly drifting around the planet as they bounce between the North and South pole, forming the radiation belts (Ukhorskiy & Sitnov, 2014). The KP-limit is a theoretical upper limit on the intensity of measured particle density within the radiation belts as described in Kennel and Petschek (1966). Recent studies into the Voyager 2 data set have shown that despite the fact that electrons in the 1 MeV energy range do challenge this limit, the proton radiation belts are far below this limit at all energies (Mauk, 2014; Mauk & Fox, 2010).

Masters et al. (2022) proposed the hypothesis that the asymmetric structure of the Uranian magnetic field, when compared to a more symmetrical dipole field structure, could reduce the fields' ability to trap high energy particles with the largest gyro-radii compared to that of a more traditional planetary dipole. They investigated the significance of radial drift introduced by the asymmetric magnetic field over a single bounce motion and found that protons at 3 MeV (highest proton energies that Voyager 2's instruments were able to detect) can have their guiding center trajectories shifted away from their trajectory within a pure dipole field structure.

In this study, we build on that work by Masters et al. (2022) by using the Boris algorithm (Hairer & Lubich, 2018; Qin et al., 2013) to simulate full drift motions (one complete rotation around the dipole axis) of high energy test protons around Uranus at discrete radial distances. We show how the asymmetry of the field could be causing azimuthal variations in the particle drift velocity. This would result in regions of particle depletion (faster drift) and regions of surplus particles (slower drift). We hypothesize that Voyager 2's low high-energy proton intensity observation could in-part be a result of it measuring a region of depletion at the time of its flyby and that the proton radiation belts are not "weak", but rather highly spatially dynamic.

## 2. Simulating Test Protons in Uranus' Asymmetric Magnetic Field

As Voyager 2 completed its flyby of Uranus, it was continuously taking magnetic field measurements. From these observations, Connerney et al. (1987) was able to construct a model of the field by using the spherical harmonic representation of magnetic fields. We use a more updated model, with Gauss coefficients from Herbert (2009). In this study, we only used up to the second order of structure (quadrupole) in our model, beyond this, the higher order terms, like the octupole, become insignificant to our results given we are only concerned with regions $>4R_U$ ($1R_U = 25559$ km) which represents the closest approach of Voyager 2. Hence, our magnetic environment is the dipole + quadrupole (DQ) intrinsic field of Uranus. This allows us to introduce the magnetic axial asymmetry that would not be possible to model by use of the simple dipole approximation.

The base coordinate system we will be using in this paper is the same system in which the spherical harmonic model is defined; the $z$-axis aligned with the rotation axis of Uranus and the $x$-axis is aligned with the prime meridian at the reference epoch, the origin located at the center of the planet, and the system rotates with the planet (this accounts for rotation of the field automatically). The $y$-axis completes the Cartesian system and, along with the $x$-axis, represents the equatorial plane—defined as in the NASA PDS U1 system (Garrett et al., 2015). Our models' coordinate system can be found by using the spherical harmonic coefficients to rotate the $z$-axis to align with the magnetic dipole axis via consecutive rotations about the $x$- and then $y$-axis. The new $xy$-plane represents the magnetic dipole equator. We will henceforth refer to this coordinate system as U-Mag. When we refer to any "azimuthal" variations, that is referring to angular variations about the U-Mag $z$-axis (dipole axis).

For this study, we ignore the effects of intra-particle and wave-particle interactions. These are reasonable assumptions to make as the lack of plasma within Uranus' inner magnetosphere means that particles interact on much larger timescales than the dynamics we are considering. Waves are able to remove particles from the system or even alter their radial position in the radiation belts (Kollmann et al., 2017; Nénon et al., 2018), but once again this happens on timescales much larger than what we consider in this study. Our simulations also neglect electric fields which can have a strong effect on low energy plasma; but in our high energy proton case, the dynamics would be dominated by the magnetic field anyway as magnetic effects (such as gyro-motion and mirror modes) scale with energy (Hao et al., 2020). However, there currently is no real consensus on the structure of Uranus' local electric field given the small sample of data we have (Cao & Paty, 2017; Selesnick, 1988). Hence, we do not really know how strongly the electric field of Uranus could affect particle motion.

To model the motion of protons around Uranus, the Boris algorithm is utilized (e.g., Qin et al., 2013). This algorithm uses a leapfrog method to solve the Lorentz equation—the process is specifically designed to conserve phase space volume and pushes particles using "half-steps" in velocity (Hairer & Lubich, 2018). The fact that this algorithm conserves phase space volume means that it will also conserve energy, an attribute that is not held by more traditional particle pusher algorithms (such as Euler's method and Runge-Kutta). This means that the Boris algorithm is able to complete long time integrations of particles and effectively simulate multi-scale dynamics of particles in electromagnetic fields; this makes it a great tool for simulating long particle drift motion around planets. However, it should be noted that the Boris algorithm does introduce some error into the simulation which is due to the finite resolution of the time-step. To minimize this, we use a quasi-adaptive time-step defined by,

$$dt = \frac{T_{\text{gyro}}}{50} \tag{2}$$

where $T_{\text{gyro}}$ is the gyro-period of the particle. $T_{\text{gyro}}$ is then updated every 50th time-step. This means that one full gyro-rotation will take ∼50 time-steps. Since the time it takes to complete one full bounce motion is significantly larger than the gyro-period, this means that positional error can be reasonably minimized while also not affecting the resolution of the gyro-motion.

## 3. Results and Discussion

Particles are initialized on the $x$-axis in the U-Mag system at a known distance from the planet with a set energy and pitch angle and pushed until they reach their maximal radial distance from the planet along the field line it started on. This is considered the starting point, and then the particle is pushed until one full drift motion is completed. In theory, the maximum radial distance of the particle's guiding center should remain constant in a dipole field. Similarly, the distance at which the particles are at their minimal radial distance from the planet (mirror points) should also remain constant (Soni et al., 2020).

We chose to initialize our protons on the $x$-axis with the guiding center at 4, 5 and $6R_U$ from Uranus and a gyrophase (angular position of the proton relative to the guiding center) of $0^{\circ}$. This region was chosen as it represents the innermost bounds of the Voyager 2 trajectory and where the quadrupole component is most significant to its measurements; the magnetic field model was also built upon measurements from this region (Connerney et al., 1987; Herbert, 2009). We considered protons with an energy of 3 MeV and pitch angle of $170^{\circ}$ as this approximately represents the highest energy band that Voyager 2 was equipped to measure with its Low Energy Charge Particle Investigation instrument (LECP) (Cheng et al., 1987; Garrett et al., 2015). The relatively high pitch angle allows the particles to pass along nearly the entire field line so we can sample the effects of the entire field, not just the field near the dipole equator. An example of the output trajectory from our simulation for a particle initialized at $5R_U$ is shown in Figures 1a and 1b, this shows the significant effect that the quadrupole has on the path of a high energy proton across a full drift motion compared to its path within the pure dipole field of Uranus. This also shows that radial drift does not reduce the fields' ability to trap particles at this distance as Masters et al. (2022) suggests, as over one full bounce motion the particle returns to the same radial distance it was at when it started. The error in our simulation can be quantified by calculating the radial drift of the particle in the dipole only case; we would expect that in a dipole field, the only drift component would be azimuthal, so any radial drift we see must be due to positional error in the algorithm. From the purple trajectory in Figure 1c, we determined that over one full drift motion the positional error of the maximum radial distance points was $<0.05\%$ and so, for our purposes, this was deemed insignificant.

To investigate how azimuthal drift velocity varies, we fix the set of initial conditions for high energy protons and allow them to be pushed until they have completed one full drift motion within the DQ field of Uranus. By tracking the distance between consecutive bounce motion maximum radial distance positions and the time it takes the particle to move between them, we can get an estimate for the average total drift velocity between those two points. This would allow us to build a drift velocity profile of the particle as a function of azimuthal angle. This distribution is shown in Figure 2.

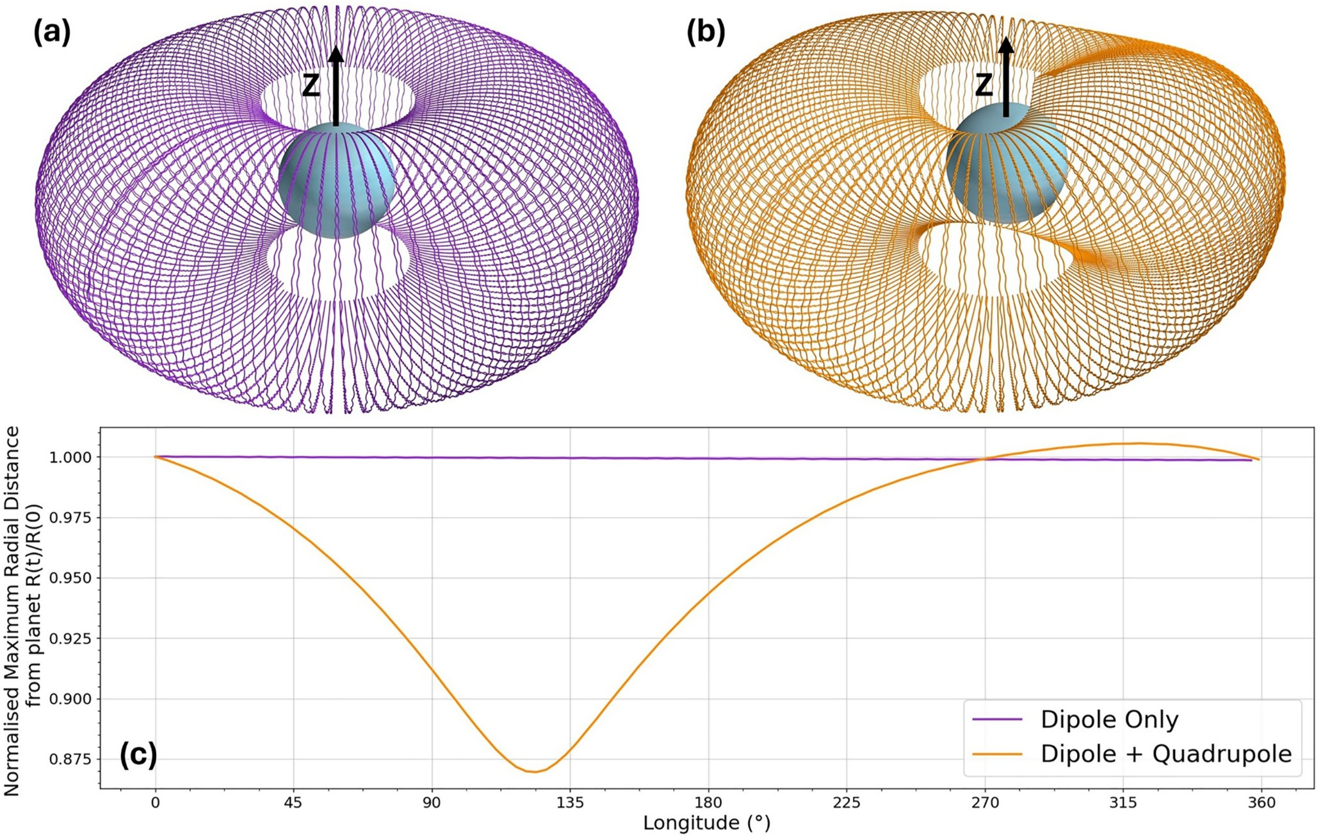


**Figure 1.** Visualization of the trajectory of a 3 MeV proton around Uranus initialized at a starting radial distance of $5R_U$ in the (a) dipole field only in purple, versus (b) the dipole + quadrupole (DQ) field in orange. This highlights how even at $5R_U$ the quadrupole component of the magnetic field can have a significant effect on the trajectory of a particle. Panel (c) shows a comparison of the evolution of the maximum radial distance points during the protons full drift motion; in the dipole case, this distance remains roughly constant, whereas in the DQ case, there is substantial inward and outward radial drift. The labeled $z$-axis corresponds to the dipole axis, as in the U-Mag coordinate system.

The asymmetric nature of the DQ field is shown to cause extreme variations in drift velocity, this effect becomes increasingly more significant at smaller initial radial distances from the planet (where the quadrupole becomes more significant). For a particle starting at $4R_U$, the drift velocity can deviate approximately $\pm 13\%$ from the dipole drift velocity during a full drift motion.

When considering the trajectory of Voyager 2 through the Uranus system in the frame of the magnetic field, we can see that its closest approach occurred in an azimuthal region of "fast" drift motion at a radial distance of approximately $4.2R_U$. This could imply that Voyager 2 did indeed pass through a region of high energy proton depletion during its flyby.

To demonstrate the phenomenon of azimuthal particle bunching and spreading, we simulated 10,000 particles and initialized them at a set distance from Uranus ($4R_U$), distributed equally around the planet and given the azimuthal velocity profile from the $4R_U$ case in Figure 2. These particles were then "pushed" in the angular direction using a simple Euler method for several full rotations around the planet. Tracking the volume of particles in discrete azimuthal regions over time will allow us to see if there are sections where particles bunch up and where they spread out because of this drift velocity profile.

Figure 3 compares the evolution of the azimuthal distribution of particles for a drift velocity profile at $4R_U$ from Figure 2 to the distribution of particles in a dipole field only drift velocity distribution (constant drift). We can observe that between $110^\circ$ and $140^\circ$ where the drift velocity is slowest, there is a persistent peak in the number of particles which can grow to as high as 25% above the base dipole distribution. We can also see that the "fast" drift regions either side of the "slow" drift region exhibit opposite behavior in that there is a persistent depletion of particles. Once again comparing Voyager 2's trajectory to this distribution, we can see the closest approach

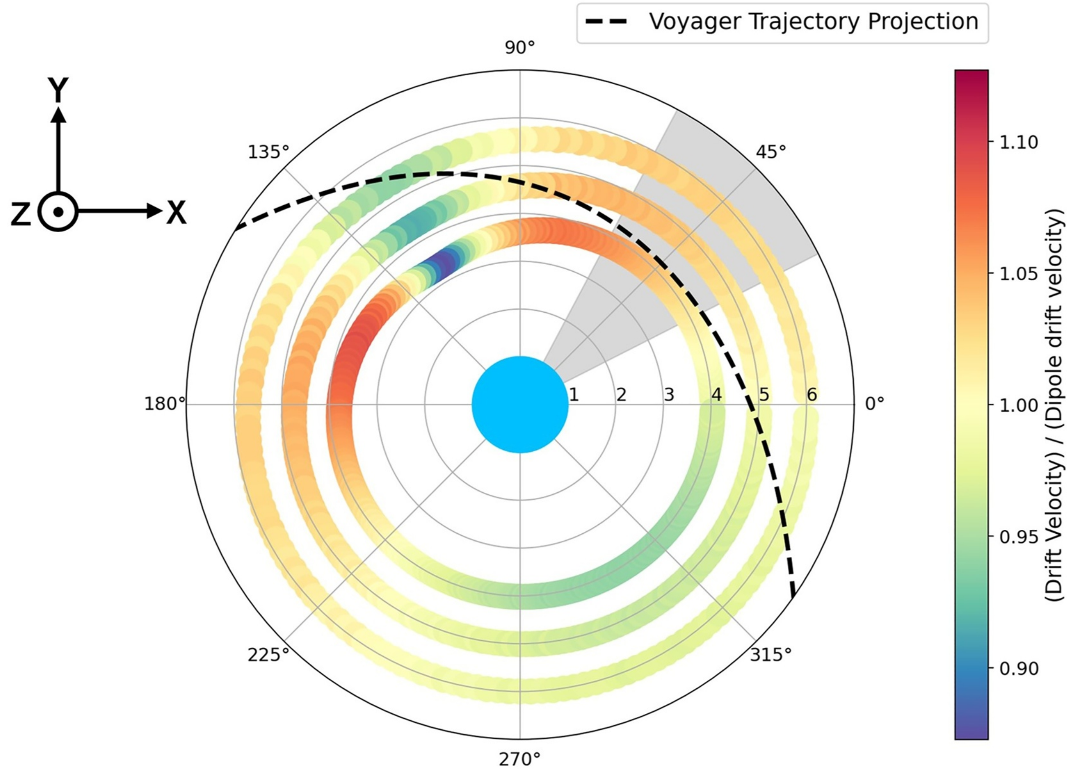


**Figure 2.** Polar plot of the dipole equator, highlighting the variations in total drift velocity relative to the dipole drift velocity. The colored dots represent the position of a proton at its maximum radial distance from the planet after a single bounce motion and its color denotes its drift velocity at that point (Yellow implies the altered drift velocity matches the drift velocity in a pure dipole field). The black dashed line represents Voyager 2's trajectory in the U-Mag system projected onto the *xy*-plane. The gray angular region highlights the closest approach of Voyager 2.

occurred in a region where there is a predominant depletion of particles by as much as 20% below the dipole base level.

Comparing the distribution at different slices in time also implies that the particle distribution with the DQ drift velocity distribution, although it does show clear and consistent trends in specific angular regions, varies significantly with respect to the dipole distribution. However, the situation we are simulating is an idealized version of the real problem; it is likely that over the course of millions of rotations, rather than just the few that we are limited to simulating, the system could reach a form of "steady state" distribution where the general trend described above dominates over the local fluctuations, similar to the distribution shown in Figure 3d. Conversely, Figure 3 does show that any perturbations caused by external dynamical processes could cause strong variations in this steady state distribution which will propagate in azimuth. This is demonstrated by a perturbation at $\sim 180^{\circ}$ longitude in Figure 3b propagating to $\sim 280^{\circ}$ in Figure 3c, and then to $\sim 60^{\circ}$ in Figure 3d, within 45 min.

We have now shown that the asymmetric nature of Uranus' magnetic field does cause variations in the azimuthal drift velocity of high energy protons. We have also shown that this variation can cause significant alteration to the azimuthal high energy proton distribution within the inner magnetosphere, and most importantly, in the region where Voyager 2 had its closest approach. It is important to note that this effect will only be significant for high energy protons as this is a finite gyro-radius effect—electrons, with their much smaller mass, will not have their trajectory as drastically altered as the protons by the quadrupole component of the field with their much smaller gyro-radius (Equation 1). There would still be an asymmetry in their drift velocity distribution, but it would be to a much smaller extent. This is relevant as Voyager 2 only measured a weak high energy proton radiation belt; the electron radiation belt, in comparison, was at the KP limit (Mauk & Fox, 2010).

When comparing our results to the Voyager 2 trajectory data, we can see that the spacecraft would have passed through a region which favors faster drift and hence an overall lower particle distribution than would be expected

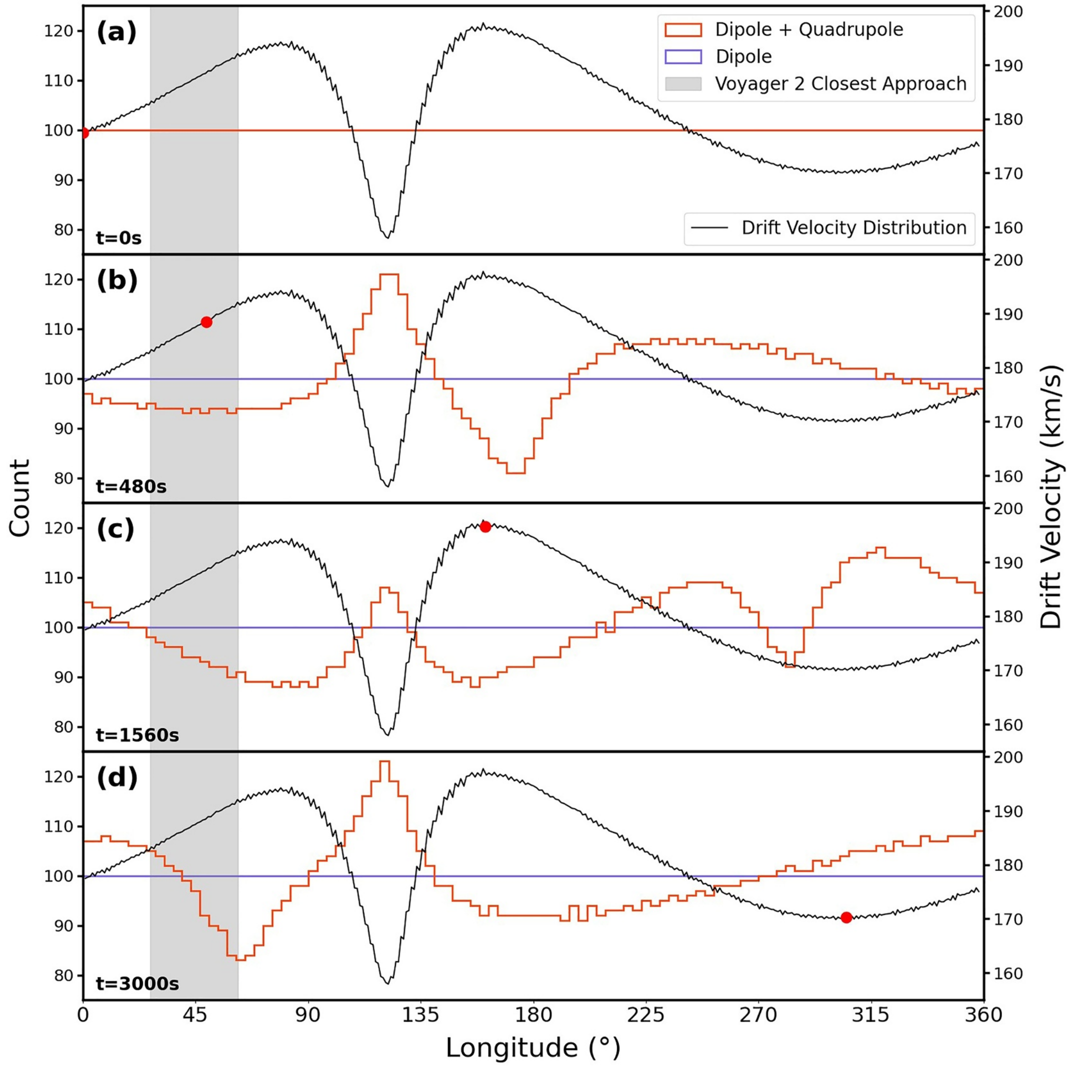


**Figure 3.** Plot of the evolution of a distribution of 10,000 particles which are equally spaced in azimuth around Uranus and given the angular velocity distribution associated with the drift velocity distribution found for a proton initialsed at a maximum radial distance of $4R_U$ in Figure 2 (shown in orange) in spherical polar coordinates. The purple histogram outline represents the distribution of particles which are given the velocity distribution associated with a particle in Uranus' dipole only field. Each subplot shows the distribution at a different point in time during a full rotation, (a) $t = 0$ s, (b) $t = 480$ s, (c) $t = 1,560$ s, and (d) $t = 3,000$ s. The black line shows the angular velocity distribution and the red dot on that line represents where a particle which was initialized at $t = 0$, longitude $= 0^{\circ}$ would be after that given amount of time.

of a dipole driven radiation belt shell. This deficiency peaks at ∼20% below the dipole distribution, which is significant and likely measurable for a future spacecraft. However, it would not fully account for the difference between the ion intensities expected from the KP-limit and the observed intensities which are of order 100 times lower than this limit (Mauk et al., 1987). It is possible that with the inclusion of more complex system dynamics this effect compounds to be a more significant contribution to this deficiency. This puts emphasis on the need for a future Uranus flagship mission which will allow us to understand which processes are most dominant in the planets' local environment.

If we consider the magnetic field beyond $6R_U$, the field structure becomes more dominated by the dipole field component. This means that the drift velocity distribution will become flatter, and we would expect to see more traditional radiation belt structure. On the other hand, this investigation highlights the peculiar phenomena that can occur within the inner regions of the magnetosphere where the quadrupole component becomes significant.

Further in than $4R_U$, we would expect even more extreme behavior that would require higher order moments of spherical harmonics to model accurately.

## 4. Conclusion

We have shown that the asymmetric magnetic field of Uranus causes variations in the azimuthal drift velocity of high energy protons and how this could be causing fluctuations in the angular density profile of these protons. We have also shown that this unusual drift velocity profile can cause temporal variations in ion distribution around the planet. However, if other dynamics were included in the simulation, these variations would likely tend toward a steady-state distribution with maximum deviations of $\pm 20\%$ from the base dipole distribution at $4R_U$. We also showed that the drift velocity profile can cause perturbations to this distribution to propagate in azimuth. Although our findings do show that portions of Uranus' radiation belts should be weaker than expected, and that Voyager 2 went through a region of depletion (fast drift), they do not fully account for the observed ion intensities being approximately 100 times lower than the KP-limit. Despite this, asymmetric drift velocity is clearly still a significant effect that we would expect to be prevalent at any planet that supports an asymmetric magnetic field, similar to that of Uranus. A future study of this effect at Neptune could shed light on the significance of variational drift velocity in a system other than Uranus as Neptune shows these similar characteristics of an asymmetric field structure. This lack of conclusiveness of results surrounding the icy giants highlights the need for a future flagship mission to one of these planets—to understand these mechanisms fully, more data would be needed within the inner magnetosphere where the quadrupole (and higher order terms) become significant so that we can fully interpret the intertwined nature of the particle distributions with the magnetic field structure.

## Data Availability Statement

Calibrated magnetic field and position data from the Voyager 2 mission are available from the Planetary Plasma Interaction (PPI) Node of NASA's Planetary Data System (PDS) (https://pds-ppi.igpp.ucla.edu/mission/Voyager/VG2) in the folders VG2-U-POS-5-SUMM-U1COORDS-48SEC-V1.0 and VG2-U-MAG-4-SUMM-U1COORDS-48SEC-V1.0. The derived data shown in Figures 1–3 can be found in the *Zenodo* data repository (Acevski, 2024) https://doi.org/10.5281/zenodo.11094122.

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