POLAR spacecraft observations of helium ion angular anisotropy in the Earth’s radiation belts

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Received: 19 June 1998 / Revised: 30 October 1998 / Accepted: 16 November 1998

Abstract. New observations of energetic helium ion fluxes in the Earth’s radiation belts have been obtained with the CAMMICE/HIT instrument on the ISTP/GGS POLAR spacecraft during the extended geomagnetically low activity period April through October 1996. POLAR executes a high inclination trajectory that crosses over both polar cap regions and passes over the geomagnetic equator in the heart of the radiation belts. The latter attribute makes possible direct observations of nearly the full equatorial helium ion pitch angle distributions in the heart of the Earth’s radiation belt region. Additionally, the spacecraft often re-encounters the same geomagnetic flux tube at a substantially off-equatorial location within a few tens of minutes prior to or after the equatorial crossing. This makes both the equatorial pitch angle distribution and an expanded view of the local off-equatorial pitch angle distribution observable. The orbit of POLAR also permitted observations to be made in conjugate magnetic local time sectors over the course of the same day, and this afforded direct comparison of observations on diametrically opposite locations in the Earth’s radiation belt region at closely spaced times. Results from four helium ion data channels covering ion kinetic energies from 520 to 8200 KeV show that the distributions display trapped particle characteristics with angular flux peaks for equatorially mirroring particles as one might reasonably expect. However, the helium ion pitch angle distributions generally flattened out for equatorial pitch angles below about 45°. Significant and systematic helium ion anisotropy difference at conjugate magnetic local time were also observed, and we report quiet time azimuthal variations of the anisotropy index.

Key words. Magnetospheric physics (energetic particles, trapped; magnetospheric configuration and dynamics; plasmasphere).

Introduction

The Earth’s radiation belts have been studied since the beginning of the space era (e.g., summaries by Roederer, 1970; Schulz and Lanzerotti, 1974; Spjeldvik and Rothwell, 1985; Walt, 1994), and ions heavier than protons have become recognized as important components of the terrestrial space environment (e.g., Mogro-Campero, 1972; Hovestadt et al., 1972; Krimigis and Van Allen, 1976; Spjeldvik, 1979; Spjeldvik and Fritz, 1983; Spjeldvik, 1996a; and references therein). Theoretical attention to expected angular distributions of geomagnetically confined ions was given as early as in the 1960s and 1970s (e.g., Northrop and Teller, 1960; Hamlin et al., 1961; Dungey, 1966; Roederer and Schulz, 1971; Stern, 1971; Schulz, 1972; Kivelson and Southwood, 1975a,b; Southwood and Kivelson, 1975; and references therein).

Except for times of sudden impulsive injections or shock-like events, radiation belt energetic ions at MeV kinetic energies convect so slowly across geomagnetic field lines that the long time scale diffusive transport dominates dynamic behavior. To evaluate steady state radial and pitch angle distributions of helium ions in the interior of the radiation belts, one must consider a balance between transport and losses (e.g. Nakada and Mead, 1965; Cornwall, 1972). In an early Russian work, Tverskoy (1971) modeled the L-shell location of the equatorially mirroring peak fluxes to occur where the characteristic time scales of cross-L transport coincide. For helium ions at E ~ 1 MeV, the effective local loss time scale is similar to, or smaller than, the cross-L diffusive transport time scale at L < 3.5 (e.g. Spjeldvik and Fritz, 1978, 1981) at the geomagnetic equator, and the L-shell range where this is true expands towards higher L-shells with lower equatorial pitch angles. This is so because charged particles with low equatorial pitch angles encounter a denser bounce-averaged exosphere, and thus suffer comparatively...
greater collisional interactions and losses (e.g., quantitative evaluation by Smith and Bewtra, 1978; Smith et al., 1981).

Moreover, ions with different pitch angles observed at \( L = 3 \) (for example) come from different parts of the ion spectrum in the source population at higher \( L \)-shells (since the parallel ion kinetic energy adiabatically varies as \( L^{-2} \) while the perpendicular energy varies as \( L^{-3} \) in the dipole B-field approximation), and this couples the observable radiation belt ion anisotropy with both the outer zone source spectrum and the energy and pitch angle dependent cross-field diffusive transport rate. It is therefore to be expected that the ion pitch angle distributions within the radiation belts should be determined by the combination of pitch angle dependent source mechanisms, by pitch angle dependent loss processes, by the cross-\( L \) transport characteristics, and to some extent by electric and magnetic \( L \)-shell splitting in the interior of the radiation belts.

It is known that plasma waves in the whistler mode help control the structure of the electron radiation belts (i.e., Lyons and Thorne, 1973), and plasma waves in the ion-cyclotron mode are certainly important for protons and other ions in the lower keV energy range (e.g., Taylor and Lyons, 1976; Joselyn and Lyons, 1976; and others), yet there is little reliable information to unambiguously establish an importance of wave scattering of MeV ions. Part of the reason for this has been the limited availability of detailed pitch angle distributions of different ion species in the central parts of the radiation belts where these ions are abundant. The observational findings presented herein may help remedy this empirical dearth.

Except for large injection events and magnetic shock transitions through the magnetosphere, helium ions can diffusively populate the radiation belts from an external source region such as the solar wind and solar energetic particles (e.g., Cornwall, 1972; Schulz and Lanzerotti, 1974; Lyons and Evans, 1976; Fritz and Spjeldvik, 1978, 1979, 1981; Spjeldvik and Fritz, 1978, 1981; Sheldon and Hamilton, 1993). Additionally, such ions (both \(^{3}\)He and \(^{4}\)He) can also be generated in situ in the inner radiation zone by local nuclear interactions (e.g., Chen et al., 1994, 1996a,b; Pugacheva et al., 1996; Selesnick and Mewaldt, 1996; Spjeldvik et al., 1996; Gusev et al., 1996; and references therein). There have been several modeling studies of geomagnetically trapped energetic helium ions (e.g., Tverskoy, 1971; Cornwall, 1972; Krimigis and Van Allen, 1976; Fritz and Spjeldvik, 1978, 1979, 1982; Panasyuk and Vlasova, 1981; Spjeldvik and Fritz, 1978, 1981, 1983; Sheldon and Hamilton, 1993; Chen et al., 1994, 1996a,b; Selesnick and Mewaldt, 1996; Spjeldvik, 1996b; Pugacheva et al., 1996; and others).

For radiation belt protons, there exist empirical models compiled by NASA as well as a survey of proton pitch angle anisotropies with local time, energy and \( L \)-shell (e.g., Garcia and Spjeldvik, 1985). But for radiation belt ions heavier than hydrogen, detailed data to carry out a local time variation assessment have until now not been available. Using data from the well-instrumented POLAR spacecraft in the NASA/ISTP program, we here study details of the MeV helium ion anisotropies and azimuthal asymmetries in the radiation belt region.

In an earlier conference paper we have reported on azimuthal helium ion asymmetries in the radiation belts (Spjeldvik et al., 1998), showing shifts in the radial location of the helium ion flux maxima and observed variations in helium ion flux intensities with magnetic local time. In this work we investigate the character of the observed angular anisotropies of hundreds of keV and several MeV helium ions. The CAMMICE/HIT instrument does not significantly distinguish between \(^{3}\)He and \(^{4}\)He, so our results pertain to the overall helium ion population.

**Helium ion observations**

The POLAR spacecraft was launched on February 24, 1997, and it achieved a near polar orbit with an initial inclination \( \sim 86^\circ \) to the equator, an initial perigee of \( \sim 1.8 \) Earth radii over the Earth’s south pole, an initial apogee of \( \sim 9 \) Earth radii over the north pole, and a spacecraft spin time scale of six seconds. Among the extensive instrumentation on the POLAR spacecraft is the CAMMICE instrument package which contains the heavy ion telescope (HIT) consisting of a stack of solid state detectors and electronic discriminators. HIT is mounted perpendicular to the spacecraft spin axis where it operates with an angular and temporal resolution of 16 sector samples per spacecraft spin period. The spacecraft spin axis orientation is nominally perpendicular to the orbital plane such that instruments with pointing direction perpendicular to the spin axis sample virtually all directions angular to the geomagnetic field in each spin as POLAR crosses the geomagnetic equatorial plane. We here report observations of geomagnetically trapped helium ions in four energy ranges (data channels HID5–8) from 520 to 8200 keV ion kinetic energy. These are specified in Table 1. The geometric factor of the CAMMICE/HIT instrument is \( g = 9.13 \times 10^{-3} \) cm\(^2\) sr, and the HIT aperture opening angle is \( \pm 8^\circ \). Except for the highest energy channel which extends up to 8200 keV, these POLAR helium ion channels are similar in energy coverage and functionality to the helium ion detector channels, \( \Delta a1, \Delta a2, \Delta a3 \) and \( \Delta a4 \) utilized on the previous Explorer-45 spacecraft in magnetospheric near-equatorial orbit (e.g. Fritz and Spjeldvik, 1978, 1982).

The POLAR spacecraft made particle and field observations during the low solar activity in the spring, summer and autumn of 1996, and POLAR continues to be operational as of this writing. In the interior of the radiation belts, this time interval constitutes a rather long period of geomagnetic quiescence with the \( D_s \) ring current activity index rarely depressed by more than a few tens of nanoTesla between a minor magnetic “storm” on January 13 (with provisional minimum \( D_s = -88 \) nT) and another “storm” on October 23, 1996 (with provisional minimum \( Dst = -110 \) nT). Thus the period from the launch of POLAR to the October 1996 storm represents an opportunity to study the