Losses of ring current ions by strong pitch angle scattering

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Abstract. High angular resolution measurements of 155 keV ions in the ring current during the magnetic storm of August 6, 1998 show filled loss cones indicating that very rapid pitch angle scattering is taking place above the satellite location. The measurements were made with the SEPS detector on the Polar satellite during its passages through the ring current regions, usually at magnetic latitudes near $\pm$ 45° and at magnetic local times of about 04:00 and 16:00 hrs. The observed strong pitch angle scattering implies a trapping lifetime of less than an hour and may explain the early rapid recovery of Dst during magnetic storms.

1. Introduction

Processes leading to the removal of ring current ions during the recovery phase of geomagnetic storms include charge exchange, radial diffusion and convection, coulomb energy loss, and pitch angle scattering into the loss cone. The relative importance of these processes is controversial, particularly the losses by pitch angle scattering. While charge exchange collisions appear to be dominant in the late recovery stage [*Jorgensen et al.*, 2001] the early recovery stage losses are more rapid than charge exchange can support [*Fok et al.*, 1995]. Convection of protons out of the magnetopause boundary has been modeled by *Liemohn et al.*, [1999] who concluded that many ring current protons leave the magnetosphere before completing a drift orbit and thus cause a rapid increase in Dst. On the other hand *Feldstein et al.*, [2000] suggested that the early recovery in Dst is caused by the decay of magnetopause and tail currents.

Pitch angle scattering which transfers protons into the bounce loss cone has also been recognized as a loss process [*Cornwall et al.*, 1970]. Observations at low altitude of ring current protons precipitating into the atmosphere have been reported by *Hultqvist et al.*, [1976], *Kozyra et al.*, [1998], *Soraas et al.*, [1999] and others. Theoretical models have been used to calculate the growth of electromagnetic ion cyclotron waves in the anisotropic ring current proton distributions [*Jordanova et al.*, 2001; *Kozyra et al.*, 1998]. These results indicate that ion cyclotron wave growth and scattering of protons by these waves will lead to losses of ring current protons. Recently *Erlandson and Ukhorskiy* [2001] have reported measurements of ring current ions diffusing into the loss cone in the presence of waves.

This paper describes observations of ring current ions well inside the loss cone during the main and early recovery phases of a magnetic storm. Although the measurements were made at

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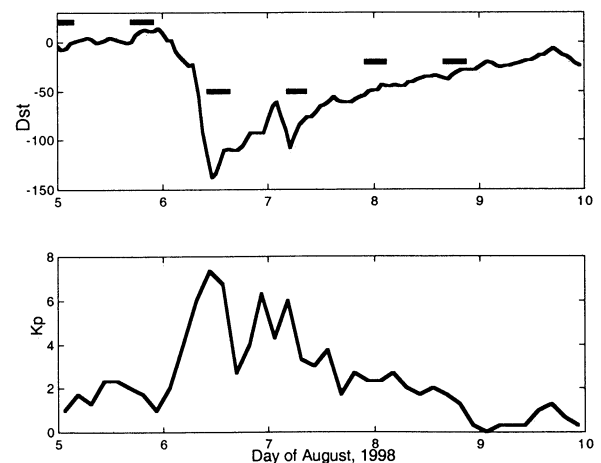2Department of Physics, Taylor University, Upland IN 46989

only two local times so that the longitudinal extent of the precipitation is not known, the loss rates inferred from these measurements indicate that pitch angle scattering is an important loss process near minimum Dst.

2. Energetic ion measurements

The data were obtained with the Source/Loss Cone Energetic Particle spectrometer (SEPS) [Blake et al., 1995] on the Polar satellite, which was in an eccentric, polar orbit with apogee at about 9 earth radii over the north pole and perigee at about 2 earth radii in the southern hemisphere. In each 18 hour orbit Polar passed through the 3<L<6 shells 4 times at different local times and latitudes. During the storm of August 6, 1998 discussed here, the ring current region was sampled at magnetic local times (MLT) near 04:00 and 16:00 hrs. Ion pitch angle distributions were measured with two identical ion detectors (Zenith and Nadir) which were oriented to face in opposite directions. Each detector had a field of view 20°x20° and a focal plane of 128 pixels, each of which measured directional flux with an angular resolution of about 1.5 °.

SEPS was mounted on the despun platform of Polar and in about half the passages through the ring current region the axes of the telescopes were aligned near the geomagnetic field direction. At these times the Zenith detector observed ions moving downward along the field lines and the Nadir detector measured ions streaming upwards toward the equator. When the despun platform was not aligned with the magnetic field, SEPS measured particles at larger pitch angles and thus gave a measurement of the trapped flux. By combining data from several passes the overall pitch angle distribution could be sketched.
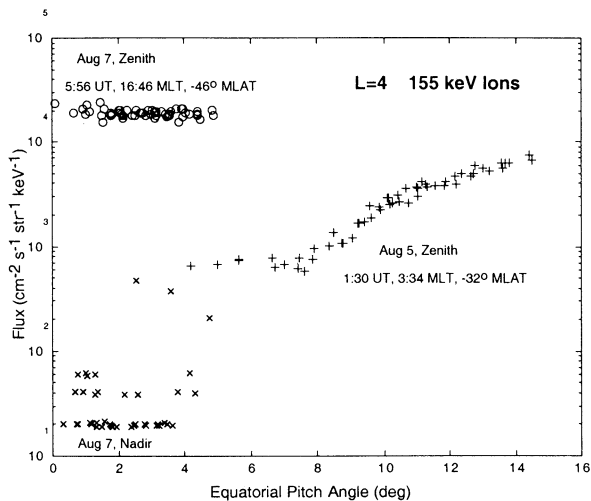
Each count was pulse height analyzed by an 8 bin analyzer with channel widths of 39 keV and a lowest energy channel

Figure 1. Dst and Kp record for the August 6, 1998 magnetic storm. The heavy lines denote times when Polar passed through the ring current region.

Figure 2. Examples of pitch angle distributions of 155 keV ions on August 5, 1998 ,a quiet day, and on August 7, during the recovery phase of a magnetic storm. Each data point represents an independent measurement by one pixel in the detector focal plane. The UT, MLT, and magnetic latitude of Polar at the times of the measurements are given.

centered at 155 keV. Counts from each pixel were accumulated and read out every 37 s. Electrons were excluded by magnets at the detector apertures. It is assumed that most of the counts were produced by protons although heavier ions of somewhat higher energy would also be detected.

3. Precipitating proton fluxes

On August 6, 1998 a magnetic storm occurred with a minimum Dst of 138 nT. Figure 1 depicts Dst and the 3 hour Kp record during the storm. The day before the storm, August 5, was extremely quiet and fluxes measured at that time represent quiet time radiation belt conditions. The heavy lines above the Dst curve denote times when Polar sampled the ring current region.

Figure 2 shows examples of pitch angle distributions obtained at L=4 on August 5 (a quiet day) and on August 7 (during storm recovery). The August 5 curve shows a normal pitch angle distribution with a depleted loss cone. On August 7 the Zenith pointing detector observed a filled loss cone with a flat angular distribution. Simultaneously the Nadir detector observed very low fluxes confirming that the Zenith counts were not background from penetrating particles. The scatter in the Nadir data is statistical as most pixels accumulated only zero, 1, 2 or 3 counts.

Figure 3 presents differential, directional fluxes of 155 keV protons obtained on the passes through L=4.5 on August 5, 6, and 7. On this scale individual pixels are not distinguishable, and each line segment represent the centroids of the data points obtained during that L=4.5 crossing. These measurements were made at various latitudes, but all distributions have been projected to the equatorial plane. The UT and MLT values of the loss cone data for August 6 and 7 are included in the figure to indicate the time sequence and to facilitate a comparison with Dst in Figure 1.

The measurements for the quiet day, August 5, reveal similar pitch angle distributions at all crossings with a loss cone edge at about $5°$. The low level fluxes inside the loss cone are believed to be background from penetrating particles since the fluxes are similar in both the upward and downward directions.

On August 6 and 7 (Figure 3b and 3c) precipitation is apparent inside the loss cone and the loss cone fluxes change with UT and/or MLT. On August 6 the precipitation in the early morning sector was larger than that of the afternoon sector, which was traversed 46 min earlier, but during the dynamic period of the storm this difference may represent a time variation rather than a spatial difference.

In Figure 3c similar data for August 7 shows that at 16:51 MLT the precipitating fluxes were above 10^4 cm^{-2} s^{-1} str^{-1} kev^{-1} and were comparable to the trapped flux at $25°$ equatorial pitch angle. About 40 minutes later the outbound pass at 03:15 MLT showed much lower fluxes. At this time it appears that the precipitation is much stronger in the afternoon sector than in the early morning sector. On the next orbit through the afternoon sector which occurred 17.5 hrs later (at 23:56 UT) the loss cone had reformed and precipitation was confined to particles with pitch angles just inside the edge of the loss cone. No appreciable precipitation was found on August 8.

Figure 4 (a and b) summarizes the L dependence of average loss cone fluxes of 155 keV protons during four passes through the belt on August 5 and two passes each on August 6 and 7. The August 5 prestorm data are given by the narrow lines in the lower part of Figure 4a. The two passes each on August 6 and August 7 are labeled with the UT and MLT of the L=4.5 crossings. Precipitation on August 6 extended from L=4.25 to beyond L=6 in the early morning time sector and from L=4.25 to about L=5.5 in the mid afternoon sector. At L=4.25 the fluxes are nearly equal on the inbound pass (MLT= 15:18 hrs) and the outbound pass (MLT=4:22 hrs). The two points at L=4.25 were taken on opposite sides of the earth
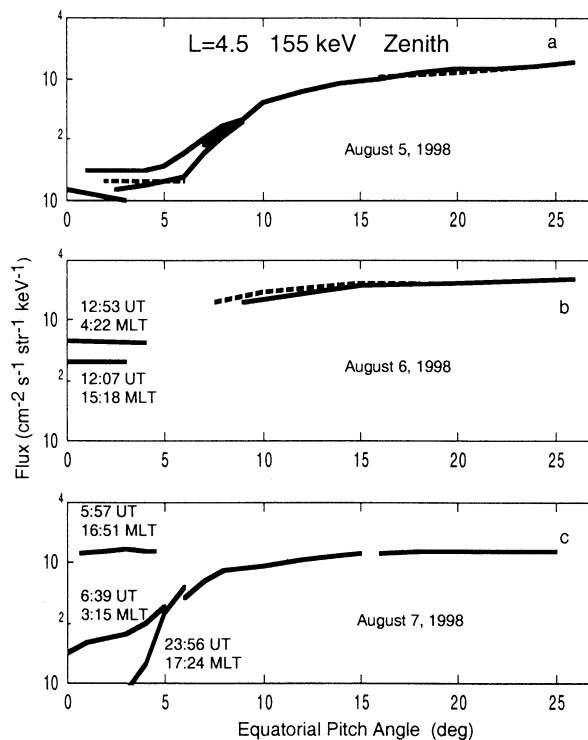
Figure 3. Equatorial pitch angle distributions of 155 keV ions at L=4.5 observed on August 5 (prestorm) and during the main phase and recovery phase on August 6 and 7, 1998. Each line segment represents the differential flux in the detector field of view during an L=4.5 crossing. Different line styles are used to distinguish crossings where the data overlap. The UT and MLT values are given for those cases when ion precipitation occurred.
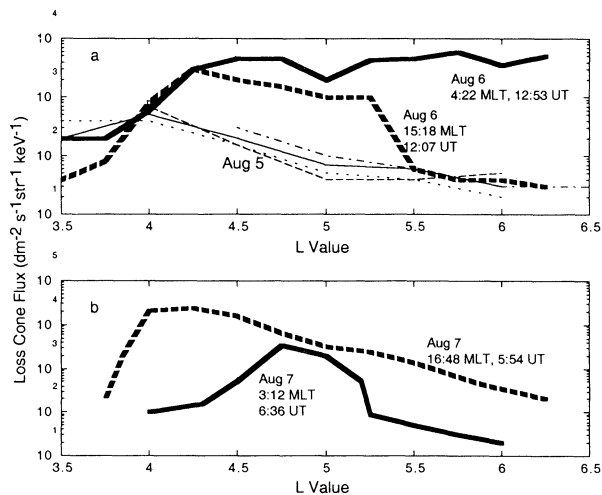
Figure 4. (a) Average loss cone fluxes on quiet day, August 5, 1998 (thin lines at bottom) and on August 6 as a function of L. (b) Average loss cone fluxes on August 7, 1998 during the recovery phase.

only 50 minutes apart indicating that at this L value the precipitation is similar on the day and night side.

In the two passes on August 7 the precipitation was much more intense in the afternoon sector and had moved inward to L=4. Between L=4 and 4.5, the precipitating fluxes were comparable to the trapped fluxes observed when SEPS was oriented to measure trapped ions at larger pitch angles. Within the loss cone, the fluxes were isotropic indicating that the pitch angle scattering was strong enough to fill the loss cone during a single bounce. Throughout this period of strong precipitation the fluxes moving upward along the field lines were at background levels. By August 8 the precipitation had ceased, and the pitch angle distributions showed normal loss cones. Since Polar was at magnetic latitudes between 46° and 51° during the observations of filled loss cones, the scattering occurred equatorward of these latitudes.

4. Discussion and conclusions

These results are in general agreement with *Jordanova et al.* [2001] and *Erlandson and Ukhorskiy* [2001] in showing a preference for ring current precipitation in the afternoon local time zone. However, the observed isotropic angular distribution within the loss cone requires a much stronger diffusion process than the theoretical estimates. The isotropy within the loss cone is similar to that measured by *Soraas et al.* [1999] at low altitude.

In strong diffusion the trapping lifetime is given by $\tau \approx <\tau_b>/2\sin^2\alpha_{LC}$, where $<\tau_b>$ is the average bounce period of the protons and α_{LC} is the equatorial loss cone angle. This process would result in lifetimes of about 0.27 hrs for 155 keV protons at L=4. This lifetime value is close to that of *Gonzales et al.* [1989] who concluded the early recovery of Dst required an ion lifetime of about 0.25 hrs. However, the measurements reported here were made at only 2 local times so the longitudinal extent of the strong precipitation is not known.

Recent measurements of ring current ion loss by Energetic Neutral Atom (ENA) detection [*Jorgensen et al.*, 2001] have found that the escaping ENA fluxes are too small to explain the observed rapid increase in Dst. Precipitation into the atmosphere at small pitch angles would not lead to escaping ENA fluxes observable from satellites, and thus pitch angle scattering could be the required loss mechanism. Deconvolution of ENA images to derive proton distributions by *Perez et al.* [2001] has in some cases required filled loss cones to give physically realistic results. However, their analysis, done for a different magnetic storm, indicates that the upward loss cones are sometimes filled in contradiction to our measurements.

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