X-646-72-242

PREPRINT

NASA TM X- 65963

PARTICLE AND FIELD OBSERVATIONS FROM EXPLORER 45 DURING THE DECEMBER 1971 MAGNETIC STORM PERIOD

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JULY 1972

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The magnetic signatures of the extra-terrestrial ring current have been measured by means of satellite-borne magnetometers on several occasions (Smith et al, 1960; Cahill, 1966; Coleman and Cummings, 1967; Sugiura et al, 1971). In only one case have the charged particles of the magnetic storm-time extra-terrestrial ring current system been directly observed (Frank, 1967). In this note we present simultaneous observations from the S^3-A (Explorer 45) satellite of the magnetic signature of the ring current and complete measurements of the proton ring current to distances of 5.24 R_E during the double magnetic storm of December 16-19, 1971. Magnetic records from low latitude and auroral magnetic observatories for this period have already been presented (Cahill, 1972).

Field Deformations and Proton Energy Density Distributions

The simultaneous observations of the magnetic field and the proton distributions for four orbits during the storm period are presented in Figures 1-4. Each figure contains the following data:

(1) ΔB (gammas) equals the measured scaler magnetic field less the reference scaler magnetic field (POGO 8/69 Coefficients, Cain and Sweeney, 1970).

(2) The total energy density of protons from 1 to 855 kev and the measured magnetic field energy density, $B^2/8\pi$, along the trajectory of the satellite.

(3) The ratio of the proton energy density to the magnetic field energy density, or β.

Figure 1 contains data from Orbit 99 during the storm which did not develop a symmetric ring current (Cahill, 1972; Smith and Hoffman, 1972). The outbound portion of the orbit in the evening hours displayed some of the usual charactertistics of an inflated magnetic field, a constant negative ΔB out towards the region of maximum particle energy density, a minimum in the field near the maximum of the protons, and a recovery at larger distances. The inner maximum in the proton distribution was produced by the more energetic protons which exist during quiet times (> 105 kev) and the outer maximum by the storm time protons (< 105 kev). Only in the latter region was β appreciable, attaining a value of about 0.6 to 0.7.

The inbound portion of the pass showed a magnetic character similar to that reported by Sugiura et al, (1971) for the midnight region for Kp = 2 or 3. The proton energy density profile had no maximum, but remained constant to 3.5 R_E, with somewhat more energy than in the evening sector.

For S^3 this was a high latitude orbit, remaining at 12 to 14 degrees magnetic latitude during most of the entire orbit. Assuming the ratio of the magnetic field at the satellite to the field at the magnetic equator to be that given by the reference field (in reality this ratio was probably larger because of the greater inflation at the equator), and also assuming the energy density at the equator was the same as along the orbit (an extrapolation of the pitch angle distribution indicates that the equatorial energy density would have been less than 10% larger), the values of β for the equator were recalculated, and are also plotted in Figure 1. For the region of orbit beyond 5 R_E, β almost doubled.

During the development of the main phase of the magnetic storm commencing at 1506 U.T. on December 17, 1968, the radial profiles of the field deformation and proton energy densities were different from Orbit 99 outbound only in their magnitudes. Orbit 101 outbound shown in Figure 2 again had the minimum in ΔB near the maximum of the proton intensities, although the field minimum was much sharper in L than the proton maximum. In contrast to Orbit 99 inbound, Orbit 101 inbound during the initial recovery phase also showed classical ring current signatures both in the field and particles. However, a comparison of the outbound and inbound portions of Orbit 101 reveals that the ring current had moved to lower altitudes by one earth radii. The most striking feature of Orbit 101 is the large value of β, reaching six at two locations, and remaining well above one beyond 4 R_E.

Orbit 102 (Figure 3) occurred well into the recovery phase, where the ring current protons and inflation appeared symmetric. Except for a considerable decrease in the inflation of the field, the profiles are similar to Orbit 101 inbound. The measured value of β along the trajectory of the satellite was quite small, reaching just over 0.4 near apogee.

Again, like Orbit 99, this was a "high latitude orbit". The calculated values of β for the equator increase considerably over those along the orbit, but still had a maximum of only about 0.8 near apogee.

The observations during Orbit 103 were somewhat anomalous (Figure 4). While they occurred later in the recovery phase than Orbit 102, the maximum proton intensities were 40% larger than the previous orbit, or at least 30% larger than the estimated energy densities for Orbit 102 at the equator. Yet ΔB was no larger in magnitude, although the location of maximum inflation had retracted to ½ R_E higher altitude, as expected.

One feature in the orbital profile of β consistently appeared in each pass. Almost exactly at apogee (22 hours local time), β increased. For Orbits 99 and 101 the cause was a sudden decrease in the magnetic field strength, and not to an increase in the proton energy density; whereas, for Orbits 102 and 103 it was due to a sudden increase in the proton energy density with no accompanying decrease in field strength. A similar lack of a relationship between the protons and magnetic field depression has previously been deduced from OGO-5 data (Sugiura, 1971; Frank, 1971). In this portion of the orbit the S^3 satellite was moving predominantly in local time, rather than radially.

Flux Limitations

Since the beginnings of particle population measurements, the question of "loading" Magnetic field lines by charged particles has continuously arisen in discussions of the trapping capability of the magnetosphere (Dessler, 1960; Van Allen, 1966; Hess, 1968). Two candidates process which limit the loading have been suggested:

1) A maximum β.

2) Wave-particle instabilities.

We have previously shown (Hoffman and Bracken, 1967) that the static earth's magnetic field could easily hold a ring current with a β of at least 5, and therefore, concluded that the limitation to the proton fluxes must be a dynamic mechanism. The S^3 data provide additional evidence to support this conclusion, and in addition, suggest that the dominant wave-particle instability may be a process like the ion-cyclotron resonance interaction.

It is shown by Williams et al, (1972) that the initiation of the pitch angle instabilities, that is, the transition from normal distributions to non-normal distributions (maximum intensity at 90° to off 90°) occurred during Orbit 99 inbound in the region from about an L of 3.4 to near 5. The estimated values of β at the equator over the same L region increased from about 0.1 to 0.8 (Figure 1). The electric field measurements indicated that the plasmapause location was at L = 3.45, so that most of the effects on the particles occurred outside of this definition of the plasmapause, with lowest energies being affected at lowest altitudes.

On the other hand, during Orbit 101 outbound the non-normal pitch angle distributions were measured in the region L = 3.8 to 4.5. The L value at which each energy population was initially affected by this instability is plotted at the bottom of Figure 2. In contrast to Orbit 99, the highest energies were affected at lowest L values, and the phenomena occurred inside the plasmapause location as defined by the electric field measurements (Maynard and Cauffman, 1972). In spite of the onset of the instability, β increased from 0.5 to 6 in this region, about an order of magnitude larger than during Orbit 99.

While considerably more detailed analysis is required to completely understand this apparent contradiction in conditions between Orbits 99 and 101, some clarification can be provided if we assume conditions for the ion-cyclotron instability (Kennel and Petschek, 1966). The dominant parameter governing the onset of the instability during Orbit 99 appears to be the plasma density. Fluxes of protons above the initial level existed in the partial ring current of the first magnetic storm (Smith and Hoffman, 1972). Since the resonant energy depends inversely on the total plasma density, $E_R \propto B^2/8\pi N$, the resonant energy increased with increasing L as the plasma density decreased at the plasmapause.

Orbit 101 outbound encountered a more dynamic state during the development of the main phase of the second storm. The large flux of newly existing protons from an L of 3.7 to 4.5 produced a very large inflation of the magnetic field. Since the resonant proton energy also depends directly upon the energy density of the magnetic field, this field depression apparently governed the onset of the instability. Note that the ratio of energy of resonant protons to field energy density was constant from L = 3.8 to 4.02, or from energies from about 800 kev down to 200 kev. However, in order for the magnetic field to be the governing parameter, the plasma density must have been low at L values below the observed resonance, so that the resonant energy be above the energies measured. Note in Figure 5 of Maynard and Cauffman (1972) that multiple plasmapause boundaries were encountered beginning at an L of about 3.5, and the observation of such boundaries depends not only upon the plasma density but also its temperature (see their Figure 2). Thus, the plasma density must have fallen precipitously at an L of about 3.5 at the beginning of the large gradient in the ring current proton intensities (see Smith and Hoffman, 1972, Figure 4), and remained low so that the resonance first appeared at high energies at an L of 3.8.

The problem remains how the proton intensities were able to increase to the large values observed during Orbit 101 in the presence of the loss mechanism, but not during Orbit 99. The intensity increases could continue provided the source scale time was less than the minimum lifetime from the instability. For strong pitch angle diffusion the lifetime approaches the minimum lifetime $\tau = 2\ T_B/\alpha_o^2$, where T_B is the bounce period and α_o the size of the loss cone (Kennel, 1969). τ is at least an hour at an L of 4. In contrast to a loss time of at least an hour, Davis (1969) has provided evidence that the injection of particle energy during a main phase storm is burst-like, with individual bursts having durations of several tens of minutes in coincidence with peaks in substorm activity.

Thus during Orbit 101 outbound, the source seems to have dominated over the loss so that β increased to 6 during the existence of the resonance interaction. On the other hand, the resonance conditions also existed during Orbit 99 inbound when β was much less than 1, and when there was little energy input to the ring current (note the lack of substorm activity at 0600 U.T., Dec. 16, Cahill, 1972, Figure 1). Therefore, important conditions for loading field lines are not β but the injection rate of energy into the ring current and the minimum lifetime from strong pitch angle diffusion resulting from a dynamic mechanism like the ion-cyclotron resonance.

ACKNOWLEDGMENTS

The collaboration with the other S^3 experimenters in the interpretation of the data is gratefully acknowledged, especially the assistance from Dr. L. J. Cahill, Jr., in making available analyzed magnetic data.

Analysis assistance from Dr. P. H. Smith and Mrs. Christine Gloeckler is appreciated.

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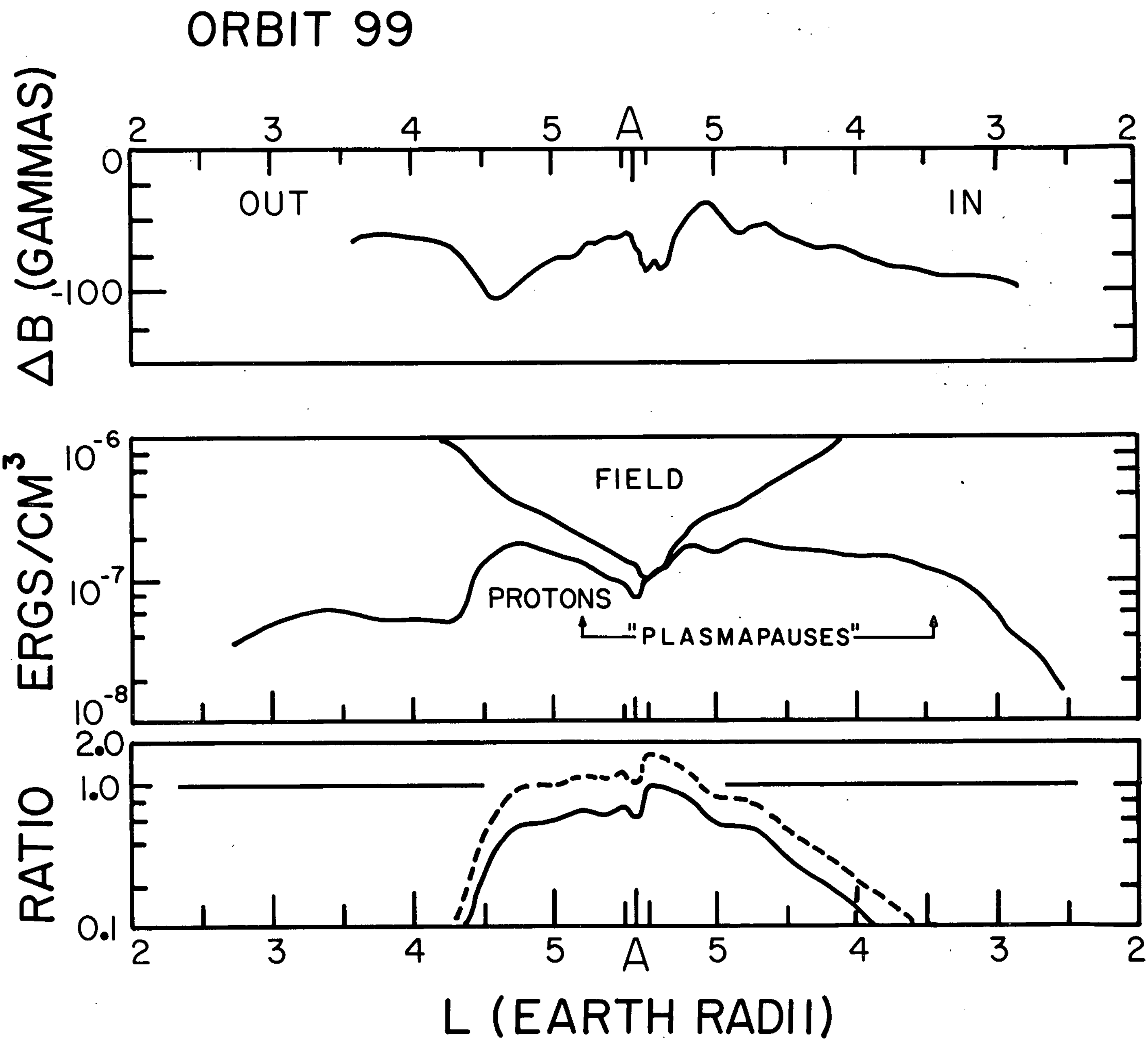
FIGURE CAPTIONS

Figure 1. Magnetic field variation measurements and magnetic field and proton energy densities as a function of L for Orbit 99 from 0011 to 0657 U.T. on December 17, 1971. See text for an explanation of the data sets.

Figure 2. Same as Figure 1 for Orbit 101 from 1542 to 2224 U.T. on December 17, 1971.

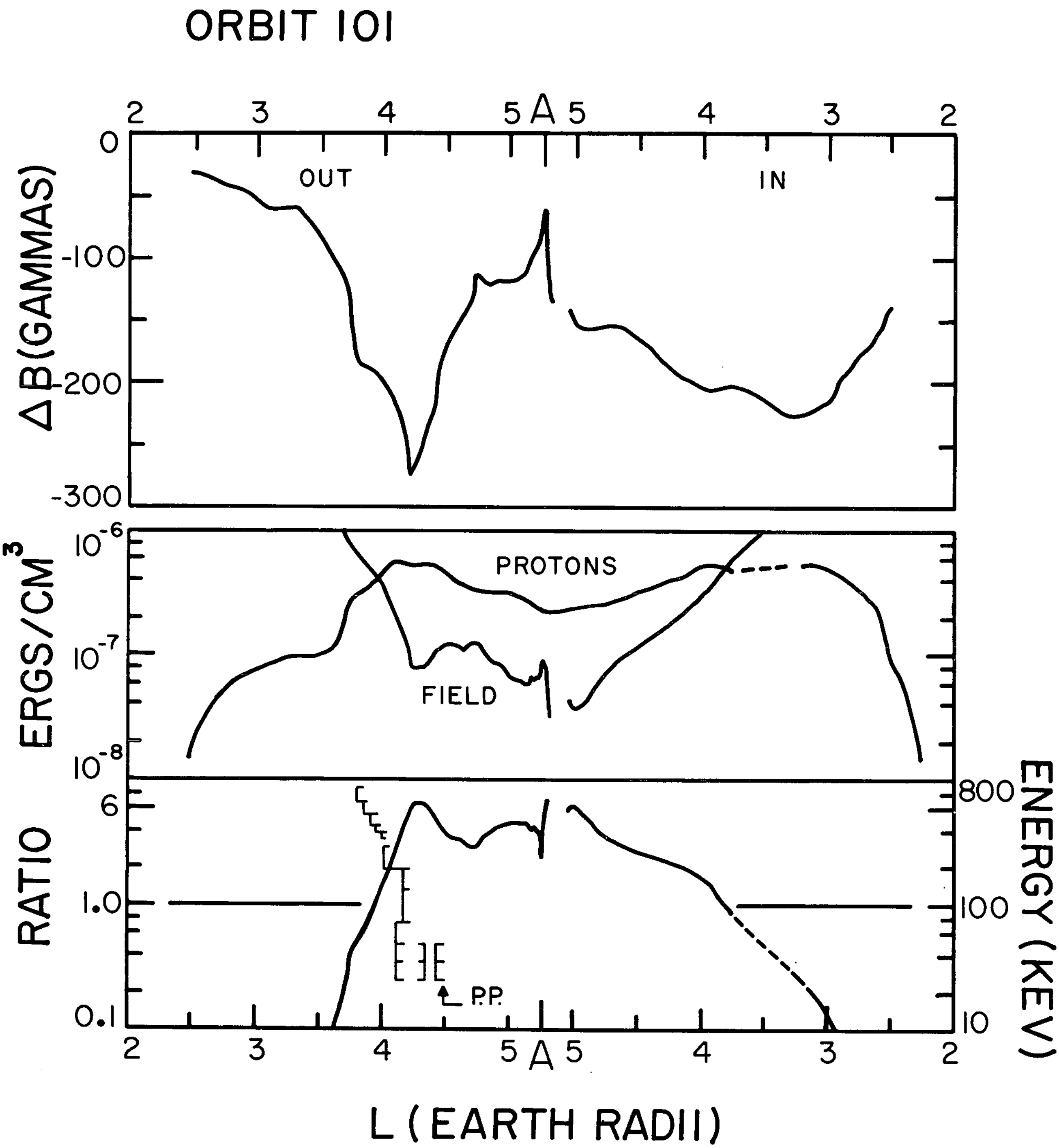
Figure 3. Same as Figure 1 for Orbit 102 from 2328, December 17 to 0613, December 18, 1971.

Figure 4. Same as Figure 1 for Orbit 103 from 0715 to 1354 U.T. on December 18, 1971.



ORBIT 99
ΔB (GAMMAS)
0
-100
OUT
IN
2
3
4
5
A
5
4
3
2
ERGS/CM3
10-6
10-7
10-8
FIELD
PROTONS
"PLASMAPAUSES"
RATIO
2.0
1.0
0.1
L (EARTH RADII)

FIGURE 1



ORBIT 101
OUT
IN
ΔB (GAMMAS)
0
-100
-200
-300
PROTONS
FIELD
ERGS/CM³
10⁻⁶
10⁻⁷
10⁻⁸
RATIO
6
1.0
0.1
P.P.
ENERGY (KEV)
800
100
10
2
3
4
5
A
L (EARTH RADII)

FIGURE 2

ORBIT 102

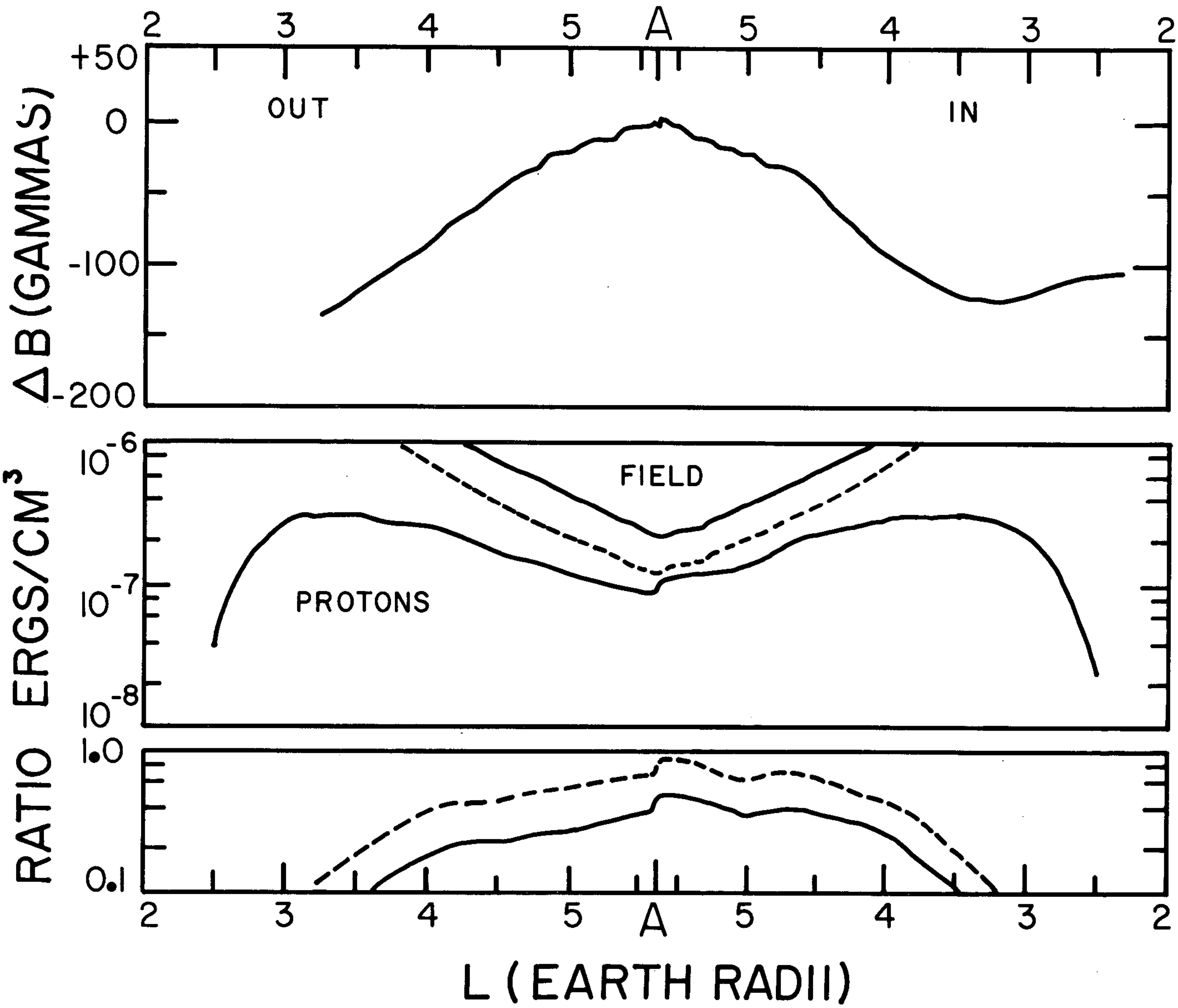
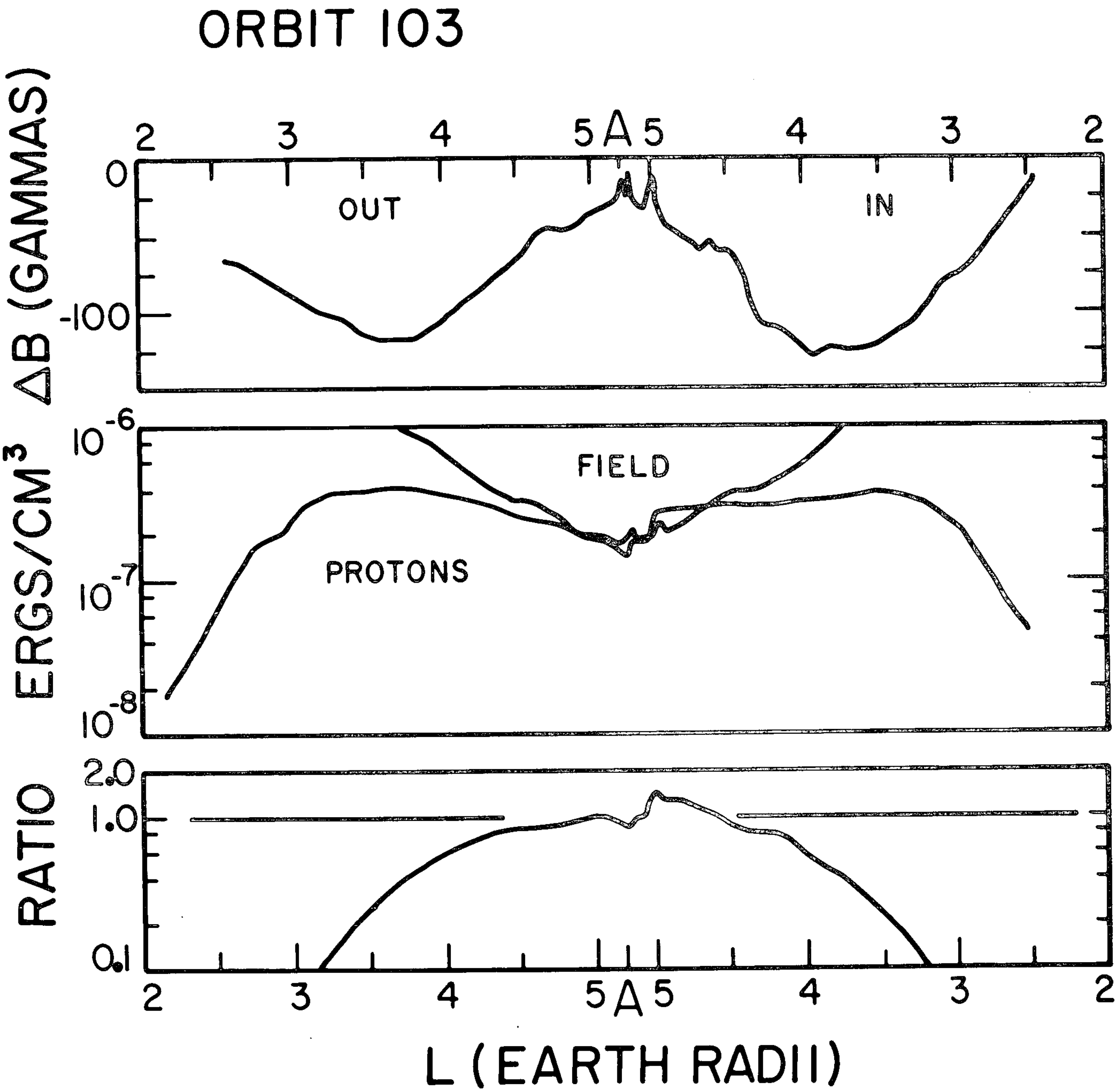


FIGURE 3



ORBIT 103
ΔB (GAMMAS)
2
3
4
5 A 5
4
3
2
0
-100
OUT
IN
ERGS/CM3
10-6
10-7
10-8
FIELD
PROTONS
RATIO
2.0
1.0
0.1
2
3
4
5 A 5
4
3
2
L (EARTH RADII)

FIGURE 4