

## Plasmaspheric depletion and refilling associated with the September 25, 1998 magnetic storm observed by ground magnetometers at $L = 2$

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**Abstract.** The plasmaspheric mass density at  $L \simeq 2$  was monitored by two IGPP/LANL ground magnetometer stations during the magnetic storm on September 25, 1998. Even at this low latitude the plasma density dropped significantly to  $\simeq 1/4$  of the pre-storm value. The total electron content (TEC) inferred by GPS signals also shows a sizable decrease during the storm. The observations suggest that the convection caused by the strong electric field associated with the magnetic storm eroded the plasmasphere as low as  $L = 2$ , which is a much lower latitude than that expected from the estimated potential drop across the polar cap together with a simple model of the magnetospheric convection pattern.

### Introduction

In the inner magnetosphere, magnetic flux tubes circulate on closed paths and form a region called the plasmasphere with dense cold plasma compared with the outer magnetosphere. The size of the plasmasphere is determined by a balance between the corotational electric field and that imposed by the solar wind [e.g., *Nishida*, 1966]. During magnetically disturbed times, the plasmapause moves closer to the Earth because of the enhanced dawn-dusk electric field. In observational aspects, our understanding of the plasmasphere is derived from both satellite measurements [e.g., *Chappell*, 1972] and whistler propagation [*Carpenter*, 1966]. More recently, the Faraday-rotation and dispersive-group-delay techniques are also used to calculate the electron content in the ionosphere and the plasmasphere by receiving signals emitted from satellites.

The observations from the Radio Beacon Experiment of the geostationary satellite ATS-6 show clear depletion of electrons in both the plasmasphere and the ionosphere during severe magnetic storms [*Degenhardt et al.*, 1977]. How-

ever, since the electron content derived from this type of experiment is along the slant path of the signal, it does not directly indicate the density at specific latitudes. In this letter, we present a new approach to study the dynamical behavior of the plasmasphere during magnetic storms. The gradient technique uses the principle that the phase difference of field line resonances observed by two closely spaced stations located along the same longitude maximizes at the eigenfrequencies of the field line midway between the two stations [*Baransky et al.*, 1985]. The plasma mass density can then be inferred by the observed eigenfrequency if appropriate models of the magnetic field and the plasma density are assumed. At mid- and low latitudes, the first harmonic of field line resonances is located in the Pc 3-4 frequency band, and it has been demonstrated that the gradient technique can reveal clear phase-difference patterns at eigenfrequencies [*Waters et al.*, 1991; 1994].

Here we examine the variation of the plasmaspheric density in the course of a severe magnetic storm on September 25, 1998, by applying the gradient technique to the data from two ground magnetometer stations at  $L \simeq 2$ . We find that the plasmaspheric density at this low latitude was significantly depleted during the recovery phase of the storm and it slowly recovered afterward. The depletion at this low latitude is unexpected since it requires a very strong electric field that is well above the values deduced from modeling the currents and circulation of plasma for the same event. We also show the decrease of the total electron content (TEC) deduced from GPS signals and discuss its possible relationship to the plasmaspheric depletion.

### Observations

On September 24, 1998, a large-scale solar wind discontinuity arrived at the Earth's magnetosphere at 2345 UT and caused the sudden commencement (SC) event observed by several spacecraft and ground magnetometer stations. A strong magnetic storm associated with this SC took place afterward and reached its maximum on the next day, September 25, 1998. The spacecraft observations of magnetic field perturbations associated with this event including the solar wind conditions are discussed by *Russell et al.* [1999] in detail.

Magnetometer stations AFA and LAL, located at Colorado Springs, Colorado and Los Alamos, New Mexico, respectively, were installed in 1998 by the Institute of Geophysics and Planetary Physics (IGPP) at UCLA and Los Alamos National Laboratory (LANL). Both systems are fluxgate magnetometers sampling at 1 Hz. They are syn-

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chronized by GPS signals in order to have the timing accuracy better than a millisecond. The noise level of both systems is about 0.1 nT. The magnetic latitudes of AFA and LAL are  $44.3^\circ$  and  $47.6^\circ$ , respectively, and both of them are located along  $\approx 320^\circ$  magnetic longitude. The latitudinal separation of this station pair is  $\approx 366$  km.

The phase differences between the magnetic fields in the  $H$  component at AFA and LAL are used to identify the eigenfrequencies of the magnetospheric field line midway between the latitudes of AFA and LAL. Starting from September 24, 1998, four days of phase-difference spectrograms are plotted in Figure 1. Since the phase-difference patterns are only seen on the dayside, all spectrograms present the interval between 1200 UT and 0200 UT of the next day, which corresponds to the local time interval 0500-1900.

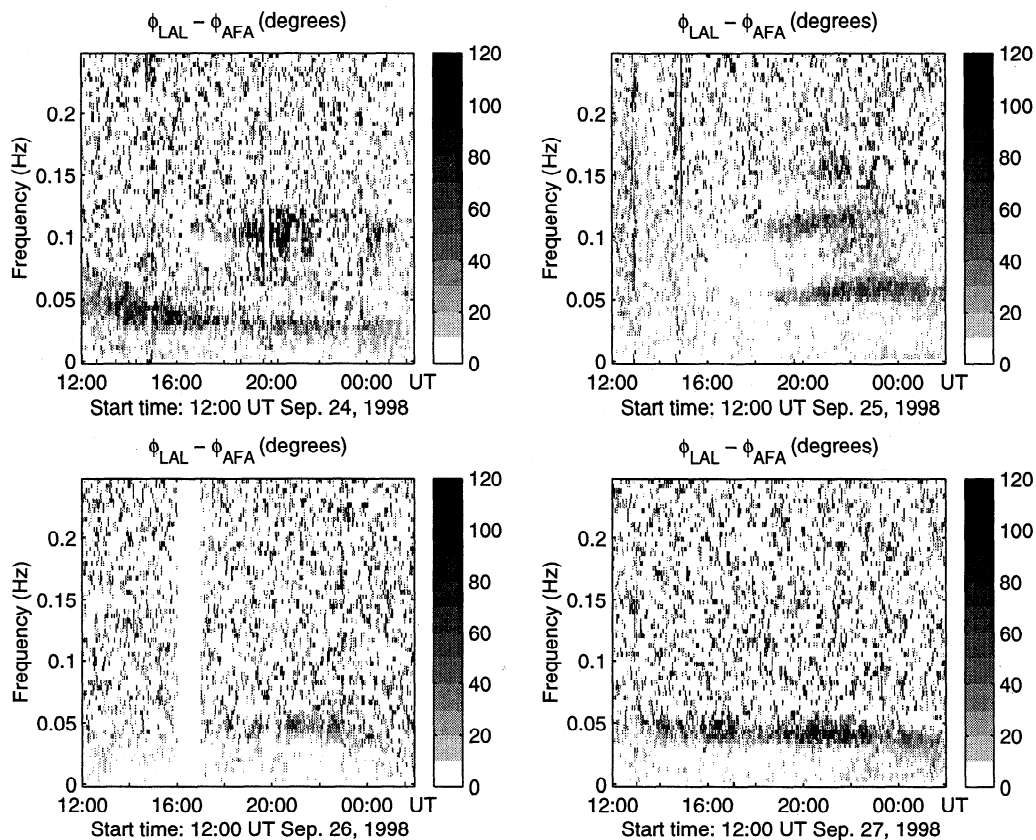
On September 24, 1998, the fundamental mode frequency at about 30 mHz can be clearly identified, and it was slightly higher in the morning than in the afternoon. The decrease of the eigenfrequency with time has also been shown by *Waters et al.* [1994], and it indicates an increase of the plasma mass density in the flux tube from the morning to the afternoon, which is caused by the outflow from the ionosphere into the equatorial plasmasphere during the day. Large phase differences are also seen at  $\approx 105$  mHz during 1800-2200 UT, and they may be associated with the third harmonic of field line resonances.

On September 25, 1998, the two stations came to the dayside region again approximately thirteen hours after the SC. The phase-difference pattern was not observed until 1700

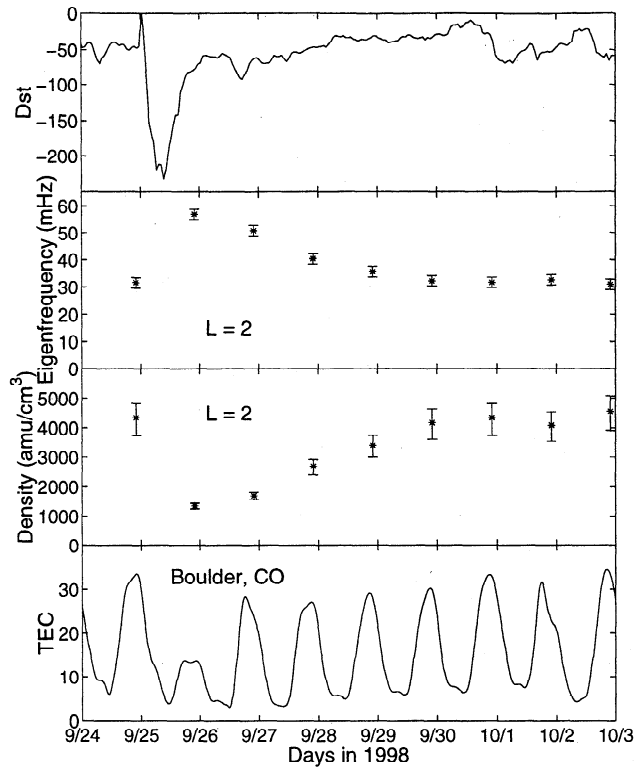
UT (1000 LT). Starting from 1830 UT, the fundamental mode and the second harmonic can be clearly identified, and a hint of a third harmonic can also be seen. The fundamental mode frequency was about 50 mHz at 1900 UT, and it increased to 60 mHz at 2400 UT. A similar percentage increase in frequency is found for the second harmonic.

On the following day, September 26, the eigenfrequency did not increase with time. It began the day at about 50 mHz and stayed steady or declined a little. The phase-difference pattern was not as clear as that on the previous day, which is probably due to the fact that much weaker Pc 3-4 wave power was seen on this day (not shown). On September 27, the eigenfrequency dropped to lower values and the trend of decreasing eigenfrequency clearly appeared, as on the day before the storm.

Several more days of phase-difference spectrograms have been examined, and the results of eigenfrequency measurements are summarized in Figure 2. The top panel of Figure 2 is the  $Dst$  index throughout the time interval from September 24 to October 2 in 1998. Since the density in the plasmasphere is a function of local time, only the values at 2200 UT (or 1500 LT) are plotted. The plasma mass densities corresponding to these eigenfrequencies can be calculated by using the formula given by *Schulz* [1996] and they are shown in the third panel. Here a dipole magnetic field and a plasma density  $\rho \sim r^{-4}$  are assumed. A clear reduction of the equatorial plasmaspheric density associated with this magnetic storm is seen. The equatorial density during the recovery phase of the magnetic storm on September 25 was less than



**Figure 1.** Phase-difference spectrograms of  $B_H$  for the station pair AFA-LAL. Each diagram shows the spectrogram for the local time interval 0500-1900.



**Figure 2.** (From top to bottom) *Dst* index, fundamental mode frequencies of field line resonances at  $L = 2$  for the local time 1500 obtained by the gradient method, equatorial plasma mass densities inferred by the observed resonant frequencies, and zenith TEC values above Boulder, Colorado.

one third of the pre-storm value. Starting from September 26, the density gradually recovered and it took 4-5 days to come back to the pre-storm value.

A significant decrease of the TEC is also found from the GPS measurements for this magnetic storm event. The bottom panel of Figure 2 shows the zenith TEC values above Boulder, Colorado during the same time interval. The method of obtaining zenith TEC values and an example for another magnetic storm are described by *Musman et al.* [1998]. Units of TEC are  $10^{12}$  electrons/cm<sup>2</sup>. Since the rapid decrease of electron density with increasing altitude, the zenith TEC values shown in Figure 2 can be used as a proxy for the electron density in the ionosphere. In addition to the typical diurnal variation of TEC, which shows the greatest value in the early afternoon and the lowest value just before sunrise, a significant drop of the daily TEC maximum by approximately 60% occurred on September 25 (Day 268) during the magnetic storm. However, unlike the plasmaspheric density at  $L = 2$ , the daily TEC maximum rose to slightly higher than 80% of the pre-storm value on the next day. A slower recovery of TEC occurred after September 27.

## Discussion

The density variation inferred from the assumed magnetic field and density models together with eigenfrequency measurements obtained by the gradient method clearly shows

a significant depletion at  $L = 2$  during the September 25, 1998, magnetic storm. We also examined the phase difference spectrograms for the station pair LAL-SGD (San Gabriel Dam, [magnetic longitude, magnetic latitude] = [307.5°, 41.1°]) and found the same result. The observations can be interpreted through a picture in which initially the inward motion of the plasmapause occurs on the night-side, and the dayside flux tubes then begin to convect toward the magnetopause, tending to erode the outer edge of the plasmasphere [Chappell, 1972]. However, our observations show that the depletion occurred at an unexpectedly low  $L$ -shell. In an oversimplified model of the magnetosphere, in which the electric field imposed by the solar wind is uniform within the magnetosphere, the corotational and convection electric fields are equal and opposite on the dusk terminator at a distance of  $L = \sqrt{183R_M/\Phi}$  where  $\Phi$  is the potential drop across the magnetosphere in kV and  $R_M$  is the radial distance in  $R_E$  to the magnetopause at the terminator. To erode the plasmasphere to a distance of 2  $R_E$  at dusk would require a potential drop  $\simeq 700$  kV, which significantly exceeds the potential drop of  $\leq 200$  kV deduced from modeling the currents and circulation of plasma on September 24-25, 1998, by using the AMIE technique [G. Lu, personal communication, 1999]. Nevertheless, the depletion at  $L = 2$  agrees with the empirical formula of the plasmapause location  $L_{pp}$  based on spacecraft and whistler observations at higher  $L$ -shells [Carpenter and Anderson, 1992]. According to this formula,  $L_{pp}$  was reduced from 4.2 to 1.8 during September 24-25 in response to an increase of  $Kp$  up to 8<sub>+</sub> at 0600-0900 UT on September 25. Alternatively, the depletion could also be related to the loss of plasma inside the newly formed plasmapause following a storm onset reported by Carpenter [1962].

Continuous observations of eigenfrequencies are also useful for discussing the refilling and depletion rates of the plasmasphere. From Figure 2, it appears that the plasmasphere was refilled at an inferred rate of  $\simeq 647$  amu·cm<sup>-3</sup>·d<sup>-1</sup>, or equivalently 27 amu·cm<sup>-3</sup>·hr<sup>-1</sup>, at the equator after it was fully eroded. However, there was also a diurnal variation of the plasmaspheric density associated with ion outflow from the ionosphere on the dayside and the loss of particles from the flux tubes in the ionosphere in the nightside. From the phase-difference spectrograms for September 24 and September 27 in Figure 1, it can be shown that the refilling rate was  $\simeq 200$  amu·cm<sup>-3</sup>·hr<sup>-1</sup> during the interval of 0900-1500 LT for both days. This refilling rate is equivalent to an upward ion flux of  $5.7 \times 10^8$  amu·cm<sup>-2</sup>·s<sup>-1</sup>, which is in agreement with the reported  $\sim 3 \times 10^8$  electrons·cm<sup>-2</sup>·s<sup>-1</sup> for  $L > 4$  [e.g., Singh and Horwitz, 1992] if the average ion mass is  $\simeq 2$  amu (e.g., 75% H<sup>+</sup>, 23% He<sup>+</sup> and He<sup>++</sup>, and 2% O<sup>+</sup>). On the other hand, the peculiar rising trend of the eigenfrequency on September 25 indicates that the plasmasphere at  $L = 2$  was being depleted at that time. Specifically, the equatorial density decreased from 1610 amu·cm<sup>-3</sup> at 1900 UT (noon) to 1210 amu·cm<sup>-3</sup> at 2300 UT (1600 LT). This suggests that the depletion rate was strong enough to give a net depletion 100 amu·cm<sup>-3</sup>·hr<sup>-1</sup> at one local time above the ionospheric supply rate that we assume stayed

near  $200 \text{ amu}\cdot\text{cm}^{-3}\cdot\text{hr}^{-1}$ .

Low TEC values may result in a slower ion outflow into the plasmasphere, but a severe depletion of the plasmasphere may not be an important cause for low TEC values because of the abundance of particles in the ionosphere. Instead, TEC values are sensitive to processes taking place in the ionosphere. For most summer ionospheric storms, changes in the chemical composition of neutral gases can reduce the number of electron donors and increase the recombination rates [e.g., Fuller-Rowell et al., 1997]. As a result the lower efficiency of ionization by the solar EUV radiation yields a lower TEC value. How this process affects the depletion and refilling of the plasmasphere is an interesting topic for future studies.

In this letter we have presented the first study using the gradient technique of magnetic pulsations to analyze the density variation of the plasmasphere under the influence of a magnetic storm. We find this a promising way to explore the dynamics of the plasmasphere. The abundant geomagnetic field data can also provide valuable information that can be complementary to satellite or whistler observations. A larger number of observations with a wider coverage in local time for the plasmaspheric depletion at low latitudes should be examined in detail to determine whether the observations are in accordance with the existing theory.

**Acknowledgments.** The establishment of the magnetic observatories at LANL and AFA was made possible with a grant from the Los Alamos branch of the IGPP. This research was supported by a grant from the UC-LANL CULAR program. Additional support for G. Le and M. B. Moldwin was provided by the National Science Foundation under grants ATM 96-33695 and ATM 96-28708 respectively. P. J. Chi is grateful to M. Schulz and H. Kawano for helpful discussions.

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(Received August 30, 1999; revised November 4, 1999; accepted November 9, 1999.)