

# An empirical plasmasphere and trough density model: CRRES observations

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**Abstract.** Combined Release and Radiation Effects Satellite (CRRES) sweep frequency receiver data were used to develop an empirical model of the plasmasphere and trough number density. The over 1000 CRRES orbits provided good statistical coverage of all local times between an  $L$  shell of 3 to 7. The CRRES density data were separated into plasmaspheric-like and trough-like by assuming a minimum density value for the plasmasphere as a function of  $L$  shell. For the plasmasphere the average number density (in  $\text{cm}^{-3}$ ) as a function of  $L$  shell ( $3 \leq L \leq 7$ ) was found to be:  $n_p = 1390 (3/L)^{4.8} \pm 440 (3/L)^{3.6}$ . For the trough the average number density (in  $\text{cm}^{-3}$ ) as a function of  $L$ -shell ( $3 \leq L \leq 7$ ) and magnetic local time ( $0 \leq \text{LT} \leq 24$ ) was found to be  $n_t = 124 (3/L)^{4.0} + 36(3/L)^{3.5} \cos\{\text{LT} - [7.7(3/L)^{2.0} + 12]\pi/12\} \pm \{78 (3/L)^{4.7} + 17 (3/L)^{3.7} \cos[(\text{LT} - 22)\pi/12]\}$ . No clear dependence on magnetic activity was found for either density model. This empirical model is an improvement over earlier models in that it is continuous in local time and can be used to track densities based on refilling history. The model standard deviations are representative of either early time or late time refilling of the trough or newly filled or saturated plasmaspheric densities.

## 1. Introduction

Low-energy plasma ( $\sim 1$  eV) fills the inner magnetosphere of the Earth. However, the steep fall off in the density of the plasma, the plasmopause, acts as a moving border between the high-density plasmasphere and the low-density trough. By using in situ measurements from satellites the average density of this plasma can be determined and a better understanding of the near-Earth environment can be formulated.

Despite its importance, very few empirical models have been developed which describe the plasma density of the inner magnetosphere. Using ISEE 1 and 2 data along with data collected from whistlers, the equatorial trough was modeled by *Carpenter and Anderson* [1992] to be

$$n_e = (5800 + 300t)L^{4.5} + \{1 - \exp[-(L - 2) / 10]\}, 00 \leq r \leq 06 \text{ MLT}$$

$$n_e = (-800 + 1400t)L^{4.5} + \{1 - \exp[-(L - 2) / 10]\}, 06 \leq r \leq 15 \text{ MLT},$$
(1)

where MLT is magnetic local time. The equatorial plasmasphere density was also modeled to be

$$\log n_e = (-0.3145L + 3.9043) + \{0.15[\cos(x) - 0.5 \cos(2x)] + 0.00127R - 0.0635\} \exp[-(L - 2) / 1.5],$$
(2)

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where  $R$  is the 13-month average sunspot number, and  $x = 2\pi (d + 9) / 365$ , where  $d$  is the day number [*Carpenter and Anderson*, 1992].

Using data from the GEOS 2 spacecraft, *Gallagher et al.* [1998] found that the local time of the maximum density in the trough at geosynchronous orbit ( $L = 6.6$ ) to be related to  $Kp$  by

$$\text{LT} = 0.145 Kp^2 - 2.63 Kp + 21.86. \quad (3)$$

Using four Los Alamos magnetospheric plasmaspheric plasma analyzer (MPA) instruments, *Lawrence et al.* [1999] studied the rate at which plasma in the plasmasphere refilled at geosynchronous orbit. These rates were separated into early-time refilling and late-time refilling. Once the late-time refilling was completed, the plasmasphere would then be saturated [*Lawrence et al.*, 1999].

Theoretically, a saturated plasmasphere's density should fall off as a function of  $L^4$  [*Angerami and Carpenter*, 1966]. This is because flux tubes increase in volume as a function of  $L^4$ . The process of plasmasphere refilling has been approached in a variety of models [e.g., *Wilson et al.*, 1992] and point out the fact that the density of a given flux tube is dependent on its time history of convection. In other words, there is a range of densities of trough or plasmaspheric flux tubes depending on whether the flux tube is in the early stages of refilling or saturated. Most plasmaspheric empirical models have contained information about saturated plasmaspheric intervals.

None of the earlier empirical models are completely satisfying because they either had limited and noncontinuous local time coverage or were based on limited data and/or valid only at geosynchronous orbit. The recent Global Core Plasma Model (GCPM) attempted to overcome these limitations by combining several previously published models by use of transition

equations in order to get a more complete description of the plasma in the inner magnetosphere. Included in the GCPM are the *Carpenter and Anderson* [1992] model, the *Gallagher et al.* [1998] model, and several others [Gallagher et al., 2000].

This study presents models for the average density and variability of the plasmasphere and trough constructed using over eight noncontinuous months worth of plasma density data from Combined Release and Radiation Effects Satellite (CRRES). These results are then compared to the previously referred to models and measurements.

## 2. Methodology

For approximately eight noncontinuous months between July of 1990 and October of 1991 the sweep frequency receiver (SFR) aboard CRRES measured the upper hybrid resonance frequency (UHR) of the plasmasphere and trough regions in the near-Earth environment. From the UHR (which is the sum of the ion cyclotron and plasma frequency) the plasma frequency can be determined and therefore the electron number density of the plasma. CRRES was launched with its apogee near 07 LT and an inclination of  $18^\circ$  from the geographic equator. The apogee precessed toward midnight at a rate of 1.3 hours per month. By October 1991 (the time of spacecraft failure) the precession of the apogee reached approximately 14 LT. During this time over 2.6 million plasma frequency readings between 100 Hz and 400 kHz were taken. The upper frequency limit results in a maximum possible reading of  $1984 \text{ cm}^{-3}$ . Figure 1 shows the log of the number of these data readings in bins of 1  $L$  shell by 1 local hour. The width of the 128 logarithmically spaced frequency channels of the SFR resulted in an error of at most 2% for each number

density reading. However, fluctuations in the density, the width of the UHR line, and instrument noise also lend to errors in the measurements of the order of 10-15% [LeDocq et al., 1994; Carpenter et al., 2000].

Models were constructed to give the average of the density for the plasmasphere and trough for the 14 months between July 1990 and October 1991. Also models describing the standard deviation of the densities over that same period were constructed. These models were constructed using a bin size of 1  $L$  shell by 1 local hour. This bin size allowed sufficient sampling in essentially all bins (see Figure 1) and allowed further binning by geomagnetic activity.

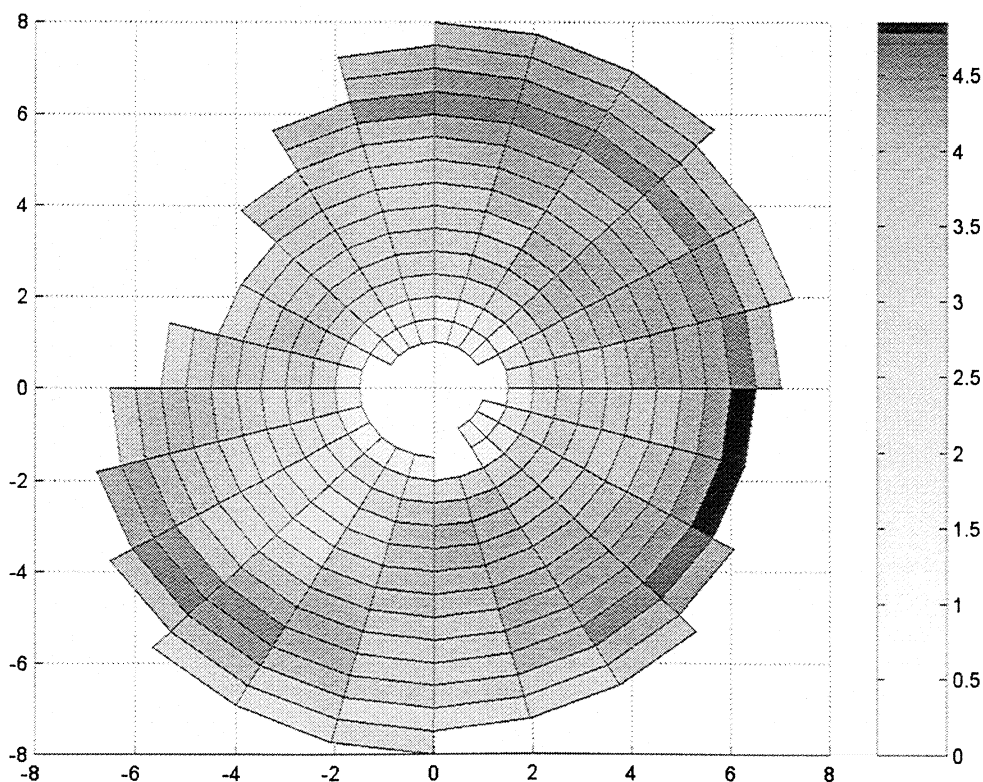
In order to determine which data readings were plasmaspheric-like and which were trough-like, an equation to represent the border between the two was constructed. In order to define "detached plasma" from the plasmasphere, *Chappell* [1974] set a minimum density for the detached plasma to be

$$n = 100 (4 / L)^4. \quad (4)$$

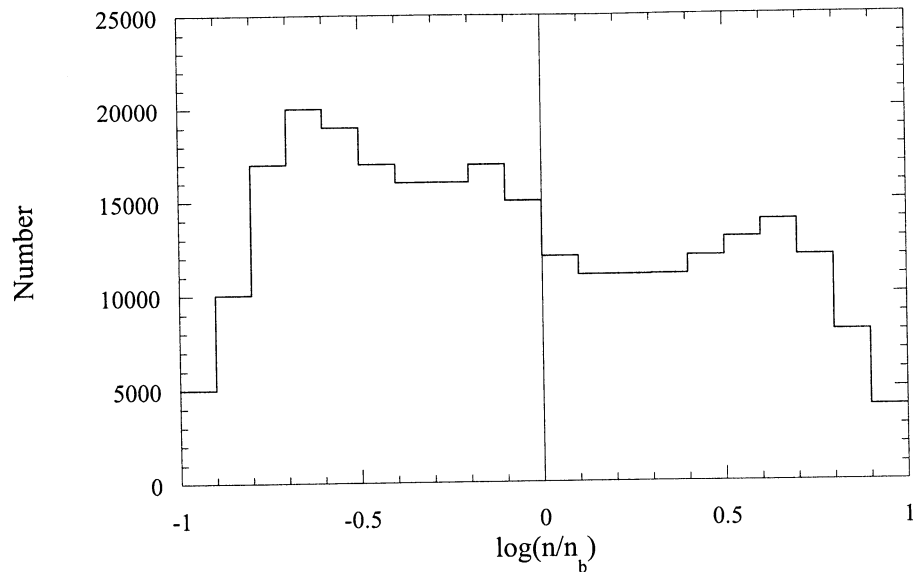
We adopted a similar equation for the separation of plasmaspheric-like and trough-like readings for CRRES [Moldwin et al., 1994]

$$n_b = 10 (6.6 / L)^4 \quad (5)$$

Density readings at or above  $n_b$  for the given  $L$  shell were considered plasmaspheric-like. Readings below  $n_b$  were considered trough-like. Figure 2 shows how the CRRES densities were separated into plasmasphere and trough. The two clear peaks show that the trough and plasmasphere have distinct (but



**Figure 1.** The CRRES data set was divided up into bins of 1  $L$  shell by 1 MLT. Bins in this plot show the log of the number of data points taken in each bin for  $L$  shells greater than 2. Magnetic noon is to the direct left. Midnight is to the right. Dawn is to the top, and dusk is at the bottom.



**Figure 2.** The histogram of the log of each density reading divided by the assumed plasmapause density shows how the data were divided into plasmasphere and trough. The data to the right of the center dividing line are classified as plasmasphere, the data to the left are classified as trough.

overlapping) mean density distributions. The non-negligible amount of data close to the separation border on both the plasmaspheric-like side and the trough-like side will cause a higher density average in the trough and a lower density average in the plasmasphere. However, comparisons of the new CRRES model to individual CRRES orbits for a variety of different activity levels shows that the “contamination” does not significantly bias the model averages.

The average for bins 1  $L$  shell by 1 local hour were then found for the plasmasphere and trough separately, and best fit curves for each  $L$  shell were then constructed. The trough showed clearly a sinusoidal variation in local time with the peak time initially around dusk and moving more toward noon as the  $L$  shell was increased (Figure 3). For the plasmasphere, however, sinusoidal best fit curves resulted in negligible amplitudes with inconsistent placements of the peak times as the  $L$  shells were compared. No local time dependence for the plasmasphere density was interpreted from this analysis (Figure 4). By finding the standard deviation of each bin, models for the standard deviations were also constructed. The standard deviation models show the variability in densities for the different regions.

### 3. Results

#### 3.1. Plasmasphere and Trough Models

When CRRES was within  $L$  shell of 3, the number of readings above the 1984  $\text{cm}^{-3}$  SFR upper limit was no longer negligible. Since these readings were defaulted to 1984  $\text{cm}^{-3}$  even if  $n > 1984 \text{ cm}^{-3}$  and then removed from the data, the averages were artificially lowered in this region. This limited the models to a region of  $L=3$  outward.

For the plasmasphere, the average density at  $L=3$  was approximately 1390  $\text{cm}^{-3}$  and fell off at a rate of  $L^{-4.8}$ . The standard deviation at  $L=3$  was approximately 440  $\text{cm}^{-3}$  (or 30%) and fell off at a rate of  $L^{-3.6}$ . At an  $L$  of 7 the number density was

approximately  $23 \pm 21 \text{ cm}^{-3}$  (or 90% variability). This results in the equation

$$n_e = 1390 (3/L)^{4.83} \pm 440 (3/L)^{3.60}, 3 \leq L \leq 7. \quad (6)$$

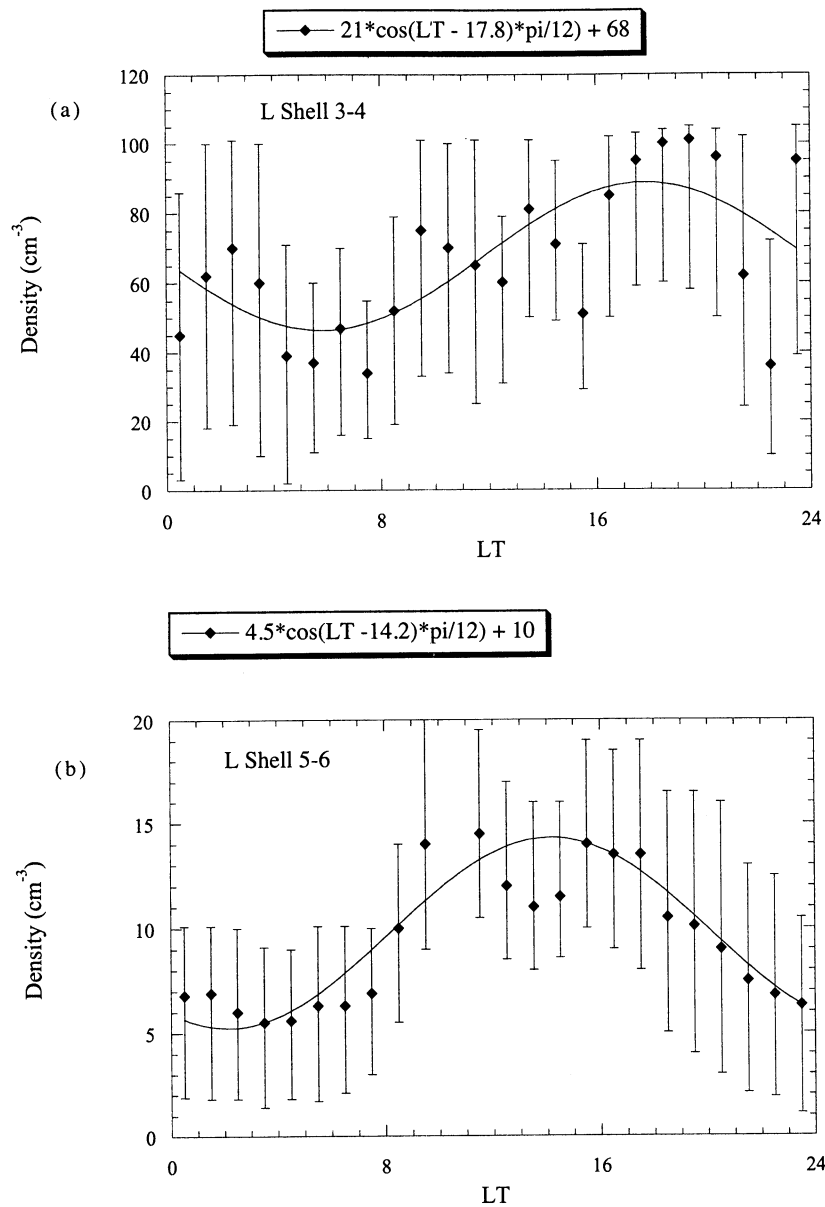
For the trough the average density at  $L=3$  was approximately 124  $\text{cm}^{-3}$  and fell off at a rate of  $L^{-4.0}$ . However, a sinusoidal variation due to local time was also found. At  $L=3$  the amplitude of the LT variation was 36  $\text{cm}^{-3}$  and fell off at a rate of  $L^{-3.5}$ . The peak of the sinusoidal variation at  $L=3$  occurred at 20 LT, and as  $L$  increased the peak moved toward 12 LT. The standard deviation was the greatest at about 22 LT. The average standard deviation at  $L=3$  was 78  $\text{cm}^{-3}$  and fell off at a rate of  $L^{-4.7}$ . The amplitude of the standard deviation variation at  $L=3$  was 17  $\text{cm}^{-3}$  and fell off as  $L^{-3.5}$ . This results in the equation

$$n_e = 124 (3/L)^{4.0} + 36 (3/L)^{3.5} \cos \{ \{ \text{LT} - [7.7 (3/L)^{2.0} + 12] \} \pi / 12 \} \pm \{ 78 (3/L)^{4.72} + 17 (3/L)^{3.75} \cos [(\text{LT} - 22)\pi / 12] \}, \quad 3 \leq L \leq 7. \quad (7)$$

Figure 5 shows how the CRRES best fit equations compared to the average density for an example local hour. The power law functional form fits the data very well and is of the same general functional form as *Carpenter and Anderson's* [1992] trough model.

#### 3.2. Geomagnetic Activity Comparison

When the average densities of each  $L$  shell for both the plasmasphere and trough were examined for different  $Kp$  values, the average densities were shown to be fairly constant (Figure 6). Variations in the activity changed the location of the plasmapause and thus where each model should be used, but the densities for each model themselves showed no consistent fluctuation. For the trough, both the amplitude of the sinusoidal variations and the peak local times did not consistently vary with  $Kp$ . Using identical methods, no dependence on  $Dst$  was determined either.



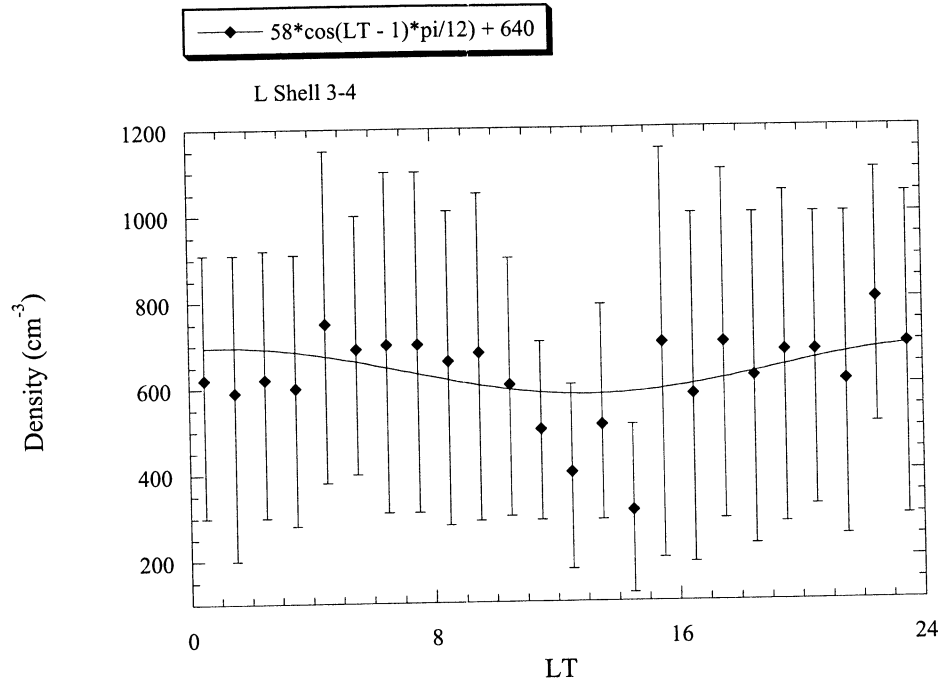
**Figure 3.** When the CRRES density data for  $3 \leq L < 4$  was binned for each local hour, an overall increase in the density was found around dusk with a minimum at dawn. Sinusoidal best fits were made for all  $L$  shells from  $3 \leq L \leq 7$  (the best fit curve equation generated for this  $L$  shell is displayed), and from these fits the trough model was constructed. The drifting of the trough density peak towards noon can also be seen comparing the best fit curves for (a)  $3 \leq L < 4$  and (b)  $5 \leq L < 6$ . The graphs show the peak moving from approximately 18 LT to approximately 14 LT as  $L$  is increased.

### 3.3. Case Study Model Comparisons

On the morning of September 2, 1990, there was a period of very quiet geomagnetic activity ( $0^+ \leq Kp \leq 1^-$ ). During this time, CRRES had apogee at 0700 LT (Figure 7a). Once CRRES passed  $L = 3$  heading outward, the density values followed the average predicted by the new CRRES model. After the spacecraft passed through the plasmapause at  $L = 5.5$ , the readings followed the maximum values predicted by the trough model (the trough average plus the standard deviation). However, once the satellite passed apogee the density readings began to follow more the lower end of the plasmasphere model (plasmasphere average minus the standard deviation) until the plasmapause was

encountered again. At this time the densities were increasingly diverging from the trough range. Before the plasmapause was reached, the densities were twice that of the predicted trough model. Once CRRES reentered the plasmasphere, the average predicted by the plasmasphere model was again followed.

During the afternoon and night of March 24, 1991, geomagnetic activity was extremely high ( $5 \leq Kp \leq 9^-$ ). Twelve hours prior to this period, the activity reached  $Kp = 9^-$ . At this time, CRRES had its apogee at 22 LT (Figure 7b). After CRRES passed  $L = 3$  on its outbound pass, the density readings were within the model plasmasphere range. However, shortly before the plasmapause was encountered, the density increased above



**Figure 4.** The process of attempting to match a sinusoidal best fit curve to the CRRES data was done for the plasmasphere just as was done for the trough; however, the amplitudes of the curves computed were much smaller compared to the average density, the locations of the maxima were inconsistent from  $L$  shell to  $L$  shell, and in most cases a sinusoidal shape was not found.

the range before lowering to the maximum levels of the trough range. When CRRES moved further out, the density decreased to the minimum values predicted by the trough model. As CRRES passed apogee, the density began to increase and passed through the predicted trough average. However, during this time, the geomagnetic activity increased again to  $Kp = 9$ . CRRES never encountered the plasmopause. Yet it should be noted that the density did slowly increase relative to the trough model and slowly moved back towards plasmasphere levels. This behavior is indicative of a refilling trough.

During the late night and early morning of July 22 and 23, 1991, respectively, the geomagnetic activity was moderate ( $3 \leq Kp \leq 5$ ). CRRES now had its apogee at 17 LT (Figure 7c). Once CRRES passed  $L = 3$  the densities followed the minimum predicted values for the plasmasphere range. After the plasmopause at  $L = 5.5$  the density fell to within the trough range. Toward apogee a plasmaspheric-like blob was encountered. Afterward, as the geomagnetic activity decreased, the plasmopause was encountered at approximately  $L = 6.3$ . From there on the CRRES readings followed the minimum plasmasphere range.

## 4. Discussion

The empirical model developed here describes the plasmaspheric and trough electron number densities for all local times from an  $L$  of 3 to 7. The standard deviations about the means give estimates of the variability of the density of the two regions. They are also indicative of the refilling process and can be used as representative of the day ( $+1\sigma$ ) or nighttime ( $-1\sigma$ ) trough (or early and late-time refilling intervals) or newly filled ( $-1\sigma$ ) or saturated ( $+1\sigma$ ) plasmasphere. The comparison of the new model with several orbits of CRRES data following different

activity histories shows that the model does a good job of describing plasmasphere and trough densities. If the activity history is known, more accurate estimates of the density can be inferred by using the upper or lower ranges of the model depending on if the intervals followed changing geomagnetic activity or steady geomagnetic activity. To further validate and understand our new model results, we next compare the CRRES model with earlier empirical models.

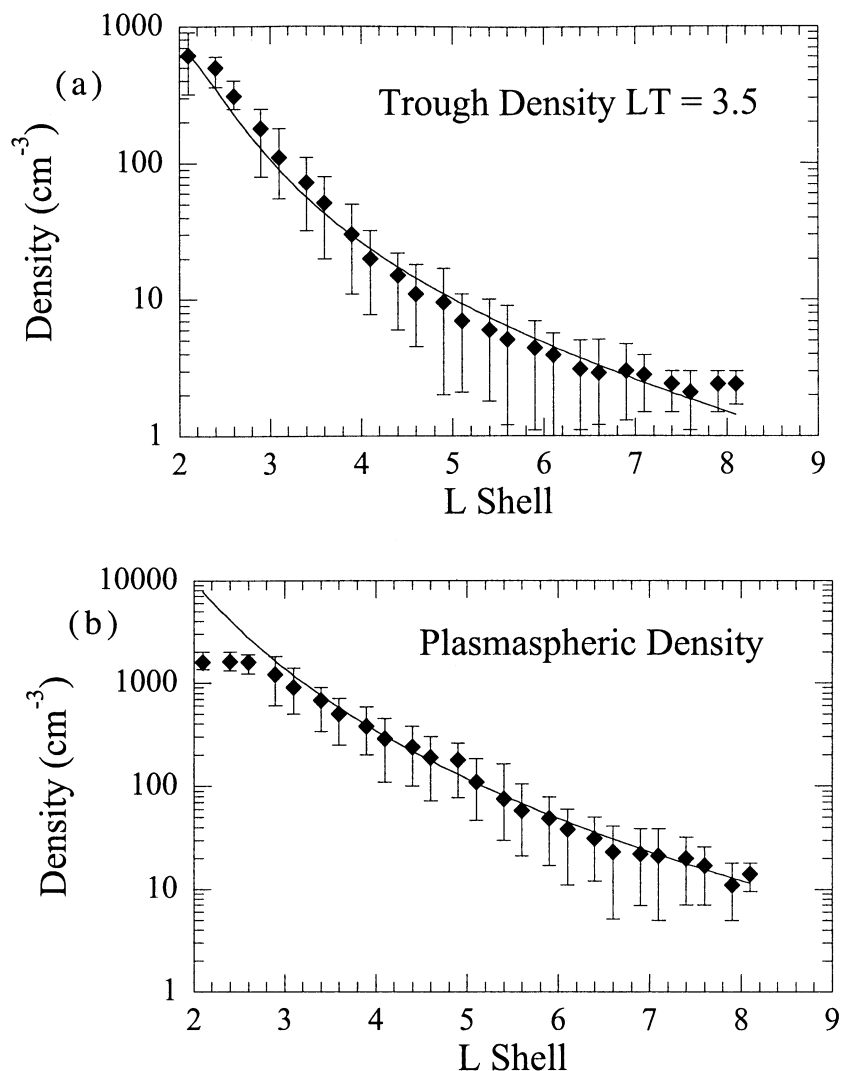
### 4.1. Comparing With Carpenter and Anderson [1992]

**4.1.1. Trough model.** The *Carpenter and Anderson* [1992] model (hereafter called C&A) was constructed from data from the ISEE satellites and whistler data. The C&A trough model, which was defined out to an  $L$  shell of 8, was given by (1).

The first of the major differences between the new CRRES model and the C&A model is that the C&A model is only defined for the local times of midnight to 15 LT, whereas the new trough model is continuous and valid at all local times. However, the C&A model is valid from an  $L$  shell of 2.25 (if the plasmopause is that far in) out to 8, whereas the new trough model is defined for  $L$  shells of 3 to 7.

The next difference is that the C&A trough model uses two separate discontinuous equations to define the trough densities, whereas the new trough model is a continuous and smooth function. The C&A model also automatically places the local time minimum at midnight. As the local time is increased, the density also increases, first with one slope up until 6 LT and then with a steeper slope up until 15 LT where the model is halted.

When the models are compared for specific local hours, there is a significant difference for some LT (greater than the standard deviation). In order to get an idea of how the models varied, two different local hours were compared (Figure 8). The two times chosen were 3.5 LT and 13.5 LT since these regions would



**Figure 5.** The CRRES models were created from best fits of the average density readings of binned data in combination with the calculated standard deviation for each bin. The diamonds show the calculated averages with the standard deviations for each bin. (a) For the trough the best fit curve follows the averages while staying well in the standard deviation ranges. This sample local hour is typical for most of the trough data. (b) For the plasmasphere the best fit curve works well for  $L$  shells at or above  $L=3$ . Although the plasmaspheric curve does not shift through local time, the averages shown are for the same local hour as the trough graph above. This is to show how the values change within the same region as the plasmapause moves in and out.

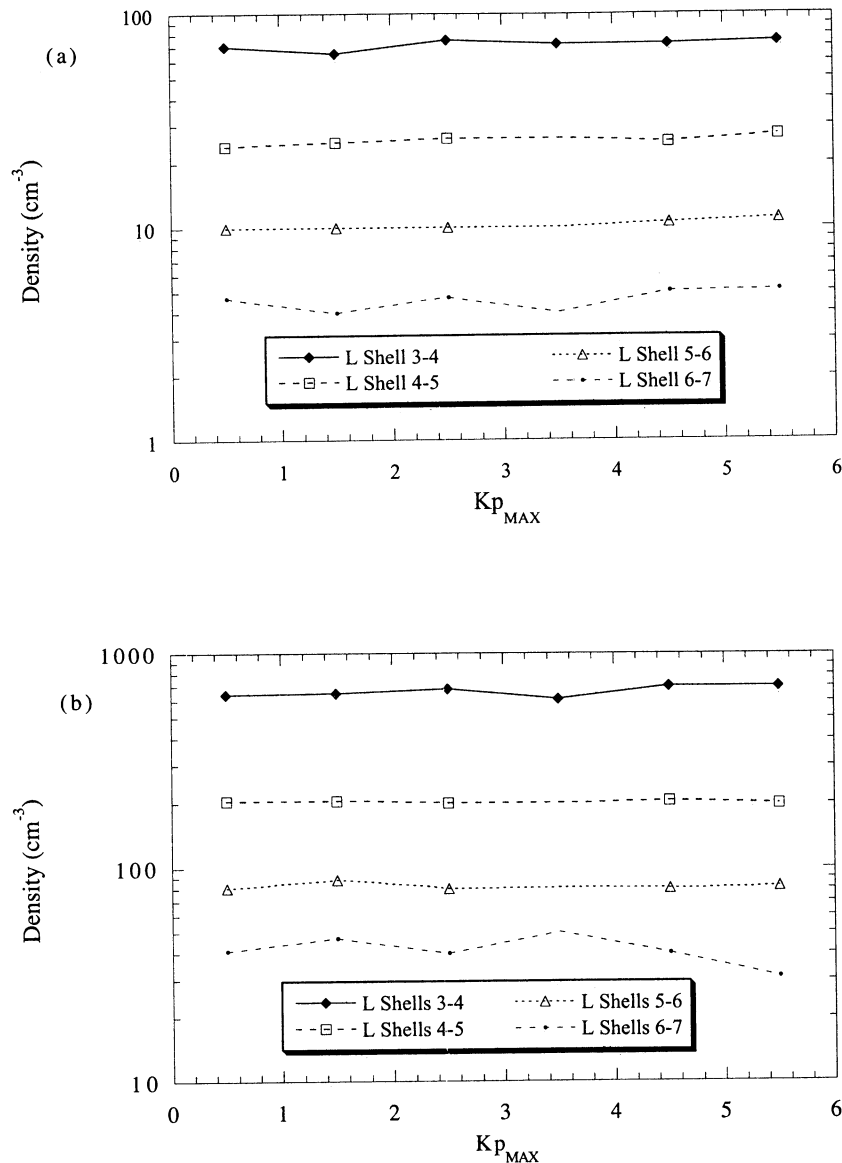
roughly show the low- and high-density ends of the new model while still within the LT range given by the C&A model.

Approximately at 3.5 LT, near the minimum in the density of the trough plasma, the new model is consistently higher than the C&A model for all  $L$  shells. However, the C&A model is always within 1 standard deviation from the CRRES model (or near the CRRES models “empty” trough value). At 13.5 LT, near the maximum of trough densities, the new model is also consistently higher than the C&A model (ranging from ~20% at  $L$  shell of 3 to ~45% at  $L$  shell of 7). However, the C&A model results are within or just outside the new CRRES models early-time refilling trough values. Also for every local hour between midnight and 15 LT the new trough model was consistently higher at all  $L$  shells (though again the C&A results were within the early-time refilling model ( $-1\sigma$ )).

There are several possibilities why the new model is consistently higher than the C&A model. The main difference is that the C&A model is more representative of an “empty” trough.

The new CRRES model includes all trough intervals, including low-density outliers that were systematically excluded by C&A. Density cavities [Carpenter *et al.*, 2000] are regions of low density apparently embedded in the plasmasphere. The densities are generally a factor of 5 below average plasmasphere densities but are significantly higher than trough densities. About 15% of the CRRES orbits contained a density cavity, but they generally had radial extents of less than 1  $L$  shell. These cavities would contribute to increasing the trough average density. However, since they are relatively rare and short lived, it is thought not to have a significant impact on the average trough densities.

Though the new model was consistently higher than the C&A model, it generally falls within  $1\sigma$  of the CRRES model for all local times. However at some LT the C&A model has a slightly faster fall-off rate as a function of  $L$  shell giving a significantly lower density at large ( $>5$ )  $L$  shells. The new CRRES trough model and the C&A model generally agree at all LT and  $L$  shells, but the new CRRES model is an improvement in that it is given



**Figure 6.** The averages for different ranges of  $L$  shells for the (a) trough and the (b) plasmasphere were compared for ranges of  $Kp_{max}$  (the maximum  $Kp$  value of the 24 hours before each SFR reading) of 0 to 1-, 1 to 2-, 2 to 3-, ..., 5 to 6-. Values of  $Kp_{max}$  of 6 and above were not analyzed due to the small number of data points. No clear  $Kp_{max}$  dependence for the density averages was found.

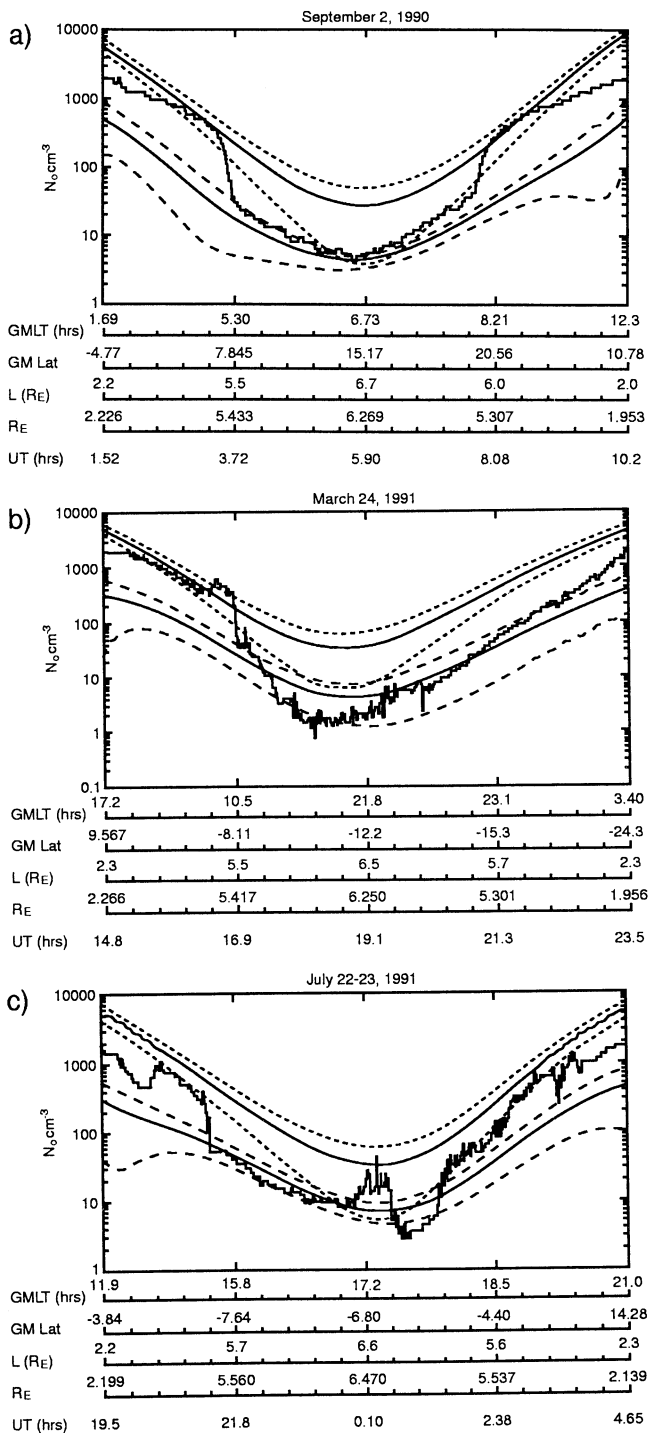
by a continuous function, is valid at all LT, and gives a measure of the trough density variability.

**4.1.2. Plasmasphere model.** *Carpenter and Anderson* [1992] also developed a plasmasphere model. The model is given in equation (2). This model includes a parameterization dependent on sunspot number ( $R$ ) and day of year. During the CRRES mission  $R$  was approximately 144. As the day of the year varies, so does the model density. The range of this variability is given by

$$\begin{aligned} &(-0.3145L + 3.9043) - 0.207093 \exp[-(L - 2) / 1.5] \leq \log n_e \\ &\leq (-0.3145L + 3.9043) + 0.130407 \exp[-(L - 2) / 1.5]. \end{aligned} \quad (8)$$

At an  $L$  shell of 3, this range allows for a variation of over 30% in the density. However, as the  $L$  shell increases, this percentage decreases rapidly making the variations much smaller by  $L$  shell of 5 (~11%) and by  $L$  shell of 7 it has reduced to 2.5%.

In Figure 9 the C&A plasmasphere model diverges from the CRRES plasmasphere model range at approximately  $L = 4$  and higher. However, the C&A model remains close to the CRRES average density of the saturated plasmasphere (average plus standard deviation) up to  $L = 7$ . The reason for the lower average values at higher  $L$  shell in the CRRES model is probably due to the new model including plasmaspheric readings while the plasmasphere was not saturated. Carpenter and Anderson's [1992] plasmasphere model describes saturated conditions only. Also any plasmaspheric blobs external to the main plasmasphere (embedded in the trough) were included in the new model, while the C&A model discounted them from the saturated plasmasphere readings. These blobs, although dense enough to be included in the plasmaspheric data set as opposed to the trough, are often less dense than the C&A model plasmasphere. This results in a decrease of the CRRES model's predicted density compared to the C&A model.



**Figure 7.** The dark solid curve represents the SFR density readings. The upper three overlaid curves show the CRRES plasmasphere model: the average density, the average plus the standard deviation, and the average minus the standard deviation. The lower three overlaid curves show the same for the CRRES trough model. (a) low magnetic activity. On September 2, 1990, between 0300 and 0900 UT the  $K_p$  was measured at 0+; for other times within the range of this plot the  $K_p$  was 1-. (b) High magnetic activity. On March 24, 1991, from 1200 and 1500 UT the  $K_p = 7+$ ; between 1500 and 1800 UT, the  $K_p$  was measured between 5+ and 5; and from 2100 to 2400 UT  $K_p = 9-$ . (c) Medium magnetic activity. Over July 22 and 23, 1991, from 21  $\leq$  UT  $\leq$  24 to 0  $\leq$  UT  $\leq$  3 the  $K_p$  fell from 5- to 4-. For the other times in this plot the  $K_p$  was at 3-.

However, the actual CRRES measurements remained within or close to the range predicted by the new model for the plasmasphere (see Figure 7). So the new model is consistent with the original data and the upper density limit ( $+1\sigma$ ) tracks the C&A model of the saturated plasmasphere fairly well. The advantage of the new CRRES model is that a range of possible values is given instead of a specific average. The standard deviation gives a quantitative measure of the variability of the plasmaspheric density and is indicative of newly filled or saturated flux tubes.

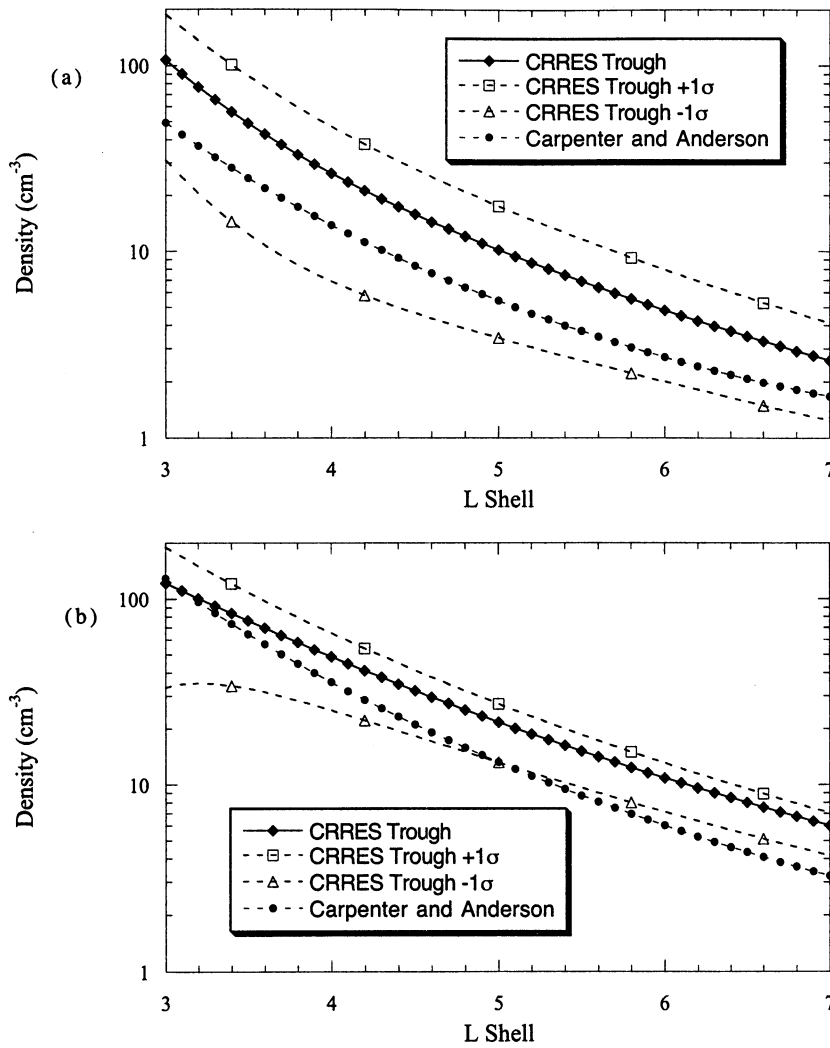
#### 4.2. Comparing With Gallagher *et al.* [1998]

In the late 1970s and early 1980s the GEOS 2 spacecraft collected in situ data on the density of the plasma from geosynchronous orbit ( $L$  shell of 6.6) [Higel and Wu, 1984]. Gallagher *et al.* [1998] used this data and determined that the local time of the peak trough density for the geosynchronous  $L$  shell was a function of  $K_p$  (equation 3). The average CRRES density behavior of the plasmasphere and trough does not show a dependence on  $K_p$  (Figure 6). The variation of the local time of the peak density also did not show a clear  $K_p$  dependence. This is in contrast with Gallagher *et al.* [1998] results for the trough that found a motion of the peak density of the trough towards noon with increasing geomagnetic activity (similar to the behavior of the plasmaspheric bulge). However, Gallagher *et al.* note that this result is based on 7 days of data over a  $K_p$  range of 2+ to 4+. For the 3 days with  $K_p$  between 4- and 4+ the trough peak density local time location varied between 1200 and 1600. Due to this large variability it is not surprising that the CRRES density averages “wash” out any local time behavior.

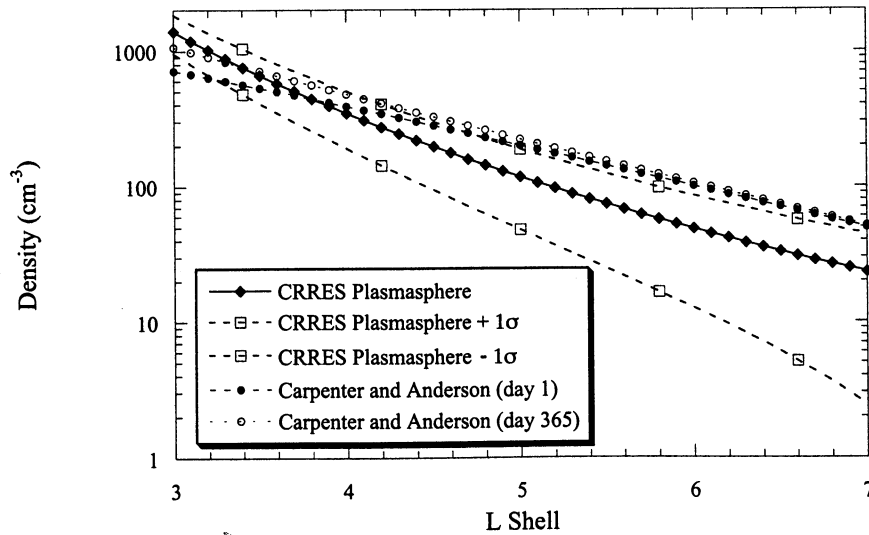
Looking at data taken by GEOS 2 on January 29, 1979, it can also be seen that the Carpenter and Anderson [1992] model fails to fit overly well (Figure 10). At local times at which the densities were at a minimum the C&A model predicts values an order of magnitude greater than the trend line for Gallagher *et al.* [1998]. When the densities were at a maximum, the C&A model predicted values that were too low. The new model for the trough fits much better in the range where maximum densities are given. The Gallagher *et al.* [1998] and GEOS 2 maximum density occurred at approximately 15 LT with number densities of approximately 7 to 8 cm<sup>-3</sup>. The new model places the maximum at 14 LT with a predicted density of 7.5 cm<sup>-3</sup>. This is an excellent agreement.

However, for the magnitude of the density minimum the new model fit does not agree as well with the Gallagher *et al.* [1998] model (but straddles the range of GEOS 2 data fairly well). The Gallagher *et al.* model places the density minimum at around 2 LT with a density of around 0.1 cm<sup>-3</sup>. The new CRRES model does place the minimum at this time but with a predicted density of 3 cm<sup>-3</sup>. The Carpenter and Anderson [1992] model predicts a density of 0.3 cm<sup>-3</sup>, which is within the CRRES range. It is noted, however, that the number of readings around the minimum are much less than that of the maximum. Also most of the data points are much higher than the Gallagher trend line, and a few are even above the Carpenter and Anderson model. The Gallagher model also finds a linearly increasing and decreasing density variation with MLT (with the peak trough density MLT or switch over from increasing to decreasing density given by (3)). A nonsinusoidal variation was also found by C&A. C&A used a discontinuous linear-two-slope refilling pattern to describe the trough density as a function of local time. However, by considering a sinusoidal model fit and allowing for the calculated

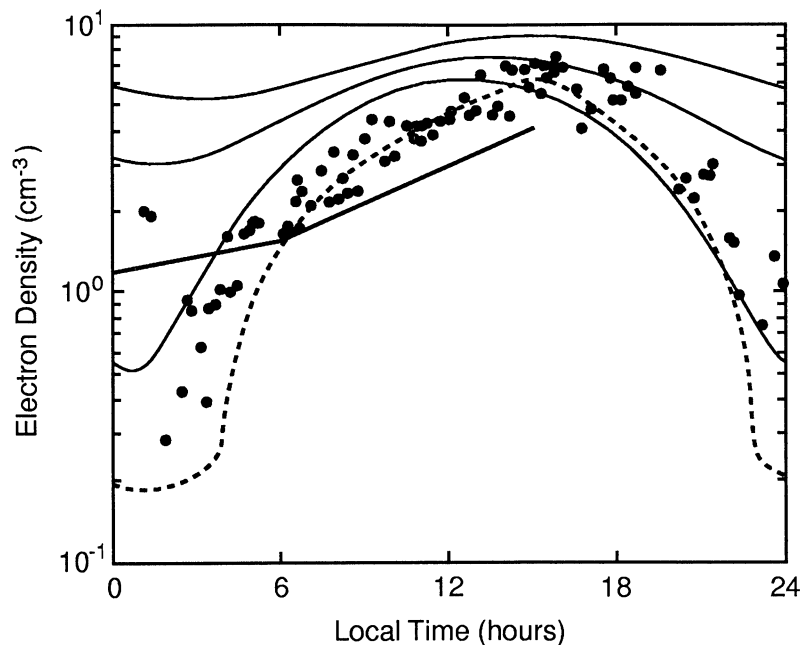




**Figure 8.** The CRRES trough density model and the Carpenter and Anderson [1992] trough model are compared for two different magnetic local times. (a) For LT = 3.5 the Carpenter and Anderson curve is consistently below the CRRES average curve but is well within the standard deviation for all *L* shells. (b) At LT = 13.5 the Carpenter and Anderson curve left the CRRES trough range at approximately *L* = 5 and diverged further at the *L* shell was increased.



**Figure 9.** The solid black diamond curve is the CRRES plasmasphere average density model. The open box curves are the CRRES plasmasphere average density model with the standard deviation added and removed. The circle curves are the range of the *Carpenter and Anderson* [1992] plasmasphere density model for the average 13-month sunspot number set to 144 (the approximate value during the period of CRRES's operation) and the day number varied between 1 and 365.



**Figure 10.** Using density measurements from GEOS 2 for January 29, 1979, from *Higel and Wu* [1984] (plotted as dots), *Gallagher et al.*, [1998] created a trough model describing the trough density at geosynchronous orbit (plotted as dashed curve). The two solid straight lines are the *Carpenter and Anderson* [1992] trough model for  $L = 6.6$ . The black solid dark curves are the CRRES trough density model (with standard deviations) for  $L = 6.6$ .

amounts of error, the variation can be reasonably approximated by the use of the cosine function. Noting that the densities from the CRRES readings follow the new trough model rather well and that the GEOS 2 data points in Figure 10 do consistently fall on or about the lower end of the trough model's range, the simplification to a single continuous equation appears to be very acceptable.

These GEOS 2 data points shown in Figure 10 were taken during a single day. The new CRRES model averaged data over a period of about 14 months. The CRRES results were averaged together for both newly emptied flux tubes and with "older" flux tubes. With this as the case the lower end of the trough range can be considered the average density of early-time refilling (or the nightside trough). The higher density end of the range can be viewed to represent late-time refilling (or the daytime trough). The flux tubes were apparently recently emptied on January 29, 1979, and therefore follow more the bottom of the CRRES model trough range.

#### 4.3. Comparing With *Lawrence et al.* [1999]

Using data from four magnetospheric plasma analyzer instruments (MPA) on the Los Alamos National Laboratory Geosynchronous Satellites, which had taken 7 years worth of data, *Lawrence et al.* [1999] measured the rate at which the plasma refills itself at geosynchronous orbit. Instead of measuring the number density of electrons, however, the number density of low-energy ions were measured, but since the plasma is assumed to be charge neutral and majority low-energy these values should be similar [*Lawrence et al.*, 1999].

The new CRRES plasmaspheric model predicts a number density of  $31 (\pm 26) \text{ cm}^{-3}$  of electrons at an  $L$  shell of 6.6. The *Lawrence et al.* [1999] study measured the rates up to the point where the plasmasphere became saturated. This is essentially the density maximum. The density of the saturated plasmasphere at

geosynchronous orbit found by *Lawrence et al.* varied between 50 and  $100 \text{ cm}^{-3}$ . The saturated densities from *Lawrence et al.* are characteristic of late-time refilling. Since the lower density values that occurred during the early-refilling time (i.e., nonsaturated density measurements) were not excluded from the new model, this results in a lower predicted average density. However, if the standard deviation of the CRRES plasmasphere model is added to the average, the density falls into the lower end of the *Lawrence* range. This shows that a "saturated condition" of the plasma densities can be estimated by using the average  $+1\sigma$  values.

The new CRRES trough model predicts number densities at an  $L$  shell of 6.6 ranging from  $3.0$  to  $7.5 \text{ cm}^{-3}$  depending on the local time being observed. The density range given by *Lawrence et al.* [1999] for a filled trough after early-time refilling was approximately  $4$  to  $10 \text{ cm}^{-3}$ . Also, if the plasmaspheric standard deviation is subtracted from the plasmasphere model, a value of  $5.1 \text{ cm}^{-3}$  is found. So both the trough model average and the lower range of the plasmasphere model can be used to give the trough density for late-time or dayside trough values.

#### 4.4. Comparing With *Gallagher et al.* [2000]

The Global Core Plasma Model (GCPM) presented by *Gallagher et al.* [2000] combines several empirically derived models that had been developed previously in order to create a continuous model of trough and plasmaspheric densities. Each of the individual models are linked together by transition equations which phase dominance from one model to another when appropriate. Included in the GCPM are the *Carpenter and Anderson* [1992] model and the *Gallagher et al.* [1998] model [*Gallagher et al.*, 2000].

Since the GCPM is dependent on the models that represent its parts, one can compare the new CRRES model with each individual model that shares jurisdiction in a particular location (i.e., comparing CRRES with *Gallagher et al.* [1998] at

geosynchronous orbit, etc.). With several of those models already compared above, advantages and disadvantages have already been stated. A detailed comparison of the CRRES model and the new GCPM will be done in the future, but it is thought that the CRRES model, which is based on a single extensive database, would give a smoother and more accurate picture than an interpolation of different models.

## 5. Summary and Conclusions

CRRES measured the electron number density of plasma around the Earth for eight nonconsecutive months between July 1990 and October 1991. The average density of the plasmasphere ( $n_e$ ) as a function of  $L$  shell ( $L$ ) is given in (6). The variation of the plasmaspheric density at low  $L$  shells is approximately  $\pm 30\%$ , while the variability increases at large  $L$  ( $\pm 90\%$  at  $L$  of 7). Therefore the plasmaspheric density can vary up to a factor of 2 at a given location depending on the previous convection history (i.e., there is a factor of 2 difference between newly filled flux tubes and saturated flux tubes).

The average density of the trough ( $n_e$ ) as a function of  $L$  shell ( $L$ ) and magnetic local time (LT) was given in (7). The lower end of the trough model's range predicts densities of the trough during times of early refilling. The trough MLT density peak moves toward noon as  $L$  shell is increased. This may be due to low-density plasma plumes convecting sunward being included in the trough model. This would imply that calculations of trough refilling might be overestimated due to the inclusion of these plasma plumes/tails.

No dependence on magnetic activity was found for the densities of the models from the CRRES data set other than the movement of the plasmopause that determined which of the two models should be used. However, convection history has a significant effect on trough and plasmaspheric density levels though  $Kp_{\max}$  does not adequately define a given flux tubes convection history.

The new CRRES trough and plasmasphere empirical models are continuous in local time and valid within the inner magnetosphere. They can be used in combination with the *Carpenter and Anderson* [1992] plasmopause location model to characterize the cold-plasma density environment. Future work includes developing a CRRES plasmopause location model.

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