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Wave-Like Variations and Sudden Density Decreases in the Lower Thermosphere as Measured by the San Marco V Satellite

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Abstract. Neutral density measurements were carried out by the microaccelerometer on board the Italian San Marco V satellite in 1988. During the final week of its existence the satellite's perigee decreased to as low as 130 km. Measured density values were compared to the corresponding CIRA '86 (MSIS '86) or to our dMSIS model values. The residuals reveal a wavy structure of different time scales. Characterising the wave amplitude by the average deviation of the residuals, its dependence on different parameters was studied. These investigations demonstrated that the wave-amplitude varies with height, local solar time and geomagnetic disturbance level. There is a particularly developed wave pattern in the average deviations below 200 km. Case studies indicated that there are sudden density decreases of 20-30 sec duration that might be in connection with plasma bubble crossings by the satellite. Altogether 261 such cases were identified and their distribution as a function of height, LST and longitude have been investigated. © 2001 Elsevier Science Ltd. All rights reserved

1 Introduction

The density measurements of the DBI (Drag Balance Instrument) microaccelerometer on-board the Italian San Marco V satellite form our data base (Arduini *et al.*, 1992). The satellite was in an equatorial orbit between 130 and 600 km altitudes from April to December 1988. The total number of observations used is 570 252 and the data base is suitable to investigate secondary, subtle variations in the upper-atmospheric density.

Density data have been compared with corresponding data of the CIRA '86 (MSIS '86) model (CIRA: 86) or with our dMSIS model (Illés-Almár *et al.*, 1997b). In a previous paper (Illés-Almár, 1993) the considerable scatter in residuals – that could not be taken into account in any upper-atmospheric model – was attributed to some kind of wave activity. The time resolution of the DBI measurements is good enough to verify such a hypothesis. A density curve measured by DBI and plotted on Fig. 1 illustrates that the waves are really present and cause the scatter in the residuals. (According to Arduini *et al.*, 1992, the waves occure more often at night which could be in connection with the more frequent occurence of plasma bubbles.) The waves have different wavelengths, the longer ones belong to gravity waves, the shorter ones to acoustic gravity waves.

2 Waves

The scatter on the residual curves has been investigated both directly and statistically. For statistical investigations the δ average deviation has been defined (Illés-Almár *et al.*,

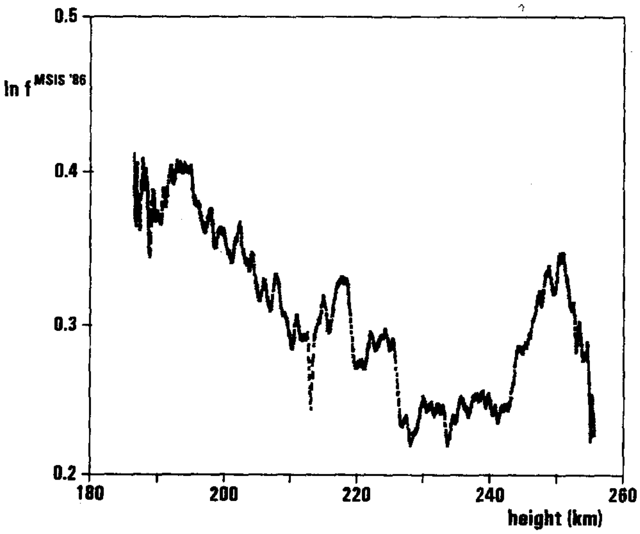

Fig.1. Wave-like fluctuations of different frequencies in the MSIS'86 residuals according to San Marco V data.

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1997b) to represent the mean amplitude of the waves:

$$\delta = \frac{\sum \left| \overline{\ln f} - \ln f \right|}{n} \qquad (1)$$

where $f = \rho^{obs}/\rho^{model}$ and n is the number of points in appropriate LST and altitude intervals.

The dependence of δ on different geographic and geophysical parameters has been investigated. The LST dependence is plotted on Fig. 2. It is evident that the amplitude (δ) of the wave activity is lower in day-time than at night, which may be due to the daily variation of ion density; the ion density and thus the ion drag – the damping of the waves – being larger by day than by night.

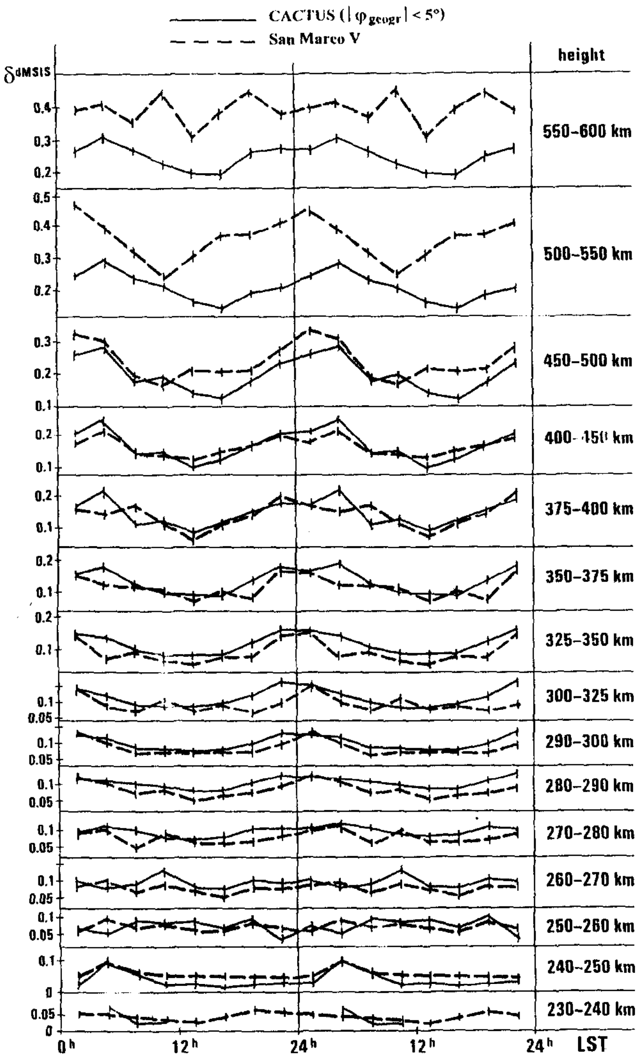

Fig.2. Diurnal variation of the average wave amplitude separated according to height (CACTUS and San Marco V data).

It is visible on Fig. 3, 4 and 5 that the amplitude (δ) is generally increasing with height, but the slope of the curve is steeper at higher altitudes. The course of the curves is different according to season, to the level of geomagnetic

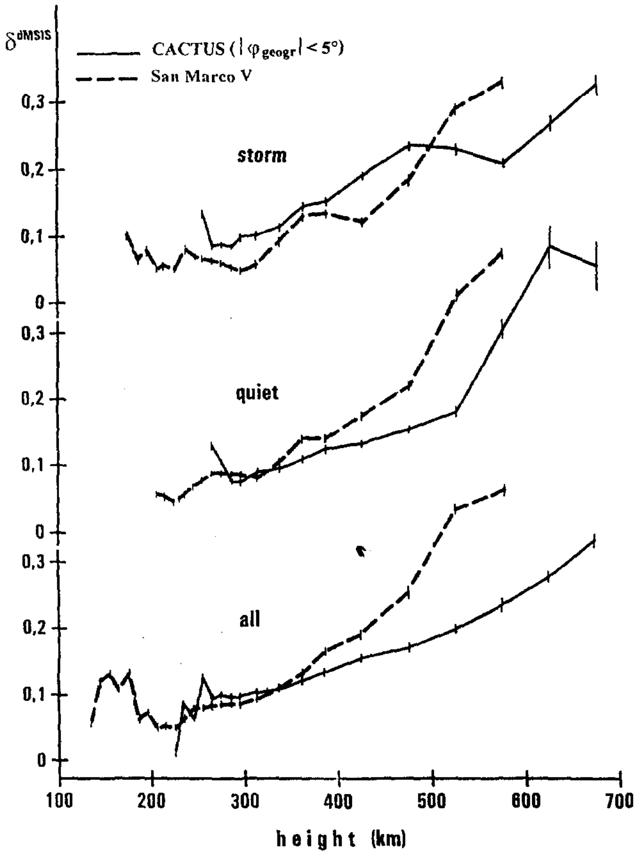

Fig.3. Height dependence of the average wave amplitude for quiet and for disturbed conditions (CACTUS and San Marco V data).

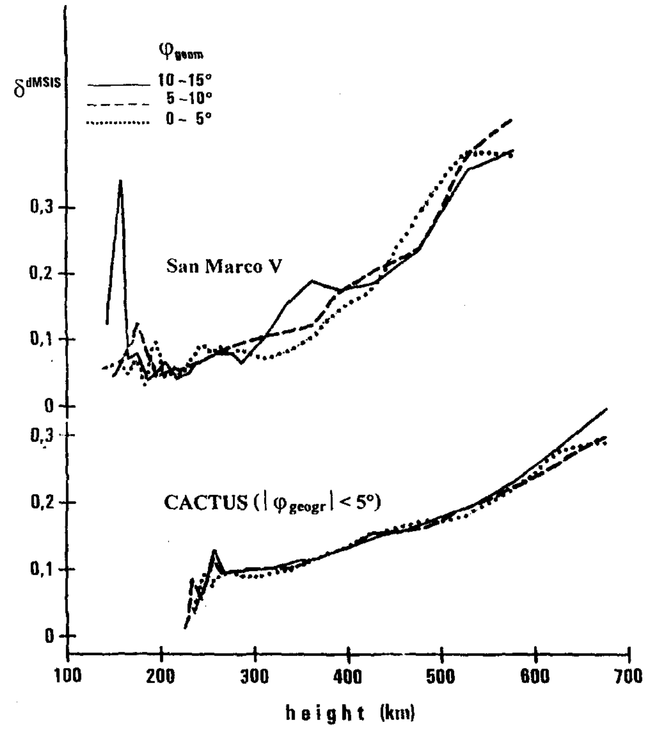

Fig.4. Height dependence of the average wave amplitude for CACTUS and for San Marco V data separated according to geomagnetic latitude. The peak under 200 km (San Marco V) is shifted towards lower altitudes at higher latitudes.

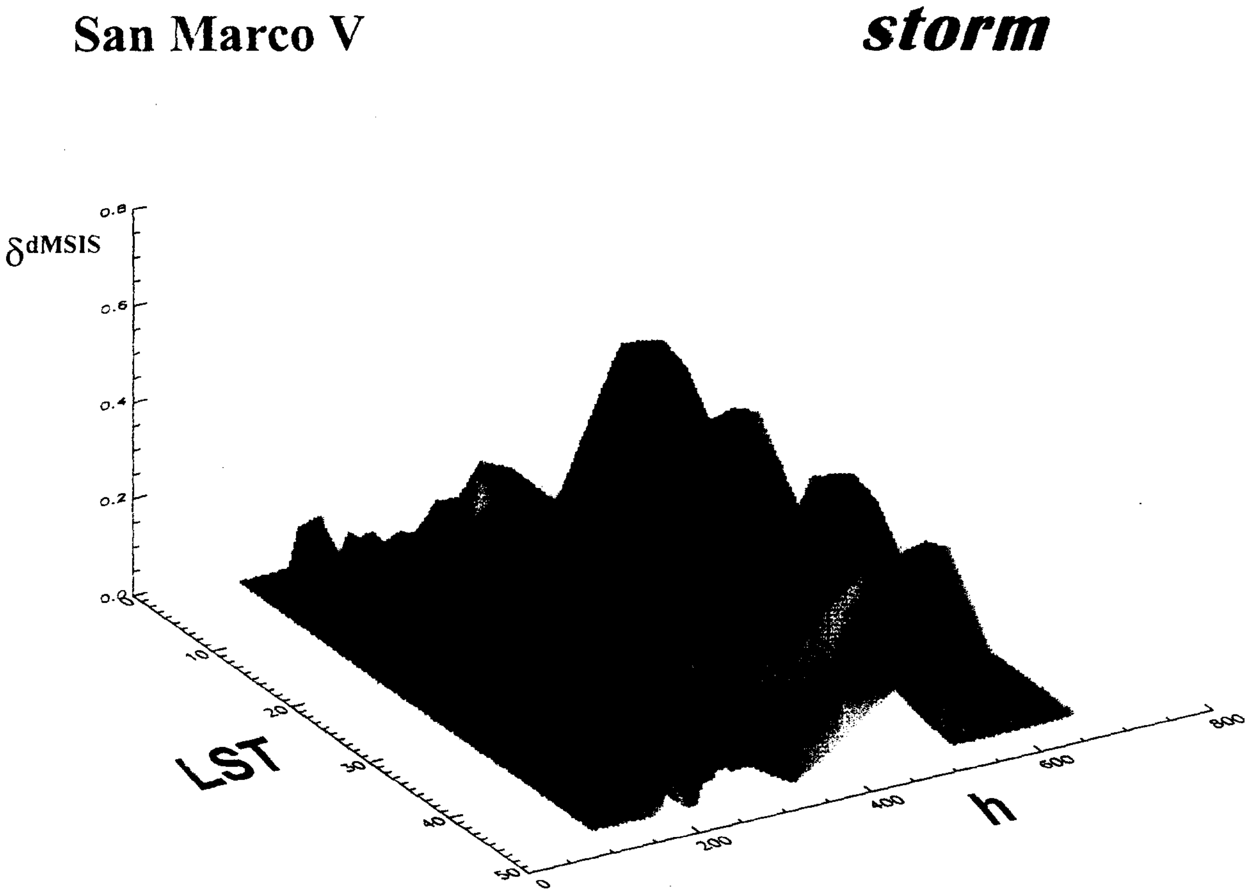

Fig.5. The dependence of the average wave amplitude on LST and height. The average level is fluctuating at low altitudes (San Marco V data).

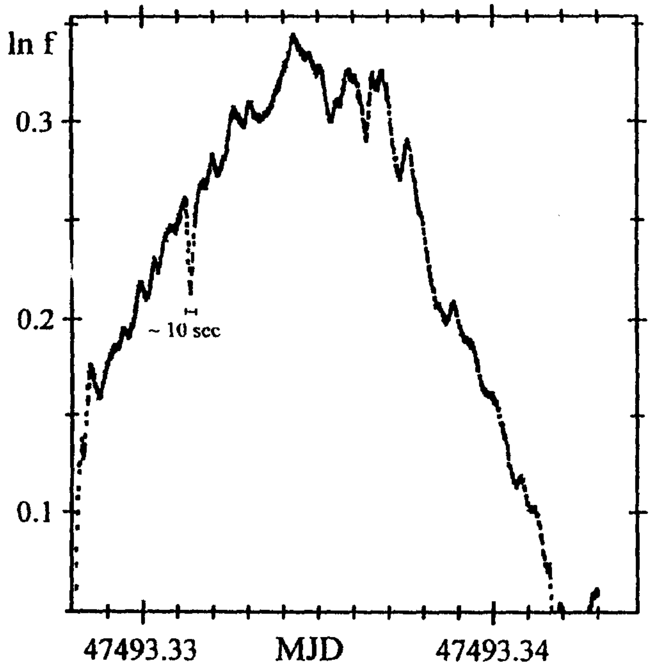

Fig.6. The density residual curve illustrates the occurrence of a typical sudden density decrease phenomenon. MSIS'86 model is used.

activity (Fig. 3) and to geomagnetic latitude (Fig. 4). (The dependence on latitude might be attributed to the Equatorial Ionospheric Anomaly, EIA effect.) At the lowest altitudes δ is increasing again, its peak is shifted towards lower altitudes on higher latitudes. On Fig. 5 the surface represents the dependence of the average wave amplitude

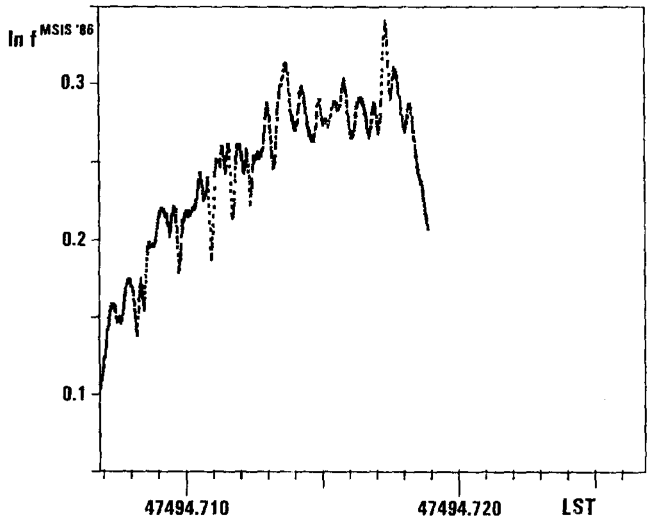

Fig.7. A series of sudden density decreases on a density residual curve.

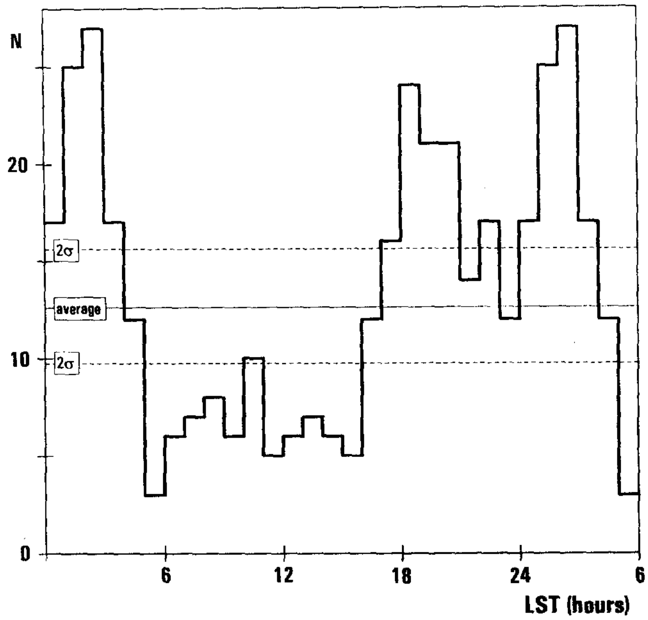

Fig.8. Histogram of sudden density decreases according to LST.

(δ) on LST and on height; it is evident that these low altitude peaks occur in all local-time periods.

3 Sudden density decreases

Another phenomenon, which was discovered directly on the density curves measured by the DBI instrument, is the occurrence of sudden density decreases from time to time (Illés-Almár *et al.*, 1997a, 1998). (Sudden density increases have been found as well, but less frequently and will be treated elsewhere.) A systematic search after sudden density decreases has been carried out in the whole data base. The criteria of the selection procedure were the following:

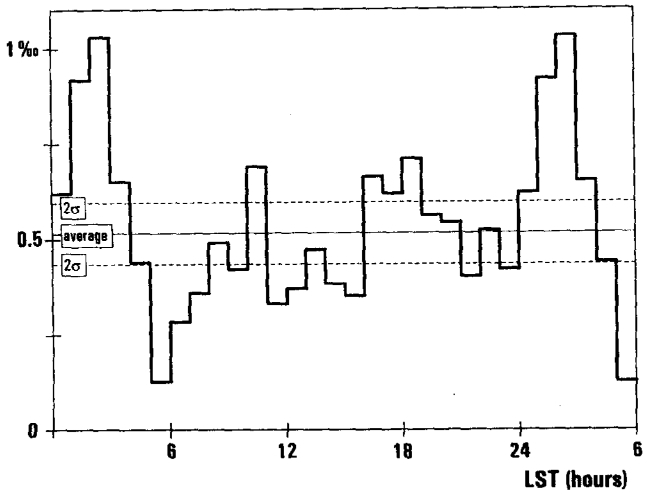

Fig.9. Histogram of sudden density decreases according to LST, normalised as fraction of the total number of observations in every hour interval.

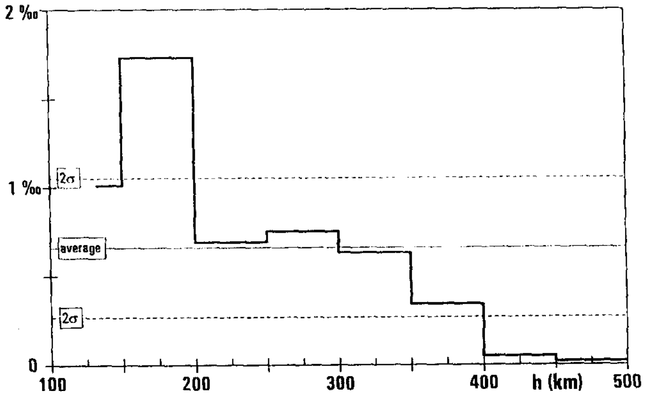

Fig.10. Histogram of sudden density decreases according to height, normalised as fraction of the total number of observations in every height interval.

- the sudden density decrease should be a well isolated, unidirectional deviation, not a wave-like feature on the curve of the density residuals, its amplitude should exceed considerably the neighbouring fluctuations (above ~ 400 km this condition is rarely fulfilled);
- the amplitude of the sudden density decrease should be larger than 1.5% of the density value itself for the sake of its correct identification;
- the time period of the decrease should be shorter than 80 sec.

The search concluded with altogether 248 cases satisfying the above criteria. The decreases in density have a relative amplitude of 2 to 26 % (mean value 4.3 %) and a time duration of 8 to 80 s (mean value 24 s) which corresponds to 60 - 600 km on the satellite's trajectory (mean value 190 km). Some of them appear individually (Fig. 6), but there

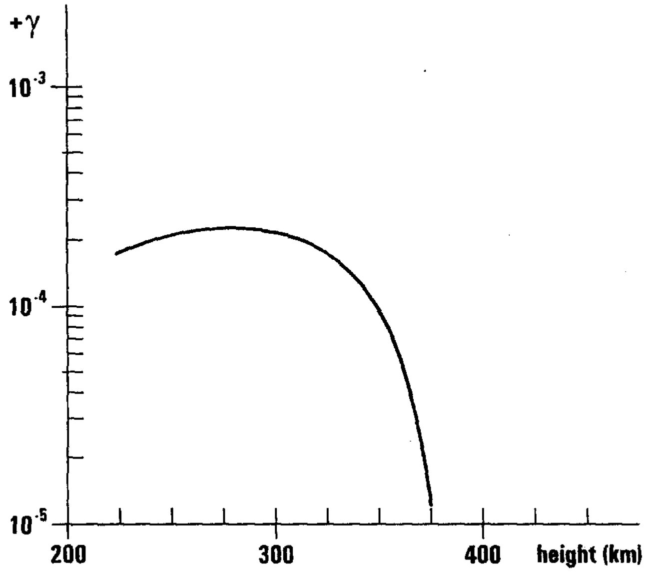

Fig.11. Variation of the growth rate γ of the gravitational Rayleigh -Taylor instability with height. The growth rate γ is indicated on the vertical axis by a logarithmic scale.

are also series of sudden density decreases (Fig. 7). In the latter cases the time interval between successive decreases in the 4 tight series is between 26 and 112 s (mean value 73 s), which corresponds to 202 - 876 km on the satellite's trajectory (mean value 571 km). All series put together, the mean values are 127 s and 970 km respectively.

We have investigated the occurrence frequency distribution of the sudden density decreases in the neutral atmosphere as a function of local solar time (LST). It is evident on the histogram (Fig. 8) that their occurrence frequency is significantly higher at night than at daytime. The occurrence frequency starts to increase at 16 h LST and the excess period lasts until 5 h. The histogram, however, shows two maxima at night, one between 18 and 21 h and the other between 1 and 3 h. Since the number of observations is not quite uniformly distributed in LST, we have normalised the occurrence frequency curve of the density decreases – taking into account the corresponding number of observations in each time interval. The result is plotted on Fig. 9. The two night-time maxima are still visible, although the height of the evening peak decreased somewhat and that of the local maximum at 10 - 11 h increased.

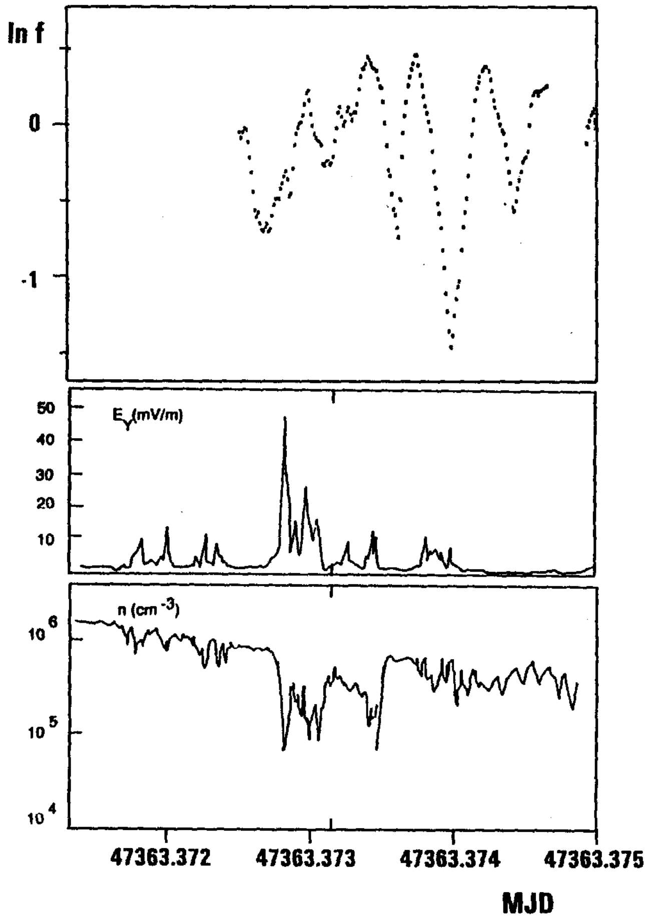

Fig.12. Upper part: variation of neutral density residuals as compared to MSIS'86 model in the time interval corresponding to plasma measurements given in the lower part of this figure. Lower part: variation of the electric field vector and of the plasma density according to Aggson *et al.* (1992) during an exceptional plasma bubble crossing.

The distribution according to height has also been plotted (Fig. 10). Although the number of sudden density decreases is highest between 250 and 300 km, if we take into account the number of observations in general, then the peak of the normalised curve is shifted to 150 - 200 km altitudes. The occurrence frequency is decreasing above and below this altitude. The height distribution of the density decreases agrees also with the height variation of the growth rate of the Rayleigh-Taylor instability γ indicating the degree of probability of plasma bubble formation (Fig.11).

The distribution according to geographic longitude proved to be very asymmetric. There is an outstanding frequency peak between 30° and 60° E, which is very probably connected to an uneven distribution of the observations themselves.

4 Discussion

We considered a working hypothesis according to which these sudden density decreases are phenomena connected to *plasma bubbles in the ionosphere.* An upward drift of ions and electrons due to the Rayleigh-Taylor instability is the cause of plasma depletions or plasma bubbles in the F-region of the equatorial ionosphere. The growth rate of the instability is increasing with increasing vertical gradient scale length, that is why plasma bubbles occur mainly at night when the vertical gradient scale in the lower F-region is the largest. Depletions may appear also in the density of the neutral upper atmosphere due to ion drag. The rising speed of the bubbles is namely much higher than the vertical component of the neutral wind. Therefore perturbations in the form of density decreases may develop also in the neutral atmosphere.

According to the literature the width of the ionospheric plasma bubbles amounts to 40 - 60 km. However the wave number power spectrum of the plasma density indicates spatial scales from more than 100 km to less than 0.1 m (Valladares, 1983). The mean width of neutral density depletions of 190 km is in fairly good agreement with this width of plasma bubbles. (The smaller depletions cannot be recognized due to the limits of resolution.) Multi bubble systems in the equatorial ionosphere were also observed for example by a driftmeter on board of the AE-C satellite (McClure *et al.*, 1977) as well as by rockets (Szuszczewicz *et al.*, 1980, 1981). The mean distance of the bubbles within the bubble systems (200 - 1000 km) agrees relatively well with the mean distance of about 571 (or 970) km found within series of neutral sudden density decreases.

The occurrence of plasma bubbles is explained according to the theory of the gravitational Rayleigh-Taylor instability by the rapid upward motion of the plasma, which is connected with a δExB drift due to an eastward electric field perturbation. This means that the formation of a plasma bubble can be promoted by any type of eastward electric field; i.e. upward plasma drift.

As regards the three maxima appearing in the daily variation of the occurrence frequency of the neutral density decreases (Fig. 9), they are probably connected to the

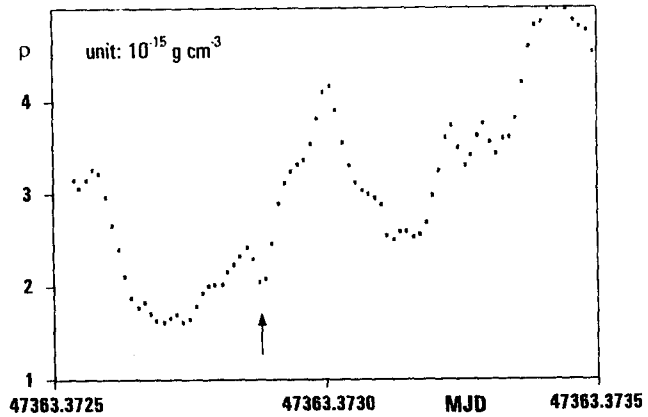

Fig.13. The enlarged part of the sudden neutral density decrease during the plasma bubble crossing published by Aggson *et al.* (1992).

maxima of the upward drift velocity in the daily variation of the F-region vertical drift. The maximum found in the period 18 - 21 h LST might be related to the evening maximum – corresponding to the postsunset enhancement of the eastward electric field (Woodman, 1970; Fejer *et al.*, 1979). The forenoon maximum might be connected to the forenoon enhanced upward drift. The maximum found at about 2 hours coincides with the nighttime maximum of the upward drift velocity, produced by eastward electric fields in the postmidnight period, and generated by the F-region disturbance dynamo (short-term and long-term effects (Fejer *et al.*, 1983, Scherliess and Fejer, 1997)). Consequently the LST distribution of the sudden density decreases can be explained by their connection to plasma bubbles.

5 A case study

There is one special case, however, when our conclusion could be directly verified. Aggson *et al.* in their paper (1992) analysed two cases of exceptional plasma bubbles in the ionosphere. They identified the bubbles by *in situ* satellite measurements of the electric field vector and the plasma density. One of these cases is particularly interesting for us, since the plasma bubble on July 21, 1988 (at 0857UT) at -12° diplatitude in 531 km height was also indicated by the microaccelerometer of the San Marco V satellite the measurements of which formed the data base of our investigations.

In this case the plasma density decreased suddenly from its $6 \cdot 10^{11}$ m^{-3} ambient value to $3 \cdot 10^{10}$ m^{-3}. This means a reduction of the plasma density to 5% of its former value, i.e. a reduction of 95%.

Searching after a counterpart on the neutral density curves an exceptionally large and definite sudden density decrease has been found at the time of the plasma bubble in question (Fig. 12 and 13). The amplitude of this neutral density decrease proved to be 19 %.

Knowing the absolute values of both the plasma and the neutral density – on the basis of the condition $\nabla J = 0$ – first the ion-neutral collision frequency ν_{in} and then from it the decreased neutral density could be calculated. The computations have given an amplitude of the neutral density decrease of 21%. This good correspondence hints also at the plasma bubble origin of the neutral density decreases.

6 Conclusions

As it has been demonstrated above, there are several temporal and spatial changes of the neutral density, which point, on the one hand, to the existence of atmospheric waves of different time scales and, on the other hand, to the effect of plasma bubbles. As regards the wave activity, there is a definite peak at low altitudes. Considering the sudden density decreases, the daily variation of their occurrence and the similarity in different characteristics (e.g. amplitude, width, mutual distances within multi bubble systems) indicate that plasma bubbles might affect the density of the neutral upper-atmosphere.

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