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Variations in Atmospheric Composition and Density during a Geomagnetic Storm

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Abstract. Data from a mass spectrometer, accelerometer and density gauge are examined during a geomagnetic storm to study the atmospheric variations in the region near 160 km. The S3-1 satellite perigee was located between 60°N and 70°N during the geomagnetic storm which reached a peak *Kp* of 7 and included a sustained period with *Kp* between 5 and 6. The density increased by more than 50% above quiet conditions at 160 km and the O/N_2 ratio varied from 1.1 to 0.3 during the storm period. The density increases at lower altitudes are caused by molecular nitrogen. The atomic oxygen exhibits variations during the storm period but these changes do not contribute substantially to the mass density changes. The density of argon exhibits strong variations during a geomagnetic storm, with increases exceeding a factor of 10 at 160 km. Localized heating during the storm produces structure in both the total density and the density profiles of individual species, with the largest variations at highest geomagnetic latitudes. The composition variations, latitudinal structure, and atmospheric response indicate the importance of the thermospheric circulation system developed during geomagnetic storm periods.

1. INTRODUCTION

The large changes which occur in the neutral atmosphere and ionosphere during periods of geomagnetic storms have been recognized for many years. However, it is only recently that *in situ* measurements have begun to provide the basic data which is necessary to study the physical processes involved. The early results on the atmospheric composition variations during a geomagnetic storm [1] have shown that in the region between 150 and 200 km the density of molecular nitrogen increased by a factor of 2, that of argon increased by more than a factor of 4 and that of atomic oxygen changed very little with a tendency to decrease. The OGO 6 data [2], representing storm variations above 400 km, have indicated temperature increases over the polar region of 400–500°K compared with the Jacchia model [3] and exhibit time lags of the order of one hour. The observed OGO 6 density ratio of O/N_2 suggested a dynamical process of vertically upward flow over the polar region. More recently ESRO 4 data have provided considerable insight into the properties associated with geomagnetic storms [4–9]. Processes involved in ionosphere–atmosphere coupling, particle precipitation and the morphology of storms have been described based on data obtained between 250 and

350 km. A major limitation in separating the thermal and dynamic processes associated with the storm periods is that both OGO 6 and ESRO 4 satellites were limited to altitudes considerably above the heating source region.

The low perigee altitude of the S3-1 satellite allows measurements near the primary heating sources associated with energy deposition and Joule heating due to current systems in the lower thermosphere. Some of the results of the storm effects in the composition measurements have been discussed [10]. Here composition and density results during two storm periods will be described.

2. OBSERVATIONS

The several instruments on the S3-1 satellite were intended to measure atmospheric density and composition, ion density and composition and atmospheric heating sources. The results described in this paper include measurements from the mass spectrometer, accelerometer and cold-cathode density gauge. The mass spectrometer is described in [10].

During the period between 8 and 15 November 1974 two geomagnetic storms occurred while the perigee of the satellite was located between 60° and 70°N latitude and at an altitude of 160 km. The first of the storm periods began with a sudden commencement event at 1414 GMT on 8 November while the second storm exhibited a sustained period of moderately high and constant *Kp*. Over the 8 day time period studied here, the 10.7 cm solar flux only varied from 78 to 84 $\times 10^{-22}$ W m^{-2} Hz^{-1}.

Figure 1 shows the variations in mass density at the 160 km perigee altitude during the storm period. The mass densities measured by the mass spectrometer and accelerometer are shown together with the ratios of the mass spectrometer to density gauge densities and mass spectrometer to accelerometer derived densities. The agreement between the three independent measuring techniques is quite good; for example, the average ratio of the mass spectrometer to accelerometer density values for the points included in this data set is 0.98 with a standard deviation of 0.10. The average ratio of the densities measured by mass spectrometer and density gauge is 0.93 ± 0.12. Some of the difference between the density gauge and mass spectrometer values is due to the fact that the mean molecular mass used in the sampling function for the density gauge is taken from a model. Some of the differences between the density measuring techniques on the satellite are described in [11].

Also shown in Fig. 1 is the ratio of the observed Ar/N_2 density ratio at 160 km to the ground-level value. The variation of this ratio from its pre-storm value of 5.5×10^{-2} reflects strongly the storm effects and shows that a large part of the energy deposition is below the 160 km altitude.

Figure 2 displays the changes in observed Ar, N_2 and O densities as ratios to the average values for five quiet-time orbits prior to the storm. The average values used for Ar, N_2 and O are respectively 8.90×10^6 cm^{-3}, 1.28×10^{10} cm^{-3}, and 1.32×10^{10} cm^{-3}. Also shown is the O/N_2 density ratio. The values for atomic oxygen in Fig. 2 have been corrected for the contribution from ambient O_2 by

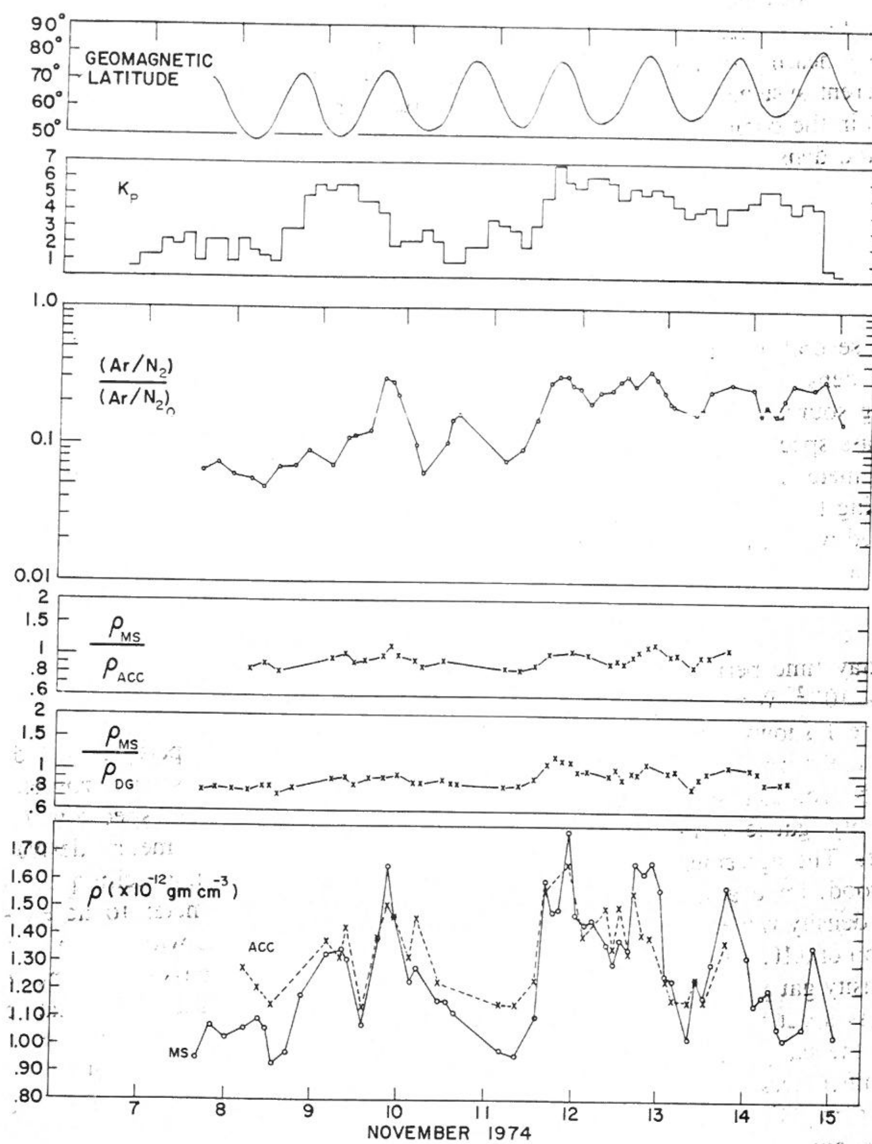

Fig. 1. The mass density measured by the mass spectrometer and accelerometer are shown together with the density ratios of the mass spectrometer to the density gauge and accelerometer. The ratios of observed to ground-level Ar/N_2 densities during the magnetic storm period are displayed. All of the data apply to 160 km altitude.

removing the amount equivalent to $2O_2$. The atomic oxygen density was determined from the relation

$$n_O = n_{(O+2O_2)} - 2\left(\frac{O_2}{N_2}\right)_{\text{model}} \times n_{N_2},$$

where the $(O_2/N_2)_{\text{model}}$ ratio was calculated from the Jacchia 1971 model [3]. The error introduced in atomic oxygen densities in making this assumption about the

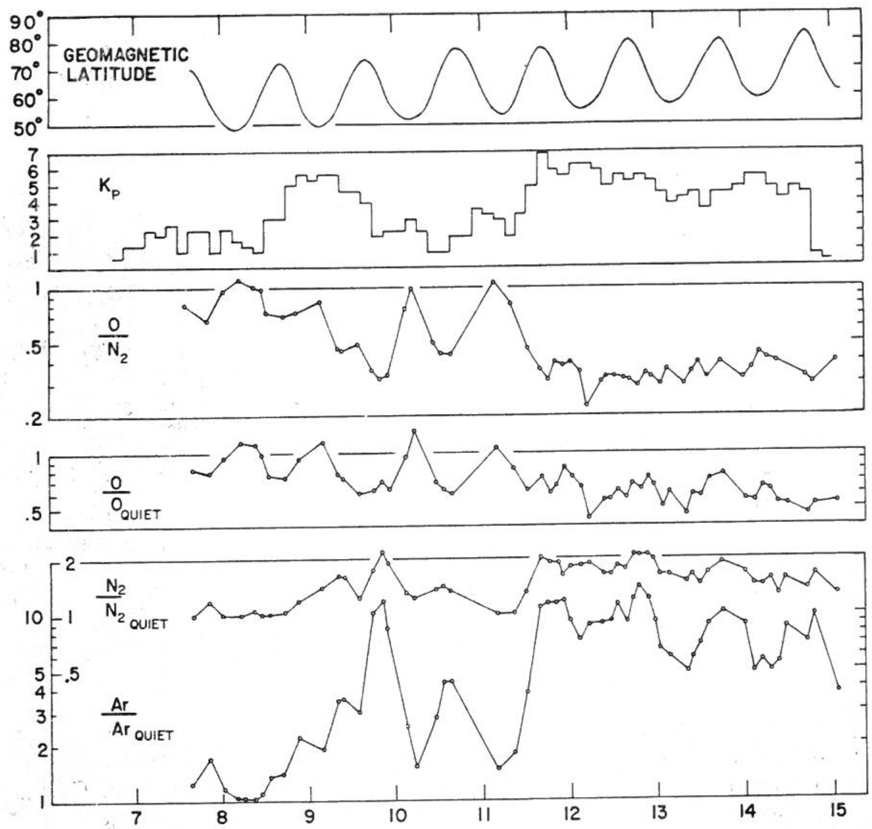

Fig. 2. The ratios of Ar, N_2 and O densities at 160 km altitude, during the same geomagnetic storms (in November 1974) as in Fig. 1, to pre-storm quiet time values. Also shown are the deduced O/N_2 density ratio, Kp, and the geomagnetic latitude at which the observations were made.

behavior of molecular oxygen should be quite small. This assumption does not enter at all into the mass density calculations. The results show that changes of N_2 and Ar densities are consistently in phase with each other and strongly reflect the storm variation. The atomic oxygen density is reduced by a fairly constant 30–40% during the sustained period of high Kp. The density of N_2 is observed to increase by a factor of 2 while that of Ar increases by more than an order of magnitude. The O/N_2 ratio changes from a value near 1.0 to about 0.3 and exhibits a negative correlation with the Ar/Ar_{quiet} ratio. Figures 1 and 2 show the expected strong correlation between the mass density and the N_2 density, which contributes more than 80% of the total mass density at 160 km during the storm. There is also a definite modulation associated with magnetic latitude which implies the largest heating at the higher magnetic latitudes, a point which has also been observed in the ESRO 4 data [6, 8].

One rather interesting feature observed when comparing density measurements with density models such as that of Jacchia 1971 [3] is that there is such generally good agreement, especially considering the wide variation in the densities of the individual species.

3. DISCUSSION

These measurements strongly reflect the heating sources present in the lower thermosphere during geomagnetic storm periods. However, it is not possible to account for the factor of 2 increase in the measured N_2 density with the temperature increases which were inferred at 400 km on OGO 6 [2] or even at 250 km on ESRO 4 [8]. The possible explanations include, among others, an upwelling of the atmosphere by convective flow at high geomagnetic latitudes as part of a thermospheric circulation system and/or significant changes in the thermal structure resulting in different profiles from those generally associated with model temperature profiles.

The relation of the effective homopause height variation to composition changes during disturbed periods proposed by Blum *et al.* [12] and applied by Jacchia *et al.* [8], is found to be in good agreement when comparing Ar and N_2 variations. Should significant circulation processes be present during storm periods, then the assumed diffusive conditions used to arrive at the lower altitude values [8] would not be valid. In addition, the atomic oxygen variations could be influenced by changes in production and loss rates in the lower thermosphere during storm periods.

The magnetic storm model proposed by Mayr and Volland [13, 14] contains the essential features which would apparently give a consistent explanation of these results. However, the magnitudes of the observed variations are larger than those cases treated in the model calculations.

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