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Momentum Source Signatures in Thermospheric Neutral Composition

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Perturbations in the structure of the neutral atmosphere were measured in narrow latitude bands near the dayside polar cusp by mass spectrometers aboard the S3-1 and Esro 4 satellites. The disturbances are characterized by an in-phase variation of both the lighter and the heavier species. They are observed to occur in latitude bands of about 5°-10° extent in the altitude region of 200 km during periods of increased geomagnetic activity. It is suggested that thermospheric winds driven by momentum sources associated with ion convection are the predominant cause for these disturbances. The narrow structure features associated with the momentum source are superimposed on the thermospheric changes caused by Joule heating. Both effects may be present simultaneously, resulting in a complex response pattern of the neutral gas composition in the thermosphere.

It is well known that geomagnetic disturbances cause severe changes in the neutral atmospheric composition [*Taeusch et al.*, 1971; *Trinks et al.*, 1975, 1976; *Wulf-Mathies et al.*, 1975; *Jacchia et al.*, 1976; *Philbrick*, 1976; *Philbrick et al.*, 1977; *Potter et al.*, 1976]. Joule heating and particle precipitation are generally considered to be the most important energy sources within the auroral oval [*Cole*, 1971, 1975; *Hays et al.*, 1973]. The atmospheric response to this energy deposition was calculated by *Mayr and Volland* [1973] and by *Mayr and Hedin* [1977] employing a three-dimensional multicomponent model. These calculations predict increased [N_2] and [Ar] densities accompanied by a decrease in [He] and small changes in [O], in substantial agreement with the measurements.

Perturbations of the neutral atmosphere have been observed by the neutral gas mass spectrometers aboard the S3-1 satellite and the Esro 4 satellite which cannot be explained as a response to the above-mentioned Joule heating or particle precipitation sources. In this paper, we present two examples of the effect which have been observed near 200 km and slightly poleward of the dayside polar cusp. In one case a strong and simultaneous decrease in [$O + 2O_2$], [N_2], and [Ar] was observed. Another event showed a strong decrease in [He] and [$O + 2O_2$], a slight decrease in [N_2], and an increase in [Ar].

In Figure 1 the first example is presented. The ambient number densities obtained by the closed ion source mass spectrometer (MSI) on the S3-1 satellite [*Philbrick*, 1976] are plotted versus time, height, geographic latitude, and geomagnetic latitude for an orbit on November 11, 1974. At the time of the measurement the geomagnetic index *Kp* had decreased slightly to 6− from a value of 7o 6 hours earlier. The Joule heating effects associated with the storm period showing a decrease of $\simeq 30\%$ in [O] with accompanying increases in [N_2] by a factor of $\simeq 2$ and [Ar] by a factor of $\simeq 12$ near the satellite perigee of 160 km have been reported [*Philbrick et al.*, 1977]. Superimposed on this large-scale heating, Figure 1 shows a localized disturbance characterized by a simultaneous decrease in the measured species densities. This same perturbation was also observed in the density measurements of an accelerometer and density gauges aboard the satellite (F. A. Marcos, J. P. McIsaac, and C. Rice, private communications, 1976). The disturbance is limited to a narrow latitude band centered at about 79° geomagnetic latitude. Compared to the smooth profile (dashed lines) obtained by extrapolation from the adjacent latitude regions, the decrease is approximately 45% for [$O + 2O_2$], 55% for [N_2], and 70% for [Ar]. A similar disturbance was observed in this region on the orbits preceding and following the one shown, suggesting that the effect was not a propagating wave.

Another similar effect was observed by the Esro 4 gas analyzer [*Trinks and von Zahn*, 1975] and is presented in Figure 2. During this measurement the magnetosphere was mildly disturbed, $Kp = 3o$, with a preceding 3-hour index of $Kp = 5o$. The structure is again limited to a narrow latitude band. In contrast to Figure 1, this disturbance exhibits an increase in [Ar] of approximately 100%, and the other constituents show a decrease. 20% for [N_2], 50% for [$O + 2O_2$], and 60% for [He]. As in the case of Figure 1, the disturbance was observed for three orbits near the same invariant latitude.

Electric field-induced ion drifts should result in a significant momentum source for the acceleration of the neutral atmosphere at higher latitudes [*Cole*, 1971; *Fedder and Banks*, 1972; *Wu et al.*, 1974; *Richmond and Matsushita*, 1975]. Neutral wind velocities as high as 1 km/s were observed from the low-*G* acceleration calibration system on a polar-orbiting satellite [*DeVries*, 1972] and were, in the first approximation, attributed to $\mathbf{E} \times \mathbf{B}/B^2$ drifts [*Wu et al.*, 1974]. From simultaneous measurements of the neutral/ion mass spectrometer (MSIV) on the S3-1 satellite we are able to infer that the ions were accelerated by an electric field during the period of these measurements. The NO^+/O^+ ratio was near unity at this altitude, near 200 km, and in this latitude region during a preceding period of low *Kp* values. During this disturbed period a

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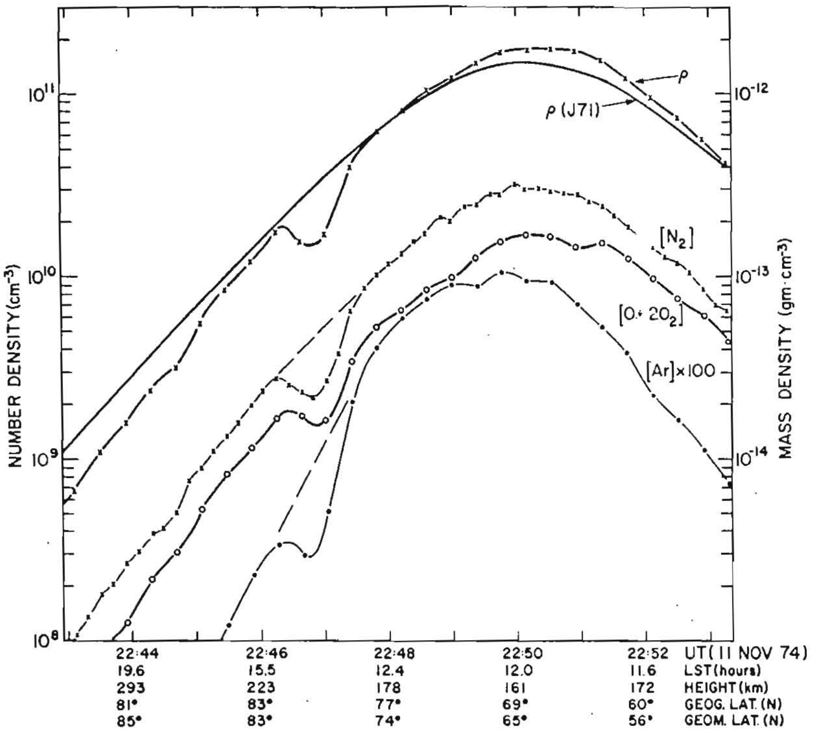

Fig. 1. Ambient number densities from the S3-1 satellite of molecular nitrogen, total oxygen, and argon, and the mass density measured and calculated from the *Jacchia* [1971] model are plotted versus universal time, height, geographic latitude, and geomagnetic latitude. The dashed lines are extended from higher and lower latitude to compare the disturbance centered at 2246:50 UT.

sharp trough is observed in the O$^+$ density over a latitude band which is wider than but centered on the neutral atmospheric structure shown in Figure 1. The NO$^+$/O$^+$ ratio in this trough is about 100 with NO$^+$ densities only slightly different from the undisturbed case. From the studies by *Banks et al.* [1974] and *Schunk et al.* [1975] an effective perpendicular electric field of about 100 mV m^{-1} can be inferred in this region. Electric fields of this magnitude and greater frequently are known to drive polar ionospheric current systems [*Heppner et al.*, 1971; *Cauffman and Gurnett*, 1971].

Composition effects associated with winds driven by ion convection have been estimated in the literature [*Mayr and Volland*, 1974]. In this model, which dealt with local time and longitudinal averages, the momentum source was purely zonal and, as such, divergence-free. However, because of the coriolis force the zonal winds are coupled with the meridional wind component, which was capable of transporting mass and energy. The results showed for the 'mode' P_2^0 a maximum in the temperature amplitude near 130 km which was due to adiabatic heating (or cooling) from the wind field. The density variations of both O and N$_2$ were in phase, qualitatively consistent with the observations presented here. In a recent paper

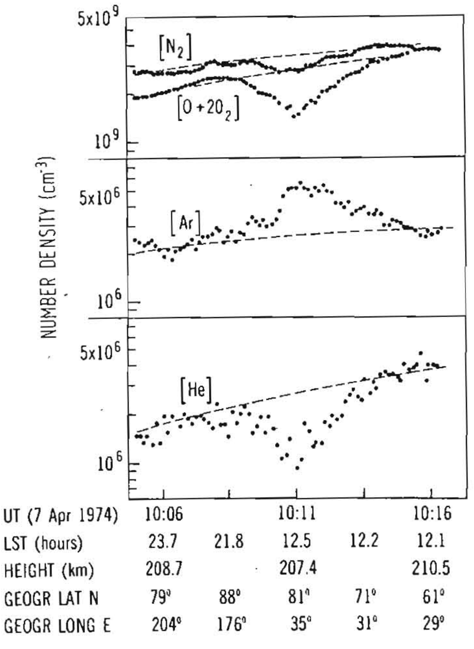

Fig. 2. Ambient number densities of molecular nitrogen, total oxygen, argon, and helium from the Esro 4 gas analyzer versus universal time, height, and geographic coordinates. The disturbance is centered at 1011 UT.

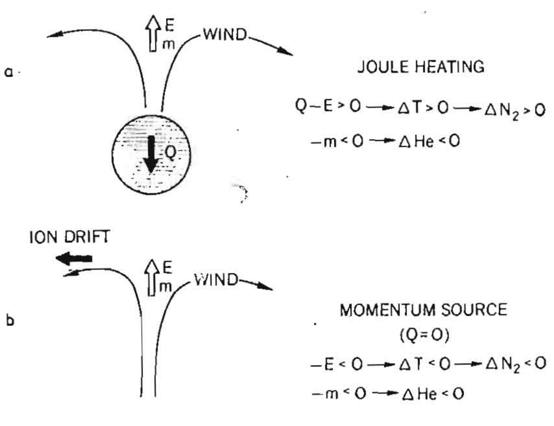

Fig. 3. Diagram illustrating the energy (E) and mass (m) budgets for (a) Joule heating and (b) momentum source. The symbols T, N$_2$, and He refer to disturbances of temperature, N$_2$ concentration, and He concentration.

[*Mayr and Harris,* 1977] these calculations have been extended to include local time variations for the thermospheric densities of He, O, N_2, and Ar at high latitudes, which is more realistic. The conclusions were basically the same and showed that momentum sources (1) affect primarily the temperature near 130 km and (2) produce density variations essentially in phase for all species.

In the presence of electric fields, momentum sources associated with ion drifts are closely related to Joule heating. Both mechanisms depend on the difference between ion and neutral velocities which in turn are driven by electrodynamic and thermodynamic forces. In discussing the data it is useful to envision the characteristics of these processes as they affect the neutral composition. Figure 3 describes the two source characteristics in schematic form: (1) With an energy input due to Joule heating (Q) the temperature and pressure increase, driving a wind system that removes energy (E) and mass (m) (Figure 3*a*). The energy loss is smaller than the initiating source, but it damps the resulting temperature increase. The densities of heavier species such as [N_2] and [Ar] which are strongly controlled by temperature effects thus increase. Mass transport (M) due to wind-induced diffusion redistributes the minor and lighter constituents. Since there is no resupply, except by thermal expansion, which is less important for lighter species, the concentrations of He and O decrease, thus producing an anticorrelation between lighter and heavier species. (2) When the wind system is driven by momentum sources alone (Figure 3*b*), energy and mass are again removed (or supplied, depending on the wind direction). However, the difference with respect to Joule heating is that now there is no input of external energy ($Q = 0$), and as a result the temperature and densities of the heavier species decrease. The lighter and minor species are again depleted by wind-induced diffusion. However, while this process was partially compensated by thermal expansion in the case of Joule heating (or particle precipitation), the temperature effect due to thermal contraction now augments the depletion by wind-induced diffusion. As a result, all species decrease simultaneously, which is consistent with the observations presented here.

In reality, both processes occur simultaneously and interfere with each other. This may account for the [Ar] increase and the weak [N_2] depletions as observed in the Esro 4 data (Figure 2). The momentum source, with its temperature minimum (or maximum) in the lower thermosphere and with density amplitudes decreasing at higher altitudes, should be expected to be more important at lower altitudes. In contrast, Joule dissipation generally produces larger density amplitudes at higher altitudes [*Mayr and Volland,* 1973, 1974]. These properties may account for the fact that momentum source signatures have not been previously observed from satellite measurements at higher altitudes where the effects of Joule heating dominate.

This is supported by our observations: During the entire mission of Esro 4 (about 1.5 years) only one event of the kind discussed above was found (optical inspection of the density plots versus time). It occurred 1 week before the decay of Esro 4 when the perigee altitude had decreased from 250 to 207 km. On the other hand, above 250-km altitude numerous disturbances of the neutral composition within or close to the dayside cusp were observed characterized by an increase in [N_2] and [Ar] and a decrease of [O] and [He] [*Wulf-Mathies et al.,* 1974].

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