Satellite Measurements of High-Altitude Twilight Mg^+ Emission

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Observations made by the ultraviolet spectrometer on board the orbiting geophysical observatory Ogo 4 confirmed the presence of resonance scattering at 2800 Å of Mg^+ ions in the twilight subtropical ionosphere. The column density reached 4×10^9 ions cm^{-2} above 160 km. Photometric measurements by the Esro TD 1 satellite revealed a maximum of the Mg^+ abundance at equinoxes in the top side *F* region. The interhemisphere asymmetries observed in the intensity distribution are essentially attributed to the effect of eastward thermospheric winds. The 2800-Å doublet was also detected by Ogo 4 at middle and high latitudes from 110 to 250 km. The brightness of the emission and other evidence indicate that evaporation of meteoritic matter cannot explain the abundance of ions at 200 km. Therefore Mg^+ ions are probably transported upward from the 100-km permanent source layer.

INTRODUCTION

The existence of a permanent layer of metallic ions, such as Fe^+, Mg^+, Na^+, Ca^+, and Al^+, in the earth's atmosphere has been firmly established by mass spectrometer measurements [cf. *Narcisi,* 1973]. Nevertheless, the only ions optically detected so far in the twilight are Ca^+ and Mg^+. The Ca II doublet at 3934 Å excited by fluorescence in the twilight spectrum was discovered by *Vallance-Jones* [1956] and has since been observed at various latitudes [*Hunten,* 1967]. The emission was very sporadic, but the feature was detectable from May to August and appeared to be related to meteor activity [*Broadfoot,* 1967]. *Anderson and Barth* [1971] observed for the first time the resonance scattering of the Mg II 2800-Å doublet with a rocket-borne ultraviolet spectrometer. The intensity was as high as 360 R, and the Mg^+ emission above 106 km was associated with the occurrence of a mid-latitude sporadic *E* layer. *Hicks et al.* [1972] identified the Mg I line at 5124 Å, arising from the $3p^3P$-$4s^3S$ transition in the nightglow spectrum. They attributed the excitation of the upper state to radiative recombination of magnesium ions.

Metallic ions in the *F* region of the equatorial ionosphere were recently observed by mass spectrometer techniques [*Hanson and Sanatani,* 1971; *Goldberg et al.,* 1974; *Krankowski and Nord,* 1974]. *Boksenberg and Gérard* [1973] reported enhancements of the UV radiation above 540 km in the subtropical regions observed by the Esro TD 1 satellite. Using only comparisons between signals measured in various photometric passbands, they tentatively attributed this enhancement to the resonance scattering of the Mg II λ2800-Å doublet. The UV signal, observed during the sunset equatorial crossings, had a maximum intensity of 500 R. After a systematic search for the Mg II λ2800-Å doublet in the Ogo 4 UV twilight spectra obtained in 1967 and 1968, it was identified in the equatorial dusk ionosphere.

The presence of these ions at great heights can be explained by **E** × **B** vertical drift which lifts ions during the day from a source layer in the lower *E* region [*Hanson et al.,* 1972]. Pronounced asymmetries in the intensity are readily explained by the effect of thermospheric neutral winds dragging the ions in their direction [*Gérard and Monfils,* 1974]. In this paper the observed asymmetries will be used to deduce information about the thermospheric wind pattern in the late afternoon hours. Annual variation of the intensity is also expected, since the vertical drift velocity and its diurnal variation are season dependent, due to the annual change in the pattern of the *E* region wind which drives the dynamo *E* field. The TD 1 data, collected during 1972 and 1973 in two longitude sectors, are described below and show that the Mg II intensity exhibits an annual variation.

Finally, the Ogo 4 spectra also reveal the sporadic presence of the 2800-Å doublet in the twilight at middle and high latitudes. Data obtained during about 9 months of operation were examined to study the altitude and annual distribution of the intensity. The local time distribution and spatial structure of the emission layer will be discussed and compared with mass spectrometer results. The possible mechanisms lifting the ions will also be indicated.

EXPERIMENTS

TD 1 S2/68 Telescope

The S2/68 ultraviolet telescope and the TD 1 satellite orbit have been described by *Boksenberg et al.* [1973]. One of the channels observing a diffuse source in the 2300- to 3200-Å region detected a glow when the satellite was in the equatorial regions. The observations were made zenithward from an altitude of about 540 km. The orbit had an inclination of 98° and was roughly sun synchronous. The satellite always crossed the equator close to the terminator plane (0600 and 1800 local time). An on-board magnetic tape recorder provided complete recovery of the data from March 19, 1972, to June 1972. Due to a tape recorder failure, only real time data were available after this date. However, some longitude sectors were sufficiently covered by low-latitude ground stations to allow the equatorial glow to be observed in these regions from August to October 1972 and from February to October 1973. The satellite tape recorder recovered in October 1973 and functioned properly until the end of the mission (January 25, 1974).

Ogo 4 UV Spectrometer

The University of Colorado Ogo 4 ultraviolet airglow spectrometer and its operation have been described by *Barth and Mackey* [1969]. It consisted of a 250-mm Ebert-Fastie monochromator which scanned the spectral region from 1100 to 3400 Å with 20-Å resolution. The F channel responded from 1750 to 3400 Å, and the G channel detected radiation from 1100 to 1750 Å. The instrument was kept stabilized to the center of the earth with a field of view of 16.8° × 11.9°. Spectral scan speed was either 37 or 9 s, which corresponds to

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a satellite displacement of 2.3° or 0.6°. The Ogo 4 satellite was launched on July 28, 1967, into an orbit inclined by 86° on the equator and precessing about 1.5°/d in local time. The orbit plane nearly coincided with the terminator plane on July 31, 1967, and about 4 months later. The altitude varied from approximately 400 to 900 km. Measurements were made during the entire 18 months of operation, but only data from the first 9 months have been fully processed and will be discussed here. Due to telemetry limitations, data could not be collected for each orbit, and occasionally, several days separate successive measurements.

DATA ANALYSIS

Resonance Scattering

Data processing of the TD 1A observations has been described by *Gérard and Monfils* [1974]. Because the observations were made at nearly constant local time and altitude, data analysis was simplified. Moreover, no atmospheric background subtraction was necessary due to the high altitude of the orbit.

On the other hand, Rayleigh scattering and nitric oxide emission, which dominate the Ogo F channel spectrum for solar zenith angles below 96°, limited the 2800-Å observations. All twilight data for solar zenith angles between 97° and 101° were examined; about 50 cases indicated a feature at 2800 Å. Twilight data were obtained in the subtropical regions only during a few days. During most of the mission, sunrise and sunset occurred at higher latitudes. The altitude of the sunlight

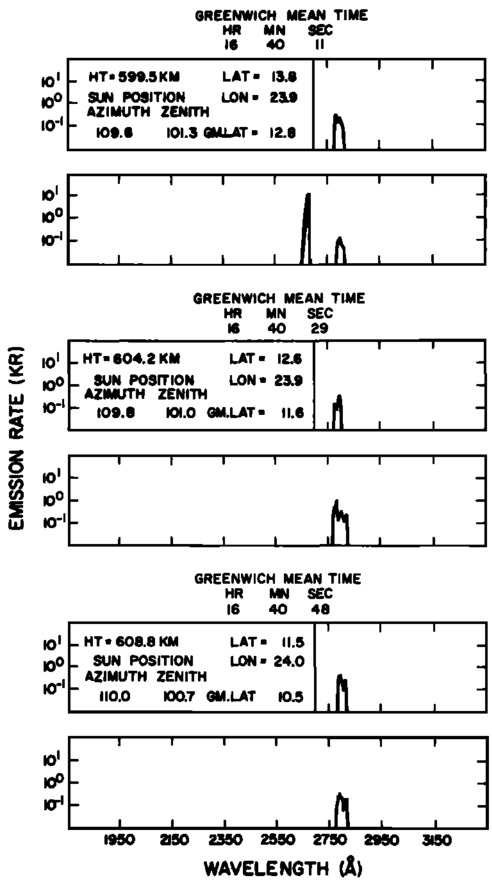

Fig. 1. Six consecutive Ogo 4 twilight spectra showing the presence of the Mg II 2800-Å emission in the equatorial *F* region on November 25, 1967. The other feature on the second frame is due to instrumental noise.

shadow, Z_s, was calculated by using $Z_s = R_e(\sec\theta - 1) + \zeta$, where R_e is the earth radius, θ the solar depression angle, and ζ the screening height due to atmospheric absorption between the sun and the observed layer. The screening height is defined here as the altitude where the transmission function of solar radiation,

$$T = \exp\left(-\sum_i \eta_i \sigma_i\right)$$

equals e^{-1}, where η_i and σ_i are the slant density and absorption cross section of the absorbing species *i*. Ozone was the only atmospheric molecule that absorbed significant radiation at 2800 Å. The O_3 cross section is 4.5×10^{-18} cm² [*Inn and Tanaka*, 1953]. Various vertical ozone distributions were used to calculate $\zeta \simeq 65 \pm 5$ km [*Rawcliffe et al.*, 1963; *Week and Smith*, 1968; *Leovy*, 1969]. Actually, the value of the screening height does not depend critically on the ozone distribution adopted.

The emission rate observed by the satellite at an altitude *S* was converted into column density by using the resonance-scattering formula

$$4\pi I = g \int_{Z_s}^{S} n(\mathrm{Mg}^+)\, dz \qquad (1)$$

where *g* is the emission rate factor, equal to 0.13 ph/ion s [*Anderson and Barth*, 1971]. *Gadsden* [1972] suggested that self-absorption between the sun and the observed layer was large enough to invalidate use of (1). A calculation shows that a unit optical depth is reached for a column density of Mg^+ ions of 8×10^{10} cm^{-2}. Such an amount has never been observed in vertical measurements (with column density of $\simeq 4 \times 10^9$ cm^{-2}) and would hardly be reached horizontally even if the ion layer were uniform. This effect has consequently not been taken into account in the following discussion, and (1) has been used to convert observed brightness into column density.

Spectral Identification

The Ogo 4 UV spectra recorded when the spacecraft was in twilight configuration in the subtropical region have been systematically examined. A feature at 2800 ± 20 Å was observed in this region on 12 occasions and fully confirms the presence of metallic ions at high altitudes in the equatorial ionosphere. Figure 1 gives an example of six successive scans of 9 s each showing the presence of the Mg II doublet observed at a solar zenith angle of about 101°, thus being above 180 km. The intensity ranged between 100 and 500 R, but the emission was not observed on all passes and varied with longitude. All 12 observations occurred in the dusk twilight but never in the morning hours, in agreement with *Gérard and Monfils'* [1974] observations.

Sensitivity and Ion Abundance

The sensitivity of the S2/68 experiment and the contribution of the various noise sources have been discussed in detail in a previous paper [*Gérard and Monfils*, 1974]. In the A_1 channel, in which the Mg II feature was observed, the threshold was about 10 counts per time interval or 50 R, corresponding to a column of $\simeq 4 \times 10^8$ ions cm^{-2}. The highest brightness observed was about 500 R.

The Ogo 4 spectrometer sensitivity threshold was ~100 R at 2800 Å. The accuracy of the calibration is ±50%, and for the relatively weak intensities considered here the statistical error is also about 50%. Consequently, the intensities are accurate within a factor of 2.

Mass spectrometer measurements [*Goldberg et al.*, 1974] have indicated that the postsunset content of Mg^+ in the equatorial ionosphere is of the order of 2.5×10^8 ions cm^{-2} between 160 km (altitude of the shadow height at 2800 Å for a solar zenith angle of 100°) and 500 km. The implications are that such an amount would not normally be detected by Ogo 4 and that an enhancement by a factor of 4 of the Mg^+ column density in the *F* region is necessary to reach the Ogo spectrometer threshold.

The total content of Mg^+ detected by mass spectrometer techniques was about 7×10^9 ions cm^{-2}, whereas *Anderson and Barth*'s [1971] optical observation of a sporadic *E* event yielded a column of 4×10^9 ions cm^{-2}. Both satellite observations indicate that occasionally, a quantity of ions comparable to the 'normal' entire column was present in the *F* region above 160 km in observations by Ogo 4 or in that above 540 km in observations by TD 1.

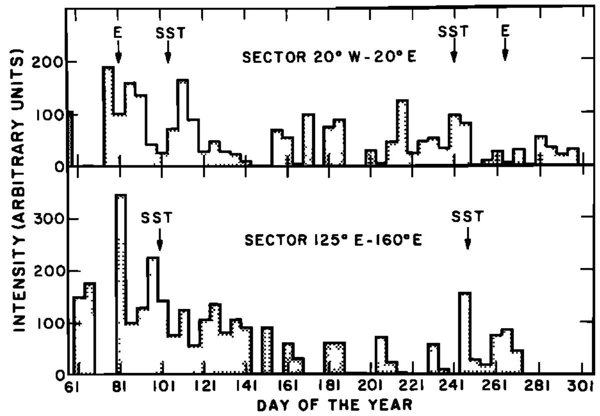

Fig. 2. Annual variation of the Mg^+ column density above 540 km as measured by the TD 1 satellite in 1972 and 1973 in two sectors. Arrows indicate astronomical equinox (E) and subsolar time (SST) (see text).

EQUATORIAL OBSERVATIONS

Annual Variation

The TD 1 data collected in 1972 and 1973 have been used to determine any annual variation of the Mg II intensity. Unfortunately, due to the tape recorder failure, valuable data could only be gathered in two sectors, 20°W–20°E (African zone) and 125°–160°E (Asian zone). Data from about 550 passes in these zones have been used in Figure 2. The intensity was summed in each sector for periods of 5 days and was normalized to the total number of available passes in this 5-day period. Gaps in the plot correspond to periods which had poor coverage. The dates of the astronomical equinox and of local subsolar time have also been indicated for both sectors. The following conclusions can be readily drawn from this figure:

1. A maximum of intensity is observed in both sectors at the time of the vernal astronomical equinox.
2. The presence of a maximum at fall is not clearly established, especially in the African sector.
3. The amplitude of the annual variation is larger in the Asian sector than in the African one.

This annual variation is most likely due to the seasonal effects on the dynamo electric field and vertical drift velocity. *Balsley* [1973] has shown that the diurnal variation of the drift velocity is season dependent and that a postsunset upward drift is generally observed in the equinoctial periods. This drift probably increases the amount of ions observed above the satellite at about 1800 local time.

Wind Effects

The large interhemisphere asymmetries in the intensity of the Mg II airglow described by *Gérard and Monfils* [1970] have been studied statistically. The north-to-south peak intensity ratio of the arcs was calculated as a function of longitude for the period of 1972 when data were fully recovered (Figure 3). This period has been divided: the first period, that before day 111, is close to astronomical equinox, and the solar declination is lower than the latitude of the dip equator in the Asian sector; the second period is closer to solstice, and solar declination is such that the subsolar point is north of the Asian dip equator.

The observed asymmetries in intensity with respect to the dip equator are probably the result of plasma transport due to thermospheric winds parallel to the field lines. Ions are lifted in the hemisphere from which the wind blows, and the amount of scattering ions above the satellite increases [*Rishbeth*, 1972]. The amount decreases for the opposite hemisphere. The wind velocity component parallel to the magnetic field line, $u_{||}$, is obtained by projecting the velocity vector on the local magnetic field line:

$$u_{||} = u_x \cos \delta \cos I + u_y \sin \delta \cos I \qquad (2)$$

where u_x and u_y are the north-south (meridional) and east-west (zonal) wind velocity components, I is the dip angle, and δ is the magnetic declination. Consequently, the intensity distribution in the sector extending from 5° to 110°E is only sensitive to meridional winds, since the magnetic declination is very small in this region. As can be seen in Figure 3, the asymmetries were rather weak in this sector for both periods of time, and statistics may not be significant.

The most conspicuous effect of high-altitude winds is seen in the Atlantic sector (0°–30°W) and to a lesser extent in the Pacific sector (110°E–70°W) and is ascribed to zonal winds. For both periods of time the asymmetries were consistent with the presence of a strong eastward zonal wind which increased the intensity of the southern arc in the Pacific sector and that of the northern arc in the Atlantic sector. The effect was most

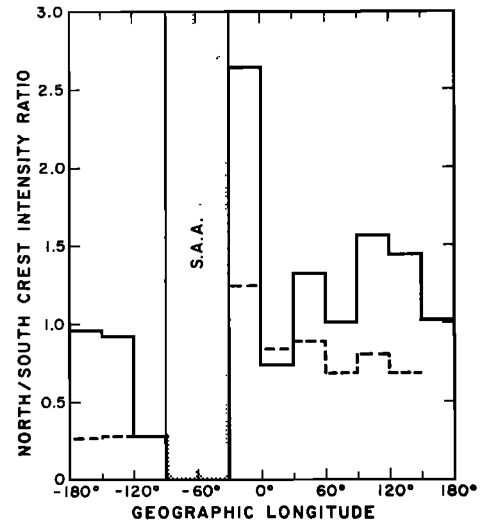

Fig. 3. Asymmetries in the Mg II emission intensity detected by TD 1 in the top side *F* region for two different periods of the year (solid line, days 79–111 of 1972; dotted line, days 112–144 of 1972). No data were obtained in the 30°–90°W sector due to the effect of the South Atlantic anomaly (SAA).

pronounced near equinox in the Atlantic and later in the Pacific. The higher asymmetries observed in the Atlantic sector during equinox conditions might be due to stronger zonal winds resulting from the rising ionization level near the equator after sunset [*Anderson and Roble*, 1974].

Equation (2) shows that the ratio of efficiency of meridional to zonal wind is equal to $tg\delta$, where δ is the magnetic declination. This attenuation factor is 4.7 in the Pacific zone and 2.7 in the Atlantic zone. Consequently, the asymmetries observed in the Mg II high-altitude airglow indicate a strong eastward wind at 1800 local time, with velocity exceeding 5 times that of the meridional wind. This wind would enhance the western arc. This result is consistent with theoretical calculations which indicate that at a given time the zonal wind velocity does not vary significantly with latitude [*Challinor*, 1970]; however, the meridional velocity is zero near the dip equator and increases with latitude [*Reber et al.*, 1973].

MID- AND HIGH-LATITUDE OBSERVATIONS

Intensity and Occurrence

The spectra collected by the Ogo 4 UV spectrometer during the first 9 months of operation were studied to extend the investigation of the presence of Mg^+ ions to middle and high latitudes. More than 50 spectra showed clearly the presence of the 2800-Å doublet at various latitudes and solar zenith angles. The intensity ranged from threshold (~100 R) to 600 R, and the shadow altitude varied from 105 km to as high as 250 km. Most generally, the feature was only observed on a single spectrum (37 s), but occasionally, it was observed on three or four successive spectra. Thus the horizontal extent of the ion layer varied from less than 275 km to 825 km. Figure 4 illustrates the daily intensity of the Mg II dayglow as a function of the day of the year. When sufficient data were available, the intensity was normalized to the overall time of observation of that particular day. Figure 4 also displays the solar zenith angle and altitude of the shadow, the local solar time, and the latitude of the observations. Due to the satellite motion, twilight conditions mostly occurred at high latitudes (Figure 4), and the Mg II doublet was observed from the equator to 86° latitude. The local time of twilight also changed from day to day as an effect of the orbital precession of 1.5°/d. All local times are represented in Figure 4, and there is no evidence of a

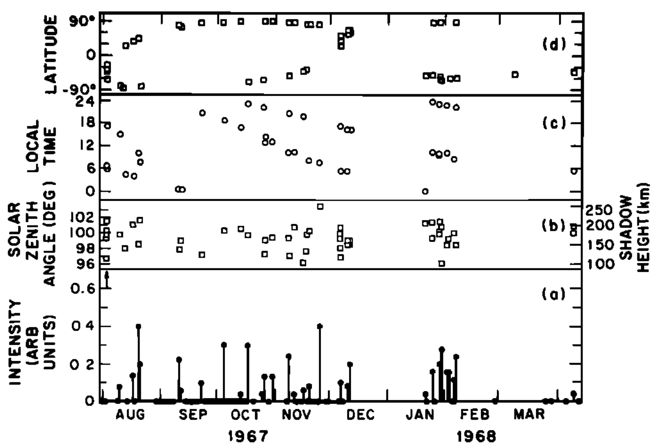

Fig. 4. Mid- and high-latitude Mg II emission detected by Ogo 4. (*a*) Normalized daily intensity of the 2800-Å airglow. (*b*) Solar zenith angle and corresponding shadow height calculated with a screening height of 65 km. (*c*) Local solar time of the observations. (*d*) Latitude of the measurements.

maximum of intensity in the morning hours, as would be expected from the daily variation of meteor precipitation [*McKinley*, 1961]. There is no obvious correlation, as there is in the case of Ca II, between the meteor showers and the observed Mg II intensity above 110 km. *Broadfoot* [1967] found a reasonable correlation between the Ca^+ amount and the intensity of long radar echoes. He also showed that current theories are not able to account quantitatively for the number of Ca^+ ions observed in the high-altitude meteor trails. A similar argument can be developed for the Mg^+ ions discussed here to show that one would expect in this case an intensity about 6 orders of magnitude less than the actual brightness measured by the spectrometer. Consequently, the high intensity of the Mg II layers, the uniform local time distribution, and the latitudinal extent of the glow reported here argue against direct observation of meteor trails.

Recent Russian mass spectrometer measurements at middle (58°) and high latitudes (81°) have shown considerable concentrations of Mg^+ ions as high as 180 km [*Zhlood'ko et al.*, 1974; *Lebedinets et al.*, 1974]. Among eight rocket launches made at various solar depressions, Mg^+ densities of the order of 10^3–10^4 cm^{-3} were observed above 150 km on four occasions. In a twilight measurement the density profile reached 3×10^3 cm^{-3} at the rocket apogee (175 km), but the altitude of maximum concentration was still higher. If Ogo 4 spectra had been taken under such conditions, the Mg II doublet probably would have been detected with an intensity above the instrument threshold. Interestingly, when high concentrations were observed at high altitudes, the *E* region peak near 100 km was absent.

These results indicate that the Mg II airglow detected by Ogo 4 was most likely due to layers or clouds of ions in the *F* and high *E* regions, transported upward from the meteor ablation region either by winds or by electromagnetic forces. Such a mechanism is not operating continuously, and as is true in the case of the equatorial arcs, a good correlation should not be expected with meteor activity. Since the magnetic inclination is large at high latitudes, neither horizontal winds nor $\mathbf{E} \times \mathbf{B}$ drift is likely to lift ions efficiently.

SUMMARY

Optical observations made by two different spacecraft in different observing conditions have been used to investigate the behavior of the Mg^+ ion distribution in the atmosphere. The following points have been deduced:

1. The high-altitude equatorial UV glow observed by TD 1 is caused by resonance scattering of Mg^+ ions at 2796–2803 Å.
2. The number of ions in the equatorial top side *F* region shows a seasonal dependence with a maximum around the vernal equinox.
3. The symmetry about the dip equator is distorted by the effect of thermospheric neutral winds. The asymmetries indicate that eastward winds dominate over meridional winds at sunset.
4. Mid- and high-latitude clouds of Mg^+ have been sporadically detected in the *F* region with a column density as high as 5×10^9 cm^{-2} but show no correlation with the meteor activity. This absence of correlation, the local time distribution, and the high intensity observed indicate that the glow is not due to direct fluorescence of meteor trails. These arguments do not rule out a meteoritic origin of metallic ions in the atmosphere but suggest that these ions are probably lifted by neutral winds or electromagnetic forces.

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