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Satellite Remote Sensing of Atmospheric Meteoric Ions and Neutral Species

Final Report
1 October 2003 to 30 September 2006
Award Number F49620-03-1-0422

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Abstract

Radiances measured with the GOME spectrometer on the ERS-2 satellite are used to derive the total content of the meteoric metal species Mg^+, Mg, Fe^+, and Fe. A retrieval algorithm has been developed and applied to determine the species content on a global scale for the year 1996. Results show total content for all the species has a maximum in late summer in both the northern and southern hemispheres. The content of neutrals relative to ions decreases in summer and the same ratio increases in winter. The content of Fe^+ is approximately equal to that of Fe. In contrast the Mg^+ content is twice that of Mg. The Fe content is five to ten times that of the Mg content. An examination of the content around the times of known meteor showers shows no measurable increases during or following the showers.

Introduction

An estimated 37×10^6 kg of interplanetary material from a variety of sources, including debris from asteroids and comets, is deposited in the Earth's atmosphere each year (Peucker-Ehrenbrink, 1996). A great deal of this incoming meteoric material is ablated in the 70 to 150 km altitude region. The resulting metal ions and neutrals are deposited in the mesosphere and lower thermosphere as first detected by ground-based sodium observations (Slipher, 1929, Cabannes and Duffy, 1938) and rocket-borne ion mass spectrometer measurements (Johnson and Meadows, 1955; Istomin and Pokhunkov, 1963; Narcisi and Bailey, 1965; Narcisi, 1968; Aikin and Goldberg, 1973). Lidar observations have added seasonal metal measurements at fixed locations (Gerding et al, 2000; Raizada and Tepley, 2003). Ionization, chemical and ion-molecule reactions occur resulting in modifications of the ablation induced distributions of the metal species, creating metal ions, and metal compounds principally in the mesosphere.

Solar irradiance in the 240 to 800 nm spectral region excites resonance radiation from transitions involving metal atoms and ions, which are components of the mesosphere and thermosphere. This radiation is part of the observed terrestrial radiance, which is composed primarily of solar radiation scattered by atmospheric molecules. Satellite-based spectrometers looking in the limb direction have detected Mg, Mg^+, and Fe^+ in the thermosphere (Gérard and Monfils, 1974; Gérard and Monfils, 1978; Mende et al, 1985; Gardner et al, 1995; Dymond et al, 2003). Since most of the metal content is below 100 km the thermospheric measurements only give a picture of the component transported from the mesosphere. The entire Mg+ content was measured using the SBUV instrument on the Nimbus satellite (Joiner and Aikin, 1996). This paper outlines a year's global observations of the total Mg^+ content. However, this represents only one species of ion and measurements were confined to one day per month. More extensive measurements of several species over an extended period of time are required to give a true picture of the metal behavior. The GOME instrument on the European ERS-2 affords this opportunity.

The 240 to 300 nm spectral region is unaffected by the presence of clouds and surface features resulting in a more uniform radiance than the radiance at longer wavelengths. This gives the 240 to 300 nm region an advantage as a spectral interval to utilize for suborbital object detection. It is therefore important to understand the origin and natural variation of spectral features in the 240 to 300 nm region. Many metals such as Na, Ca, K, and Fe have strong transitions in the 300 to 800 nm region. Analysis of GOME data from this spectral region will better define the relative abundance of meteoric metals in the atmosphere and the important chemistry for different species.

The GOME Instrument

The GOME instrument is located on the ERS-2 satellite, which was launched on 21 April 1995. The satellite has a 10:30 AM local time equatorial crossing. The spacecraft is moving at 7 km/s in a retrograde sun-synchronous, near-polar orbit at a height of 795 km, with a total of 14 orbits per day. The GOME instrument is a double monochrometer operating in the spectral range 237 to 793 nm. The instrument combines a predisperser prism and a holographic grating in each of four optical channels as dispersing elements. Photons are detected with four linear Reticon silicon diode arrays with 1024 spectral elements each. Spectra are recorded at all wavelengths simultaneously. The spectral ranges of each channel, spectral resolution, integration time and effective area covered are summarized in Table I. Channel 1A (237-307 nm, after June 1998 237-283 nm) ground coverage extends to that of ground pixels numbered 1 to 8 corresponding to 12 second integration time.

Table I
Important Parameters of the GOME Instrument

Channel	Wavelength	Resolution	Integration time	Area
	nm	nm	seconds	Km x Km
1A	237-283	0.2	12	100x960
1B	283-316	0.2	1.5	40x20
2	311-405	0.17	1.5	40x20
3	405-611	0.29	1.5	40x20
4	595-793	0.33	1.5	40x20

Previous measurements of metals using resonance radiation observations have utilized solar ultraviolet flux measurements from separate instruments mostly at times well removed from the metal measurements. The GOME instrument measured the solar flux once per day allowing for the inclusion of any short term variation in the solar flux. In the 240 to 300 nm range changes occur with different time scales and cycles, including 13 days, 27 day and the 11 year solar cycle.

Data Analysis

For the GOME instrument, which looks in the nadir direction, the observed radiance, I_{OBS}, in the wavelength interval of the spectral line is the sum of the backscattered component, I_B, the contribution from rotational-Raman scattering, I_{RRS}, and scattering from a metal constituent, I_M, such as Mg or Mg^+. The backscattered component is determined by Rayleigh scattering, and absorption by molecular oxygen, and ozone. Fluorescence from the bands of N_2, O_2, and NO is also present at selective wavelengths. The observed intensity, I_{OBS}, is the sum of the contributions from the backscattered component, I_b, the rotational-Raman scattering component, I_{RRS}, and the metal atom and ion resonant scattering component, I_M so that

$$I_{OBS} = I_M + I_B + I_{RRS}$$

The intensity of a metal resonant line is given by

$$4\pi I_M = \gamma_{J,J''} \int_0^\infty n dz$$

Where γ is

$$\gamma_{J,J''} = \frac{\pi e^2}{mc^2} \frac{A_{J,J''}}{\sum_{J''} A_{J,J''}} \sum_{J''} n_{J''} \pi F(\lambda) \lambda^2 f$$

Here e, m, and c represent the electron charge, electron mass, and the velocity of light respectively. The solar flux is F with wavelength λ. The concentration of the metal species is n.

The relative level populations of atoms participating in a transition is given by

$$\frac{n_i}{n_T} = \frac{g_i}{g_0} \exp\left(\frac{-E_i}{kT}\right)$$

Here n_T is the total initial state population, and g_0 is the total partition function

$$g_0 = \sum_i g_i \exp\left(\frac{-E_i}{kT}\right)$$

The degeneracy g = 2J+1 where J is quantum number for the initial state. The energy E_i is the energy of the initial state for the transition.

The oscillator strength is f and A is the transition probability. Both of these quantities are found at the NIST web site. Details are described by Kellhner et al., (1999). In display of data and calculation of column amounts the ratio of the radiance to the solar irradiance is used.

Line Identification in the 237 to 300 nm Region

The I/F curve shown in Figure 1 indicates the position and relative strength of lines that are above the level of the solar backscattered signal. The 237 to 300 nm wavelength range is dominated by iron lines both neutral and singly ionized. Many of

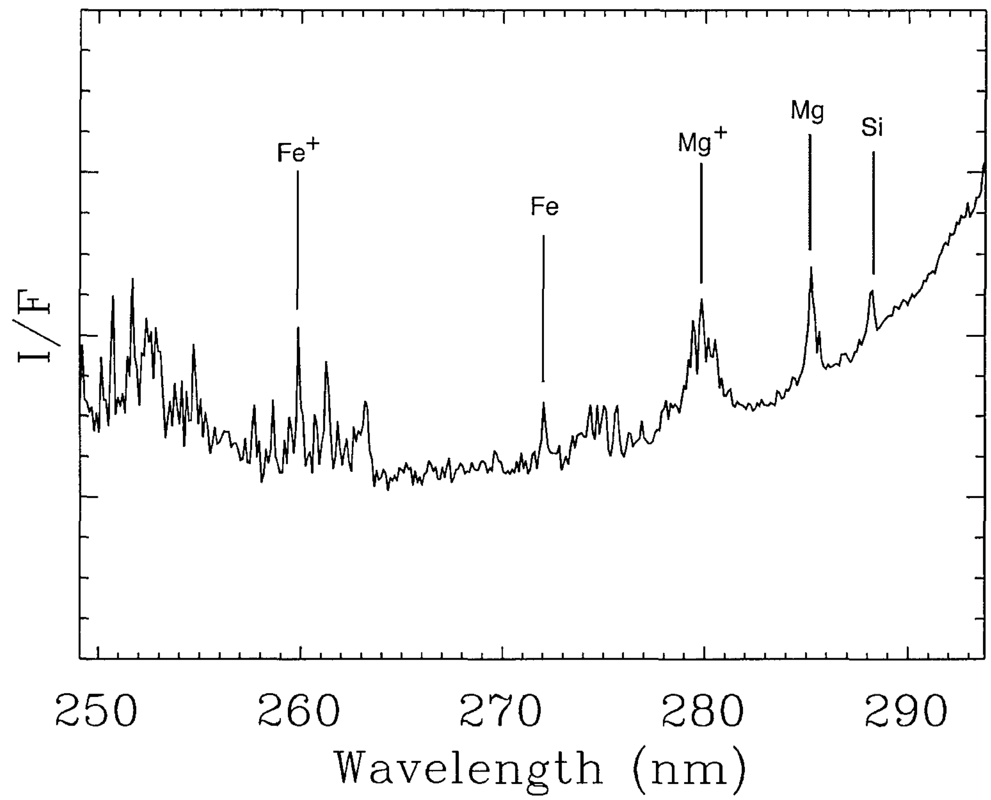

Figure 1 Ratio of the radiance, I, to the irradiance, F, for a sample spectrum. Line identifications are indicated for Fe, Fe^+, Mg, Mg^+ and a feature at 288.15, which may be Si or Na^+.

these iron lines are too weak to be used. The Fe^+ line at 259.94 nm and the Fe line at 271.9 nm have sufficient strength and are free from interference to be used for content determination. Mg ion doublet at 280.27 and 279.55 nm is also prominent. A neutral Mg line is present at 285.21 nm.

A prominent line appears at 288.15 nm. This has been identified Si, 288.158 nm or Na^+, 288.115 nm. Both of these lines have comparable f values, 0.141 and 0.104 respectively and comparable intensities as shown in the NIST atomic line web site (Kellhner et al., 1999). Both of these lines are within the 0.2 nm instrument resolution. Since both of the transitions involved in the respective lines involve excited states, no estimate has been made of the atmospheric excited state populations for these transitions. More Na^+ than Si is expected in the mesosphere. Silicon combines rapidly with oxygen to form SiO. As a result the amount of Si is expected to be small.

Results

Seasonal Variations

A full year of data on a global scale between ±90° latitude and including all longitudes was reduced for 1996. This yielded a total of 828,000 useable content measurements for the species Mg^+, Mg, Fe^+, and Fe. This report will deal with variations between ±60°. The year 1996 was chosen because it represents a full year of data for a period where the instrument has been fully characterized and any instrument deterioration is at a minimum. Solar sunspot activity is also at a minimum in 1996. Data during this period provide a base for the study of the effect of solar activity.

Figure 2 presents the temporal and latitudinal variation of column densities for species Mg^+, Mg, Fe^+, and Fe. The heavy arrows at the bottom of Figure 2 represent the approximate times of major meteor showers. The data are smoothed with a 500 point medium window, representing about 4 hours. In this way trends can be determined. The latitude range is ± 60°. All longitudes are averaged into the data curves. Each panel encompasses 10° in latitude.

The ions Mg^+ and Fe^+ exhibit a maximum in late summer in their respective hemispheres, August in the northern hemisphere and January in the southern hemisphere. A local summer ion maximum is to be expected on the basis of the fact that the background ionization of the D and E regions maximize in summer. Charge exchange between ambient ions such as NO^+ produces Mg^+ and Fe^+ by the process

$$XY^+ + Mg, Fe \rightarrow Mg^+, Fe^+ + XY$$

Direct photoionization by

$$Mg, Fe + h\nu \rightarrow Mg^+, Fe^+ + e$$

can also occur. This process maximizes in summer when the solar zenith angle is minimal. These processes must be the chief causes of the summer maximum. A correlation analysis was carried out between Mg^+ and Fe^+ and the international reference ionosphere electron densities throughout the lower ionosphere (Bilitza, 2001). A correlation of ~ 0.93 was found. At 40° to 50° S the annual variation is 75% for Mg^+. At the corresponding northern latitude range the annual variation is 64%. The equatorial zone shows smaller variations for Mg^+, 20%. These variations are in line with the seasonal changes in solar zenith angle, which determines the amount of solar Lyman alpha and x-rays that ionize the lower ionosphere. The variation of Fe^+ at 40° to 50° S is smaller that the corresponding Mg^+ change, 20%. The corresponding changes at the equator are smaller than at 40° to 50° in line with solar zenith angle changes.

The neutrals Mg and Fe exhibit nearly identical seasonal variation to their ions, but the magnitude of the seasonal variation is smaller for the neutrals than the ions. The Mg seasonal variation at 40 to 50° S is only 28%. The corresponding Fe variation is about the same. At the equator both the Mg and Fe have a summer maximum. The Fe data are consistent with lidar data at Arecibo Observatory, 18.35° N, which also has a summer maximum (Raizada and Tepley, 2003). At 40° N lidar results at night show a winter maximum (Kane and Gardner, 1993) in contrast to the present results, which are daylight measurements.

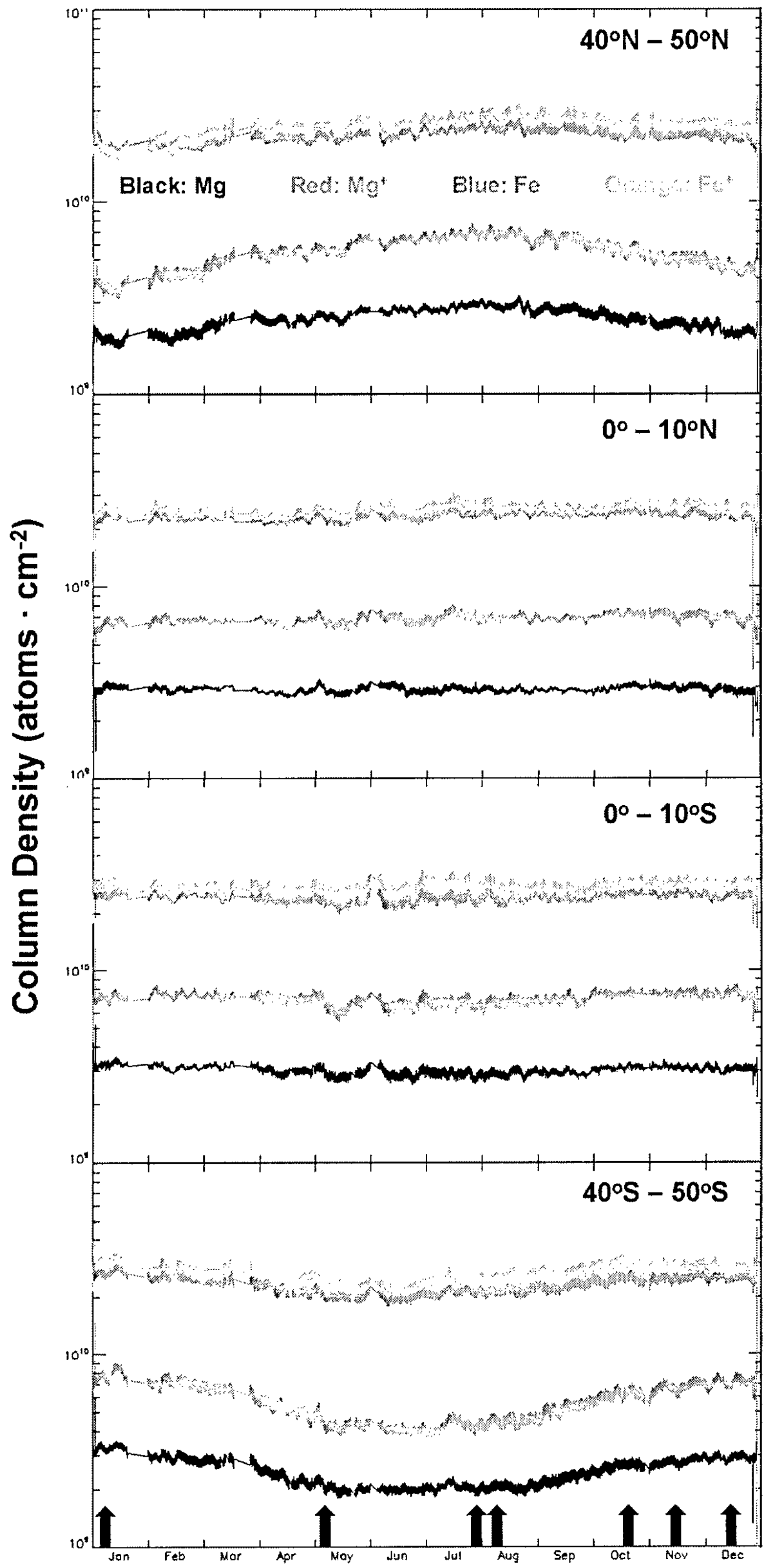

Figure 2. Medium value of the species Mg^+, Mg, Fe, and Fe^+ plotted as a function of time for the year 1996. The latitude intervals 0° to 10° N, 0° to 10° S, 40° to 50° N and 40° to 50° S.

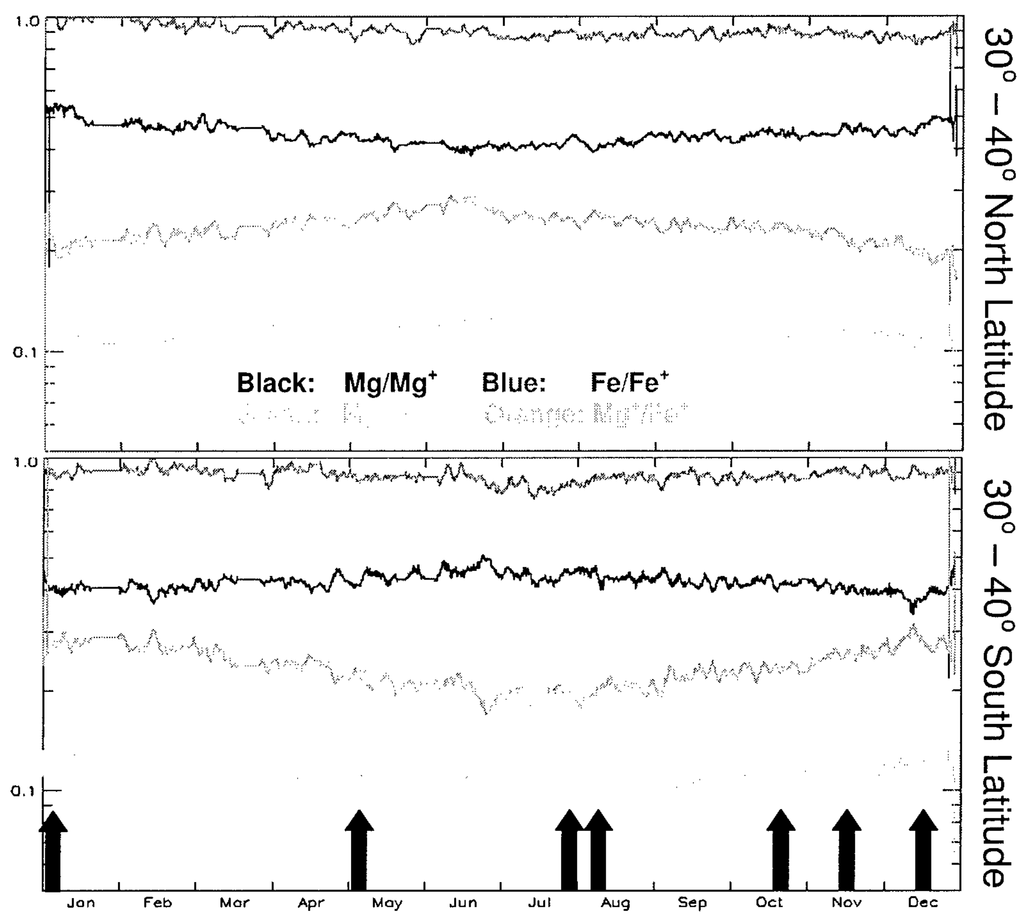

Figure 3. The ratio of the iron and magnesium ions and neutrals. The positions of prominent showers are indicated by arrows.

Figure 3 presents the ratios of Mg^+, Fe^+, Mg, and Fe. The curves of the ratios are color coded, where orange represents Mg^+/Fe^+, black is Mg/Mg^+, blue is Fe/Fe^+, and green is Mg/Fe. In general the content of Fe is approximately equal to that of Fe^+. The neutral Mg is approximately 0.5 Mg^+. The content of Fe is 5 to 10 times that of Mg. This last result may be the result of differential ablation.

The Effect of Sporadic Meteors and Meteor Streams on the Total Content

There has been considerable interest in the direct observable effects of meteors on the atmospheric metal content (Grebowsky et al., 1998; Höffner and Friedman, 2004). In a study centered on November, 1996 the effect of the Leonid shower on the metal content of Mg^+, Mg, Fe^+ and Fe was studied. It was concluded that the Leonids shower did not increase the metal content during the immediate shower period. Additional showers were examined including the Perseids. The iron and magnesium species show no measurable changes attributable to these showers. This is illustrated in Figures 2 and 3 where the arrows indicate the times of meteor showers. There are no measurable increases associated with the showers, either at the shower commencement or following the shower event.

It has been noted that the iron and magnesium species have a maximum in late summer. The metals Ca, Fe, Na, and K also exhibit summer maxima. However, in some instances this is restricted to altitudes above 100 km (Höffner and Friedman, 2004). It is suggested by these authors that the cause of this summer increase is the increase in the summer sporadic meteor flux during this time period.

Conclusions

The development and orbiting of high resolution spectrometers to measure terrestrial atmospheric radiance makes it possible to measure the resonant emissions from meteoric metal ion and neutral species. An algorithm has been developed for the reduction of nadir data and applied to data from the GOME spectrometer on ERS-2, which was launched in April 1995. Data from the entire year of 1996 has been processed to yield total atmospheric content for the species Mg, Mg^+, Fe, and Fe^+. These data allow the seasonal variations of the content of these species to be derived. There is a summer maximum in the content of all species both for the northern and southern hemispheres. There is less variation near the equator than at 40° to 50° north and south. The annual variation of the metal content is well correlated with the seasonal variation of the lower ionosphere. There is no measurable increase in global metal content during or following common meteor shower events.

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Educational Support

The data and analysis of this report have been utilized to support a doctoral student in physics at the Catholic University of America. Dr. Aikin the principal investigator of this grant has acted as an advisor to a doctoral student in physics at the University of Bremen in Bremen, Germany. This project utilizes data from the SCIAMACHY instrument on the ERS-3 satellite. This project is also measuring metals using limb observations to obtain altitude profiles of Mg and Mg^+.

Publications and Presentations

Publications

Aikin, A. C., J. M. Grebowsky, J. P. Burrows, J. Correira, and W. D. Pesnell, Temporal evolution of the vertical content of metallic ion and neutral species, *J. A. S. T. P.* **67**, 1238-1244, 2005

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