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The Relative Abundance

of Neon and Magnesium

in the Solar Corona

by

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January 1976

SUIPR Report No. 650
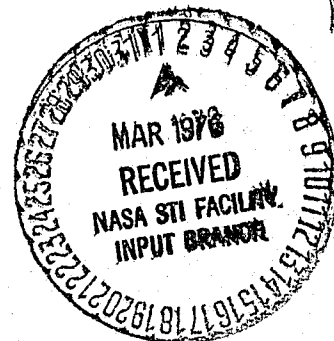
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ABSTRACT

A technique is proposed for specifically determining the relative solar coronal abundance of neon and magnesium. The relative abundance is calculated directly from the relative intensity of the resonance lines of Ne X (12.134Å) and Mg XI (9.169Å) without the need for the development of a detailed model of the thermal structure of the corona. Moderate resolution Bragg crystal spectrometer results from the OVI-10 satellite are used to determine a coronal neon to magnesium relative abundance of 1.47 ± 0.38. The application of this technique to a recent higher resolution rocket observation gives an abundance ratio of $\simeq$ 0.93 ± 0.15.

I. INTRODUCTION

Solar abundances determined from the analysis of chromospheric
line intensities are subject to uncertainties owing to the particular
atmospheric models and the values of the atomic rate constants used.
In addition, they are incomplete since the chromospheric spectrum
contains no lines from the important noble gasses. Published compi-
lations of solar system abundances are frequently strongly weighted
by meteoric data for the nonvolatile elements (Urey, 1972; Cameron,
1974). Recent determinations of solar abundances using other techniques
such as the analysis of permitted coronal lines (Pottasch, 1967; Walker,
1975), the solar wind (Bame, Ashbridge, Hundhausen and Montgomery,
1970) and solar cosmic rays (Bertsch, Fichtel and Reames, 1972;
Crawford, Price, Cartwright and Sullivan, 1975) have confirmed the
general abundance models derived from chromospheric and meteoric
studies, but have raised questions about the abundances of specific
elements, in particular neon, argon and oxygen.

In the present paper, we use an approach developed by Walker (1972)
which specifically allows the relative abundance of neon and magnesium
to be calculated directly from the relative intensity of the resonance
lines of Ne X (12.134Å) and Mg XI (9.169Å) without the development of
a detailed model of the thermal structure of the corona. The intensity
ratio of these lines is not sensitive to temperature over the temperature
range where these active region lines are efficiently excited. The
close proximity of the two lines in wavelength also minimizes the error
introduced by uncertainties in spectrometer calibration curves.

The most comprehensive set of observations, obtained on the OVI-10 satellite, are only of moderate spectral resolution, so that it is necessary to correct the neon and magnesium line intensities for line blends in order to carry out the analysis. However, even with these limitations, the present analysis has allowed us to establish the Ne/Mg abundance ratio to ±30%. The technique has also been applied to high resolution data obtained by Parkinson (1975). The Ne/Mg abundance ratios recently quoted in the literature have varied by a factor of 4. While the abundance of magnesium relative to silicon (which has been used as a standard by the workers studying meteoric abundances) is subject to some uncertainty, the variation in the most recently published work is relatively small, so that the improved Ne/Mg ratios derived in the present paper can be converted to an absolute neon abundance reasonably unambiguously.

II. THEORY

The relative flux of the Ne X and Mg XI resonance lines can be written (Walker, Rugge and Weiss, 1974a),

$$R = \frac{F(Ne)}{F(Mg)} = \frac{\lambda_{Mg}}{\lambda_{Ne}} \frac{A_{Ne}}{A_{Mg}} \frac{\int dT_e M(T_e) a_{Ne\ X}(T_e) J_{Ne\ X\ 1s^2-1s2p}(T_e)}{\int dT_e M(T_e) a_{Mg\ XI}(T_e) J_{Mg\ XI\ 1s^2-1s2p}(T_e)} \qquad (1)$$

where F is in units of ergs cm^{-2} sec^{-1}, A_Z is the abundance of element Z with respect to hydrogen, and $a_{Zz}(T_e)$ is the fractional population of ion z of element Z. The function $J(T_e)$ depends only on atomic rate constants and is, to first order, simply equal to the collisional excitation rate. We have calculated the emission functions $a_{Zz}(T_e)J_{Zz}(T_e)$ (Walker, 1972; Walker and McKenzie, 1975) including all relevant collisional and radiative and dielectronic recombination processes and cascades up to levels with $n = 6$. Earlier calculations of these emission functions carried out by Tucker and Koren (1971) agree with our latest calculations to within $\simeq 10\%$ when normalized to the same abundances. For the simple, highly charged ions of interest here, the theoretical excitation rates, often a serious source of error in this type of analysis, should be accurate to $\pm 20\%$ or better.

The results of our calculations are presented in Figure 1, from which it can be seen that the ratio I_{Ne}/I_{Mg} is approximately independent of temperature for 3×10^6 $^oK \leq T \leq 9.5 \times 10^6$ ^oK. The emission functions for the Ne X and Mg XI resonance lines have their maxima well within the temperature range where the ratio remains approximately constant. Thus, relative abundances calculated from the observed line intensity ratios, using equation (1), will depend only weakly on the shape assumed for the emission measure function.

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For the lines under consideration here, the relatively complicated active region emission measure function found by Walker, Rugge and Weiss (1974a,b) reduces to the form proposed by Chambe (1971) and used by Batstone et al. (1970) and Acton et al. (1972) to characterize active regions;

$$M(T) = C \ 10^{-T/T_1} \quad .$$
(2)

Walker, Rugge and Weiss found $T_1 = 3.5 \times 10^6 \ ^{\circ}K$ and $T_1 = 4.0 \times 10^6 \ ^{\circ}K$, Batstone et al. found $T_1 \sim 7 \times 10^6 \ ^{\circ}K$ and Acton et al., using lower energy lines, found $T_1 \sim 3.2 \times 10^6 \ ^{\circ}K$ for a large active region of the type most commonly observed by the OVI-10 satellite. We have evaluated equation (1) using the differential emission measure functional form given in equation (2) for a number of values of T_1. The results are given in Table 1. In the region which best characterizes the OVI-10 active regions, $T_1 \geq 3 \times 10^6 \ ^{\circ}K$, the variation in R derived from equations (1) and (2) is but a few percent. We conclude that variations in active region structure should result in an uncertainty of $\leq \pm 5\%$ in the relative Ne/Mg abundance derived from the Ne X and Mg XI line ratio.

TABLE 1

Dependence of the Ne X/Mg XI Intensity Ratio (R) on Active Region
Emission-Measure[*]

T_1 $(10^6 \ {}^{\circ}K)$	R	T_1 $(10^6 \ {}^{\circ}K)$	R	T_1 $(10^6 \ {}^{\circ}K)$	R
1.5	0.9	2.5	1.06	4.0	1.10
2.0	1.01	3.0	1.10	∞	1.10

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[*]A Ne/Mg abundance ratio of 1.8 has been assumed. The value of R
scales directly with the abundance ratio.

III. RESONANCE LINE OBSERVATIONS

The accuracy of the technique described in Section II is improved
if a reasonably large body of observations can be used to establish
the intensity ratio of the Ne X and Mg XI resonance lines, since the
minor effects of variations in the emission measure function will be
averaged out. The largest body of well calibrated observations with
sufficient resolution appears to be the observations obtained with the
KAP Bragg crystal spectrometer on board the OVI-10 satellite (Rugge
and Walker, 1968). The calibration of the OVI-10 spectrometer and the
procedure used to correct the observations for scattered light and to
subtract the x-ray continuum and background from lines is described
in detail by Walker, Rugge and Weiss (1974b). However, the moderate
resolution of the spectrometer results in the blending of closely
spaced lines and, when several strong localized sources are visible
on the solar disk, in confusion owing to the overlapping of the spectra
from each source. Because of this latter difficulty, only scans in
which the solar x-ray spectrum was dominated by a single active region
were used in the analysis. As a result of this weeding process, 14
orbits of data, obtained between December 1966 and April 1967, were
selected for analysis.

The Mg XI resonance line at 9.169Å is not clearly resolved from
the intercombination line $1s^2 \, {}^1S - 1s2s \, {}^3P$, and from the close dielectronic
satellite lines in the OVI-10 spectra. To overcome this difficulty we
have chosen to integrate the total number of counts above background
between 9.165 and 9.320Å, thereby including the intensities of the
resonance, intercombination, and forbidden lines of Mg XI, as well as

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all of the nearby satellite lines of Mg X. This total intensity is then corrected to yield the resonance line intensity in the following way. Parkinson's (1972) Mg XI spectrum is used to determine the relative contribution of the Mg XI lines in the wavelength interval directly. His measurements of the intensity of these He-like lines is in good agreement with recent theory (Gabriel, 1972; Bhalla, Gabriel and Presnyakov, 1974) and other observations of He-like lines (e.g., Rugge and Walker, 1971; Acton et al., 1972). The relative intensities of all the satellite lines in the wavelength interval for the OVI-10 data are calculated from the relative intensities of these lines observed by Parkinson, corrected for a temperature difference using the Bhalla et al. theory. The somewhat lower effective temperatures obtained from the OVI-10 data compared to the Parkinson data $(3.2 \times 10^6 \,^\circ K$ to $4.0 \times 10^6 \,^\circ K$, respectively) raise the satellite line fractional contribution somewhat in our spectra compared to that obtained by Parkinson. The Mg XI resonance line intensity is obtained by correcting for these additional lines in the wavelength interval. The uncertainty in this correction results primarily from the calculation of the temperature correction to the Mg X satellite line relative intensities. It is estimated to be $\sim \pm 15\%$.

The two strongest lines closest to the Ne X resonance line at 12.134Å are the Fe XVII lines at 12.12Å ($2p^6 \, ^1S - 2p^5 4d \, ^1P_1$) and at 12.26Å ($2p^6 \, ^1S - 2p^5 4d \, ^3D_1$). The 12.26Å line can be separated from the Ne X resonance line for the OVI-10 spectra, but the 12.12Å line cannot. To obtain the intensity of the 12.12Å Fe XVII line, we have chosen to establish the value of the (presumed) constant ratio between the 12.12Å line and the much stronger and easily resolved lines of Fe XVII at 15.01Å ($2p^6 \, ^1S - 2p^5 3d \, ^1P_1$) and at 16.77Å ($2p^6 \, ^1S - 2p^5 3s \, ^1P_1$).

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To obtain these ratios we have analyzed several orbits of higher resolution KAP crystal spectrometer data, obtained with the OVI-17 satellite (Walker, Rugge and Weiss, 1974c), and used the high resolution rocket spectrum obtained by Parkinson (1975). The observed ratios are in reasonable agreement with the calculations of Loulergue and Nussbaumer (1975). Thus, we calculate the line intensity of the 12.12Å Fe XVII line, which must be subtracted from the blended lines at 12.13Å to obtain the Ne X resonance line intensity, using measured ratios between this line and other strong and easily resolved Fe XVII lines also measured with the OVI-10 spectrometer. The total uncertainty in correctly assessing the intensity of the Ne X resonance line after subtracting the blended 12.12Å line is estimated to be ~ ±25%.

The ratios of the Ne X resonance line intensity (in ergs $cm^{-2}sec^{-1}$) to the Mg XI resonance line intensity (in the same units), R, obtained from the OVI-10 data are shown in Figure 2, plotted against the relative intensity (in counts) of the Mg lines near 9.2Å. As can be seen from the figure, there is little, if any, correlation between the ratio R and the total 9.2Å intensity. This should be the case if the ratio is, as expected, essentially temperature independent for the observations used. The scatter in the data is consistent with a constant ratio having the uncertainties discussed earlier. If we assume the ratio is, in fact, constant, we may average the data and obtain a ratio of the Ne X resonance line intensity to that of the Mg XI resonance line of 0.90 ± 0.24. Using the result of equation (1), this leads directly to a relative solar coronal neon to magnesium abundance of 1.47 ± 0.38.

Very recently, data which do not require corrections for blending of lines with the Ne X or Mg XI resonance lines have become available. We have applied the technique described in Section II to this single high resolution spectrum obtained by Parkinson (1975) from a rocket. The ratio of Parkinson's Ne X/Mg XI resonance line fluxes is 0.57 ± 0.10, which leads to a relative Ne/Mg abundance ratio of 0.93 ± 0.15 independent of whether or not we use his derived active region emission measure function or the function expressed in equation (2). This further emphasizes the independence of the technique from the detailed thermal structure of the active region for the Ne to Mg abundance determination.

IV. DISCUSSION

The technique described in this paper has been applied to 14 orbits of moderate resolution x-ray data obtained on the OVI-10 satellite. The relative solar coronal neon to magnesium abundance has been found to be 1.47 ± 0.38. Application of this technique to a single high resolution x-ray spectrum obtained by Parkinson (1975) yields a relative abundance of 0.93 ± 0.15. These values compare with a value recently obtained by the authors, using a less direct technique, of 1.8 (Walker, Rugge and Weiss, 1974a,b). Other recent solar results have ranged from an Ne/Mg ratio of ~ 0.6 obtained from the analysis of the Li-like lines in the solar XUV spectrum (Flower and Nussbaumer, 1975), ~ 0.8 obtained from solar cosmic ray measurements (Crawford et al., 1975), ~ 0.9 (Withbroe, 1971; Dupree, 1972) and 1.75 (Malinovsky and Heroux, 1972) obtained from coronal XUV measurements, to a ratio of ~ 2.9 (Bertsch et al., 1972) obtained from other solar cosmic ray measurements.

Since, as mentioned above, most recent measurements of the Mg abundance have been found to be between 30 and 35×10^{-6} relative to H, the OVI-10 Ne/Mg ratio obtained in this paper may be used to derive an Ne abundance relative H of $\simeq 47 \times 10^{-6}$. Parkinson's data, used in the same way, lead to an Ne abundance of $\simeq 30 \times 10^{-6}$.

We would like to again emphasize the basic simplicity of the technique described in this paper when it is applied to high resolution solar crystal spectrometer data easily obtainable with presently flown instrumentation. The ultimate accuracy of the Ne/Mg results obtained are limited only by the uncertainties in resonance line calculations and the slight variations in the resonance line intensity ratios with active region temperature.

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FIGURE CAPTIONS

Figure 1.   The intensities of the Ne X and Mg XI resonance lines (left

hand scale) and the ratio of the Ne X to the Mg XI

resonance line intensities (right hand side) plotted versus

temperature.   The calculations are carried out for an

assumed neon to magnesium relative abundance of 1.8.

Figure 2.   The measured energy ratio of the Ne X resonance line to

the Mg XI resonance line plotted against the average Mg

intensity per scan (in counts).   Each data point represents

the average of several scans; the majority represent the

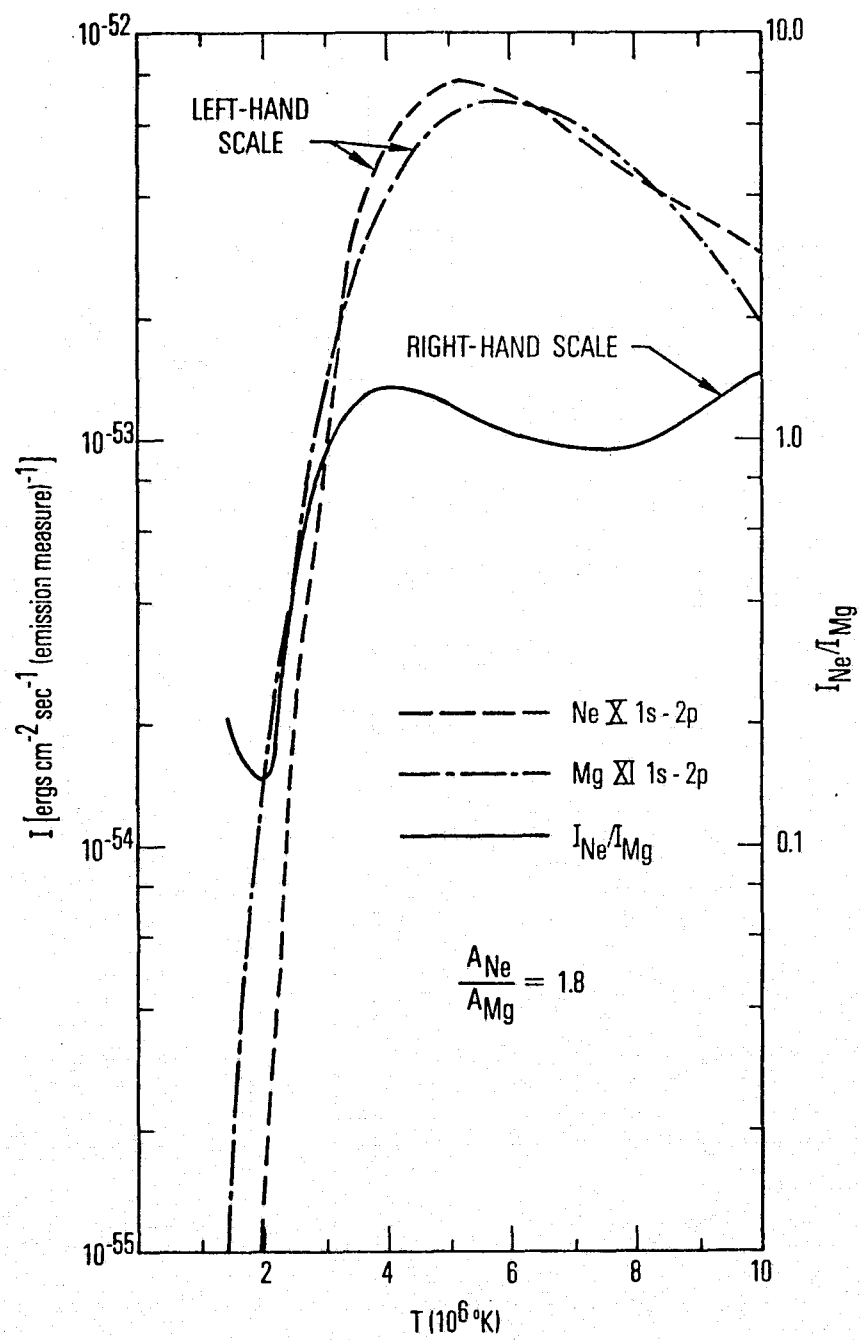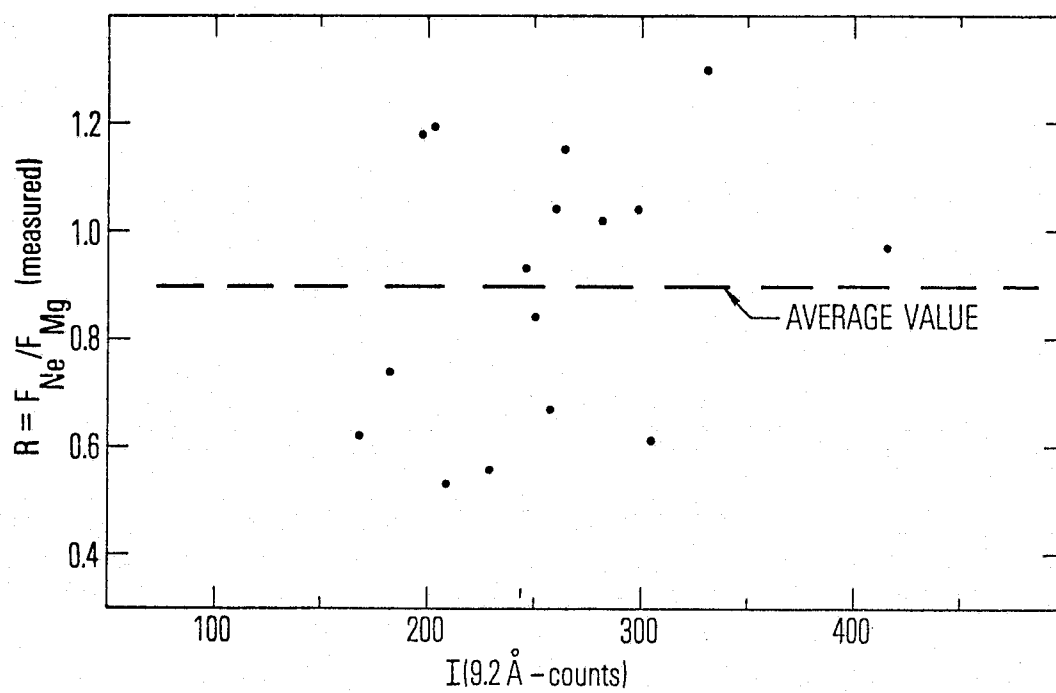average of a full orbit of data.

FIGURE 1

FIGURE 2