Pergamon

*Adv. Space Res.* Vol. 15, No. 7, pp. (7)63–(7)67, 1995
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0273–1177/95 $9.50 + 0.00

0273–1177(94)00020–4

# SPACELAB 2 MEASUREMENT OF THE SOLAR CORONAL HELIUM ABUNDANCE

A. H. Gabriel,* J. L. Culhane,** B. E. Patchett,***
E. R. Breeveld,** J. Lang,*** J. H. Parkinson,**
J. Payne*** and K. Norman**

** Institut d'Astrophysique Spatiale, Universitie Paris XI, 91405 Orsay Cedex, France*
*** Mullard Space Science Laboratory, University College London, Holmbury St. Mary RH5 6NT, U.K.*
**** Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 0QX, U.K.*

## ABSTRACT

The abundance of helium relative to hydrogen has been measured with the "Coronal Helium Abundance Spacelab Experiment" (CHASE) from the space shuttle Challenger in 1985. Previous solar measurements have proved difficult due to the temperature-sensitivity of the electron excitation rates for the observed lines. In this approach scattered Lyman Alpha (Lyα) radiation of helium and hydrogen formed in the corona were measured with a grazing-incidence spectrometer and compared with the intensity of the illuminating flux from the solar chromosphere. The abundance ratio by number of atoms was found to be 0.070 with an uncertainty of 0.011. Scattered light in the telescope is the main source of error.

## INTRODUCTION

The collisional excitation rates in the temperature region of He line formation are unusually sensitive to temperature. This leads to significant error in the deduced abundances. Lines produced by photon impact excitaton eliminate the temperature sensitivity. The effect used was first observed during a total solar eclipse where the Lyα line was observed as the brightest line in neutral hydrogen illuminated by the very intense chromospheric Lyα radiation (Gabriel 1971). Calculations (Patchett et al 1981) showed that the only other line similarly dominated by resonance fluorescence in the inner corona below 1.3 $R_{\odot}$ is He II Lyα at 30.4 nm. Regarding the chromospheric emission of the two lines as light sources, the coronal emission of the lines gives the relative abundance of the scattering species in the corona using just four measurements; disk and above-limb intensities of 121.6 nm and 30.4 nm. Application of ionization balance theory to the coronal plasma relates the ion species observed to the total hydrogen and helium abundances. Many difficult problems cancel out in the analysis. This approach was used as the basis for the CHASE by groups from RAL and MSSL. The instrument consisted of a grazing-incidence grating spectrometer, covering the range 15 nm to 135 nm, illuminated by a grazing-incidence telescope. Nine spectral lines between 28 nm and 135 nm, together with the H I Lyα (121.6 nm) and He II Lyα (30.4 nm) lines, were selected by fixed exit slits on the Roland circle each with a channel electron multiplier detector. The CHASE instrument was flown on the Space Shuttle Challenger as part of the Spacelab 2 payload from 29 July to 6 August 1985. A technical problem during ascent caused the orbiter to go into a lower orbit (315 km) than that originally intended (380 km) and considerable replanning of the observations was necessary to recover from this situation. The lower orbit posed the danger of significant atmospheric absorption for the helium line in particular. Hence the CHASE instrument executed many short observations per daylight pass so that the data were obtained as a function of sun/zenith angle and could be corrected if necessary.

## METHOD

The volume emission of H Lyα from the corona by resonance scatter is given by $\phi_i = N_i \alpha_i F_i G$ where $N_i$ is the density of scattering atoms, $F_i$ is the mean disk brightness in the integrated line profile and G describes the geometry of the photoexcitation and the re-emission (Gabriel, 1971). The factor $\alpha_i$ includes the atomic and spectroscopic properties of line i, representing either He II or H Lyα, and depends on $X_i$ the excitation energy, $f_i$ the oscillator strength and $L_i^c$ and $L_i(T)$ are the chromospheric emission line and the coronal absorption line shapes, normalized so that their respective integrals over wavelength are unity. The signal (count rate) $S_{c,i}$ recorded by the instrument when viewing along a line of sight in the corona above the limb is then given by

$$S_{c,i} = c_i \alpha_i F_i \frac{N_i}{N_e} \int N_e G \, dl \qquad (1)$$

where $c_i$ is the sensitivity of the instrumentation at the wavelength of the line i and $N_e$ is the local electron density. Since $F_i$ is related to the signal $S_{d,i}$ (the signal observed when the instrument is pointed at the solar disk) by the expression $S_{d,i} = F_i$

$C_i$, we can see that for the ratio of these two signals, $S_{c,i} / S_{d,i}$ the instrument calibration cancels. Taking the ratio of this signal ratio for the two lines observed gives for the four-fold measured intensity ratio

$$\frac{S_{c,He}/S_{d,He}}{S_{c,H}/S_{d,H}} = \frac{N_{HeII}}{N_{HII}} \frac{\alpha_{He}}{\alpha_H} \tag{2}$$

where the terms involving the geometry factors cancel on the assumption that such factors are identical for the two lines. Allowing for the ionization balance of each element $N_i/N_{\Sigma i}$, the helium/hydrogen abundance ratio is given by

$$A = \frac{N_{He}}{N_H} = \frac{S_{c,He}/S_{d,He}}{S_{c,H}/S_{d,H}} \frac{N_{HII}/N_H}{N_{HeII}/N_{He}} \frac{\alpha_H}{\alpha_{He}} \tag{3}$$

Lang et al. (1990) analysed a range of line intensities observed by CHASE and found the quiet (non-hole) coronal temperature as 1.6 ± 0.1 $10^6$ K. We adopt this value in the later analysis to give the value of $N_{HI}/N_H$ / $N_{HeII}/N_{He}$ = 1.062 $10^{-2}$

It is necessary to consider two sources of error. The atomic physics used for the ionization balance (Younger, 1981; Seaton, 1959, see figure 1) can be expected to introduce errors of ~ 10% for simple one-electron ions. Such errors will cancel in the ratio of hydrogen to helium leaving a residual error of ~ 3% in the above figure. The error of 0.1 $10^6$ K in the coronal temperature will lead to a further uncertainty of 2.5% in this value. We must also consider the line shapes $L_i'$ and $L_i$ (T). $\alpha_i$ includes the 'Profile Factor' $P_i(T) = a_0 \int L_i' L_i(T)\, d\lambda$ which is evaluated taking account of the coronal temperature. For the disk light source profiles we rely on the observed data referenced in the literature. However for the coronal absorption profiles we assume a gaussian form based on the coronal ion temperature being equal to the electron temperature. Figure 2 shows that while individual profile factors are slow functions of coronal temperature, their ratio, $R_p(T)$, is almost independent of $T_e$. Changes in the shape of the central reversal in the H I disc profile have little effect and can be neglected (Breeveld 1988). The profile factors at a coronal temperature of 1.6 $10^6$K lead to $R_p$ = 0.124 with an error of 3%.

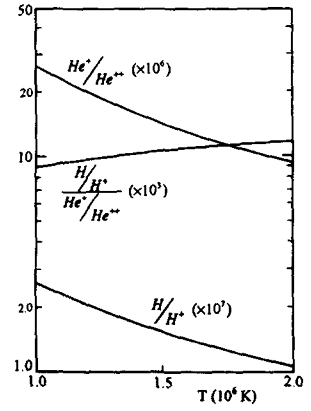

Figure 1

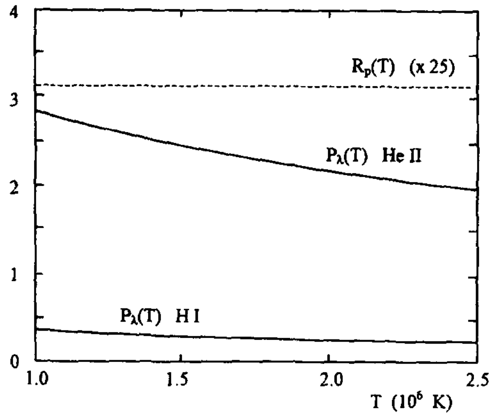

Figure 2

A small correction is necessary to the observed fluxes because the two coronal lines observed can also be excited by direct electron impact. From (1), the volume emission due to resonance scattering is given by $\Phi_i$. The emission by electron impact excitation is $\Phi_i' = N_i N_e C_p$, where $C_p$ is the electron excitation rate to the 2p $^2$P level. The ratio $\Phi_i'/\Phi_i = N_e C_p/Q_i$ is thus independent of the abundance of the ion but does depend on the electron density. To evaluate $C_p$, we use the method of Dubau and Volonté (1980) based on the Coulomb-Born approximation with the exchange calculation of Vainstein (1975). For the temperature of 1.6 $10^6$K, we obtain for the ratio of excitation to resonance scattering 0.002 for hydrogen and 0.052 for helium. To correct the observed coronal intensities in order to obtain the resonance component only, it is thus necessary to multiply by the factor $\beta = \Phi / (\Phi + \Phi')$. The value of $\beta$ is thus 0.998 for hydrogen and 0.951 for helium while the 30% uncertainty in the assumed electron density translates to an error of 1.6% in the derived resonance flux for helium.

## INSTRUMENTATION AND OBSERVATIONS

CHASE consists of a grazing incidence telescope focussing an image of the solar disk onto the entrance slit of a grazing-incidence spectrometer. The telescope had a 100 mm$^2$ projected entrance aperture Wolter type I mirror sector used at grazing incidence with an effective focal length of 280 mm and a resolution of 15 arc seconds (FWHM). The solar image was focussed onto a slit plate which acted as the entrance aperture to the spectrometer. The telescope was mounted on a transverse linear scanning platform enabling the solar image to be moved across the slit plate. Five slit geometries were available ranging from 15 x 15 to 180 x 60 arc seconds. The slit plate was mounted on a scanning platform which could be displaced in the direction of the slit length. This performed the dual function of changing between spectrometer entrance slits and offsetting the position of a slit on the solar image. The slit and mirror scan motions were orthogonal, making it possible to build up two-dimensional images of regions of the Sun. The spectrometer utilized a concave grating with a grazing angle of 4 degrees ruled at 1200 lines/mm with exit slits and detectors placed around the periphery of the 1 metre diameter Rowland circle.

Extremes of the spectral coverage were represented by the O VI line at 15.0 nm and the CII line at 133.5 nm. Eleven lines were monitored simultaneously by individual Channel Electron Multipliers (CEMs) while the range 15 - 22 nm was covered by a Channel Multiplier Array plate and position encoding electronics (CMA). The slits were aligned so that for a particular grating position, know as the 'home position', the peaks of all the selected lines were observed simultaneously. By rocking the grating about an axis perpendicular to the plane of the Rowland circle, each spectral line was then scanned across its exit slit allowing the background to be measured either side of the line and possible line blends resolved. The amplitude of this scan was sufficient to give a range of +/- 2 nm at H I 121.6 nm, and caused no effective loss of spectral resolution which was approximately 25 pm. This resolution requirement was designed to ensure an adequate second order separation between the He II 30.38nm line and the Si XI 30.33nm coronal line. A LiF filter was placed over the H I exit slit to eliminate contamination of the signal by the fourth-order He II line. The instrument also included a Sun sensor to provide an independent verification of experiment pointing. In a back-up mode it could also be used to control the Spacelab Instrument Pointing System (IPS).

One of the spectral channels, detector 15, was selected as a monitor for stray light scattered from the telescope mirror. The C II 133.6nm doublet line was chosen as it is not expected to be formed in the hot corona (Lites et al 1978). As this is close in wavelength it would give a good indication of the amount of scattered light contributing to the H I 121.6nm line.

For the operating sequences planned for helium abundance measurement, CHASE used the rectangular 1 x 3 arc min slit stepped in a radial direction from a point midway between the centre of the solar disc and the limb and outwards into the corona. The slit was oriented such that the longer axis was tangential as it crossed the limb and the incremental steps were 1 arc min. This sequence (number 127) stepped quickly to the limb of the sun from half a solar radius inside the solar disc and continued, at a fifty times slower rate, into the corona. This allowed progressively larger integration times to compensate for the lower flux. The coronal H I emission just above the limb is approximately $10^{-3}$ of the disc flux in the same line. For the He II line this ratio is about $10^{-2}$. Each spatial scan was planned to take most of a daylight pass (30 - 40 minutes).

The Space Shuttle 'Challenger' was launched from Kennedy Space Centre on 29 July 1985. A technical problem developed in the main engines during the ascent phase. This resulted in the shuttle being put into a lower orbit of altitude 315 km instead of the planned 380 km. It was feared that the lower orbit might introduce selective atmospheric attenuation. However a careful examination of the data showed the attenuation to be negligible and permitted the summing of scans taken in each daylight pass. A variety of positions around the solar disc were chosen for the radial scans, including those near the equator in coronal closed-field regions and those near the poles in coronal holes. At each position, care was taken to ensure that a single type of feature filled the slit and avoiding coronal hole boundaries, limb prominences and active regions. Because of the IPS operational difficulties referred to earlier, this was not always achieved.

At each mirror position of sequence 127, the grating was rocked to scan the home position spectral lines across their CEM detectors. Figure 3 shows He II detector data as the instrument pointed at the disc and then further into the corona. At each position mirror and slit were held stationary, while the grating scanned a small distance to cover the lines and a portion of the continuum or background. Figure 3 shows the Si XI line at 0.04 nm shorter wavelength than the He line. The Si line becomes stronger as the slit crosses the limb. Double gaussian profiles were fitted in order to separate the two line intensities. Sequence 127 failed to provide data from the C II channel for measurement of the instrument stray light levels. The background flux in the instrument was too high to detect reliably the CII photons from the solar disc being scattered into the spectrometer while pointed above the limb. Most of the attempts to measure the CII scattering failed to execute correctly during the mission due in part to limited observing time so results of good statstistical quality could not be obtained .

All of the He-abundance scans were carefully inspected to determine how many are usable. Scans were rejected if the IPS moved or drifted by 1 slit width (1 arc min) or more during a scan. A high particle background or the occurrence of sunset during an observation also led to rejection. Scans that crossed an active region within 3 arc min of the limb were also rejected as the corona would be perturbed along with scans that observed a mixture of coronal features. The remaining 12 scans had a variety of exposure factors equivalent to 20 scans with an exposure factor of unity. Study of these showed the signal from the polar coronal holes to be 30% less than from the other coronal regions. The coronal hole data were analysed separately from the rest but, because of the lower count rates, the statistical errors are correspondingly larger.

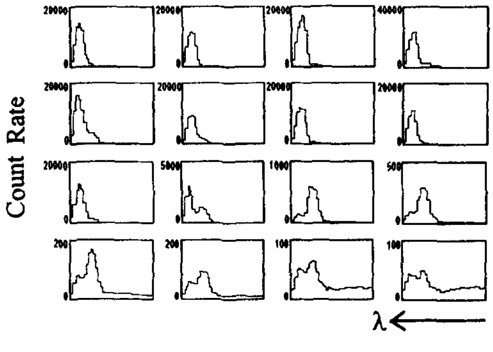

Figure 3

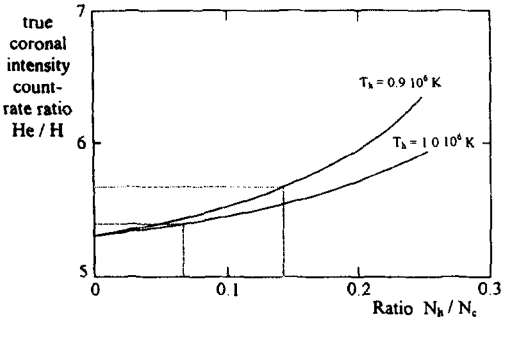

Figure 4

Analysing all the valid non-hole solar disc data from H I 121.6 nm and He II 30.4 nm gives the average count rates observed by the CHASE as $S_{d,H} = 75{,}760 \pm 750$ counts $s^{-1}$ and $S_{d,He} = 106{,}600 \pm 700$ counts $s^{-1}$. The errors are the standard error on the mean. The standard deviation of 5% in H I and 4% in He II is dominated by the solar variability rather than fitting errors, which are estimated at 2 - 3%. The ratio of the count rates is thus $S_{d,H}/S_{d,He} = 0.710 \pm 0.007$

For the coronal data we can write the *real* count rate ratio for coronal emission as

$$\frac{I_{c,i}}{I_{h,i}} = \frac{C_{c,i} - S_i}{C_{h,i} - S_i} = \frac{N_c}{N_h} \frac{F_i(T_c)}{F_i(T_h)} \frac{1}{\beta_i} . \tag{4}$$

where C is the observed count rate, of which S is due to stray scattered light from the disc, the suffixes c and h apply to the normal corona and the hole corona respectively and i represent either the He II or the H I spectral line. F(T) gives the ion population dependence on temperature as shown in Figure 1. β is the factor allowing for electron impact excitation and N is the coronal electron density. The relations indicated in (11) are used in conjunction with the observed count-rates to derive the dependence of the true coronal count-rate ratio, $I_{c,He}/I_{c,H}$, as a function of the coronal hole temperature and the hole to non-hole density ratio (Figure 4). If we assume hole temperature to be 0.9 - $1.0.10^6$ K (Gabriel 1976) and the hole to non-hole density ratio as 1/7 to 1/15 (Koutchmy 1975), then the count rate ratio $I_{c,He}/I_{c,H}$ is $5.54 \pm 0.13$. Allowing for collisional excitation, we obtain for the resonance-excited count rate ratio $S_{c,He}/S_{c,H} = 5.26 \pm 0.12$. This analysis implies that the fraction of the observed signal due to stray light is 0.53 (H) and 0.50 (He) for the non-hole corona and 0.85 (H) and 0.83 (He) for the coronal hole regions. These values are consistent with the pre-flight measurements of mirror scattering. We now substitute for all terms in (3) to obtain the abundance ratio in the quiet corona of *0.079 ± 0.011* - an overall RMS error of 14%. The Helium fraction by mass is *Y = 0.23 ± 0.03*. In spite of the unexpected operational problems of the CHASE investigation, this is the most precise solar measurement of Helium abundance available at the present time.

Normal solar models predict a helium abundance in the outer layers not influenced by production in the core and thus a measure for the region from which the solar system formed. However the presence of heavy elements in the sun shows that this material has already been processed through nuclear synthesis. Measurements of H II regions of primordial abundance (Pagel and Kazlauskas 1992), give values of Y=0.228 ± 0.005. Current models of the solar interior (Bahcall and Ulrich, 1988, Turck-Chiéze et al 1988) require values of Y=0.28. Meyer (1989) has shown from surveys of different objects that an increase in helium abundance over primordial correlates with an increase by nuclear synthesis of the heavier elements. The observed ratio of oxygen to hydrogen by number of atoms is a useful index of heavy element abundance. A comparison of helium abundance with the O/H ratio (Meyer 1989) shows that the solar model values for He/H are already below the values expected from this correlation. The CHASE value would be still lower and so not far from the primordial value. However the correlation with O/H ratios is not rigorous. This may be due to the different nature of the astronomical events assumed responsible for the two processes; nuclear synthesis in star cores for the helium and supernovae explosions in outer layers for the oxygen. Recent measurement of global solar p-modes give additional constraints on solar modelling. Inversion of these measured frequencies indicates a helium abundance of Y=0.23 ± 0.006 (Kosovicherv et al 1992). These data are consistent with the CHASE values and close to the assumed primordial concentration.

## ACKNOWLEDGEMENTS

We are particularly grateful to many colleagues at RAL and MSSL who have contributed to the success of CHASE. We also thank the flight crew led by Gordon Fullerton who were outstanding in coping with many problems that arose and who ensured that our observational objectives were met.

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