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## Global Helium Abundance Measurements in the Solar Corona

**Authors:** J. D. Moses<sup>1\*</sup>, E. Antonucci<sup>2</sup>, J. Newmark<sup>9\*</sup>, F. Auchère<sup>3</sup>, S. Fineschi<sup>2</sup>, M. Romoli<sup>5</sup>, D. Telloni<sup>2</sup>, G. Massone<sup>2</sup>, L. Zangrilli<sup>2</sup>, M. Focardi<sup>6</sup>, F. Landini<sup>6</sup>, M. Pancrazzi<sup>5</sup>, G. Rossi<sup>5</sup>, A.M. Malvezzi<sup>10</sup>, D. Wang<sup>4</sup>, J.-C. Leclech<sup>3</sup>, J.-P. Moalic<sup>3</sup>, F. Rouesnel<sup>3</sup>, L. Abbo<sup>2</sup>, A. Canou<sup>3</sup>, N. Barbey<sup>3</sup>, C. Guennou<sup>3</sup>, J. M. Laming<sup>4</sup>, J. Lemen<sup>7</sup>, J.-P. Wuelser<sup>7</sup>, J. Kohl, L. Gardner<sup>8</sup>

<sup>1</sup>National Aeronautics and Space Administration (NASA), Washington DC 20546, USA

<sup>2</sup>National Institute for Astrophysics (INAF), Astrophysical Observatory of Torino, via Osservatorio 20, 10025, Pino Torinese, Italy

<sup>3</sup>Institut d'Astrophysique Spatiale (IAS), Bâtiment 121, Université Paris Sud 11/ CNRS, 91405 Orsay, France

<sup>4</sup>Space Science Division, Naval Research Laboratory (NRL), Washington DC 20375, USA

<sup>5</sup>Università di Firenze, Largo Fermi 5, 50125 Firenze, Italy

<sup>6</sup>National Institute for Astrophysics (INAF), Astrophysical Observatory of Arcetri, Largo Fermi 2, 50125 Firenze, Italy

<sup>7</sup>Lockheed Martin Solar and Astrophysics Laboratory (LMSAL), 3251 Hanover Street, Organization A021S, Building 252, Palo Alto, CA 94304, USA

<sup>8</sup>Space Systems Research Corporation (SSRC), 1940 Duke St., Suite 200, Alexandria, VA 22314, USA

<sup>9</sup>National Aeronautics and Space Administration (NASA), Greenbelt, MD 20771, USA

<sup>10</sup>Università di Pavia, via Ferrata 1, 27100 Pavia, Italy

\*Correspondence to: include the email addresses of the corresponding author(s). Please use the asterisk (\*) symbol for the corresponding author information.

†Additional author notes should be indicated with symbols (for example, for current addresses).

**Solar abundances have historically been assumed as representative of cosmic abundances. However, the main information on the solar abundance of helium, the second most abundant element, mainly relies on models and indirect measurements through helioseismic observations, since actual measurements of are very scarce in the solar atmosphere. Helium cannot be directly measured in the photosphere because of its high first ionization potential and measurements of its abundance in the inner corona have been sporadic. In this letter, we present simultaneous global images of the helium (out to 3 R<sub>⊙</sub> -solar radii) and hydrogen emission in the solar corona during the minimum of solar activity of cycle 23 and directly derive the helium abundance in the streamer region and surrounding corona out to 2.2 R<sub>⊙</sub>. The morphology of the He<sup>+</sup> corona is markedly different from that of the H corona, due to significant spatial variations of the helium abundance. The observations show that this quantity is shaped according to and modulated by the structure of the large-scale coronal magnetic field and that helium is almost completely depleted in the equatorial regions when the Sun is in quiet conditions. This measurement provides a trace back to the coronal source**

## **of the anomalously slow solar wind observed in the heliosphere at Sun-Earth L1 in 2009, during the exceptionally long-lasting minimum of solar activity cycle 23.**

The HELium Resonance Scattering in the Corona and HELiosphere (HERSCHEL) sounding rocket investigation obtained simultaneous global images of the He and H solar corona out to 3  $R_{\odot}$ . From these images we achieved the detection of helium resonant scattering over a wide region of the corona and we derive the He abundance map in the region where the acceleration of the solar wind is anticipated to occur. Since helium is the largest contributor to the density of coronal plasma after hydrogen, and it is four times heavier than hydrogen, helium has a significant influence on the dynamics and mass flux of the solar wind [Buergi 1992, Aellig *et al.*, 2001, Hansteen & Velli 2012]. Its measurement is necessary to fully understand the mechanisms responsible for the wind origin and acceleration.

The HERSCHEL sounding rocket payload was launched on September 14<sup>th</sup>, 2009, from the White Sands Missile Range at 16:40 UT and achieved 397.4 seconds of observations. A joint observational program was conducted with the EIT, LASCO and UVCS investigations on SOHO. The instrument package was composed of the Sounding-rocket CORonagraph Experiment (SCORE), the HELium CORonagraph (HECOR) and the HERSCHEL Extreme Ultraviolet Imaging Telescope (HEIT). SCORE is an externally occulted coronagraph obtaining simultaneous narrow band H I 121.6 nm, He II 30.4 nm and visible light K-corona images from 1.5  $R_{\odot}$  to 2.2  $R_{\odot}$  (Fineschi *et al.*, in preparation, Fineschi *et al.*, 2003, Romoli *et al.*, 2007). HECOR is a high-throughput, externally occulted coronagraph obtaining narrow-band He II 30.4 nm images from 1.3  $R_{\odot}$  to 3  $R_{\odot}$  (Auchère *et al.*, 2007). HEIT is derived from an engineering model of STEREO/EUVI (Howard *et al.*, 2007) and obtains the intensity of the 30.4 nm He II disk emission.

The H I and He II images obtained with SCORE over the west half of the solar corona clearly show markedly different morphology (Figure 1 a, b). The H I emission is roughly uniform throughout the region across the equator, whereas the He II emission, dimmed in the equatorial region, shows a more complex structure (Figure 1c) similar to the green corona (Fe XIV 530.3 nm) pattern observed during low solar activity in the previous cycle (Schwenn *et al.*, 1997). The H and He coronal configuration is also reminiscent of the striking difference between HI Ly  $\alpha$  and OVI images of quiescent streamers observed with UVCS/SOHO, characterized by core dimming in the oxygen emission (Noci *et al.*, 1997) in the central region of the streamer belt. As expected, little emission is present in either line over the polar coronal holes where the plasma has both a low density and a high radial velocity. The very good morphological match between the He II images obtained from SCORE and HECOR (Figure 1c) - although these instruments have slightly different passbands centered on the He II 30.4nm line-, combined with the good match between the HECOR westernmost extensions and the LASCO C2 image (Figure 1d), indicates that the unique structures observed in He II are not instrumental nor nearby line contamination artifacts.

The helium coronal abundance is deduced from the H I and He II line intensity ratio as described in the Methods section. The polar profiles of the He abundance are plotted in Figure 2 for three different altitudes: 1.7, 1.9 and 2.1  $R_{\odot}$ . Extremely low values ( $\leq 3$  %) are observed within  $\pm 15^{\circ}$  across the equator at the west limb, with a minimum value (0.6 %) close to the equator. The increase in He abundance with distance from the equatorial region is better observed in the northern hemisphere, that corresponds to higher latitude degrees. These values are well below 4.8 %, the value measured at 1.5  $R_{\odot}$  in the central region of a quiescent equatorial streamer during the solar minimum of cycle 22 (Raymond *et al.*, 1997) with UVCS observing the He II 108.5 nm

Balmer line. In Figure 3 the He abundance values are superposed to the lines extrapolated from the photospheric magnetic field in the force free potential approximation and to the observed EIT/HECOR He II composite image. The center of the region of the lowest He abundance observed with SCORE falls in between the two closed loop systems characterizing the inner corona below 1.7-1.8  $R_{\odot}$ . Outside this latitude range and beyond 1.7  $R_{\odot}$ , where the magnetic field lines are predominantly open toward the interplanetary space (Figure 3), the He abundance progressively increases although retaining a value  $\leq 10\%$ , limit that is close to the outer convection zone abundance. In Figure 2, the He abundance is reported only in the latitude ranges, where this quantity is marginally affected by the coronal outflows which induce a dimming of the H and He emission lines (Withbroe G. L. *et al.*, 1982). The coronal abundance data matches that observed *in situ* where an anomalous drop in the He abundance of the solar wind was detected at Sun-Earth L1 with the Wind spacecraft in 2009, during the solar minimum of cycle 23, when extremely low values ranging within 3.5 %, for wind flowing at 560 km s<sup>-1</sup>, and a value < 0.5 %, for the slowest wind flowing at 260 km s<sup>-1</sup> were observed (Kasper *et al.*, 2012).

The exceptionally low speed solar wind observed at L1 originates in the equatorial region where the magnetic neutral line of the source surface field at 2.5  $R_{\odot}$  is located according to the Wilcox Observatory data. The neutral line extends outward in the heliospheric current sheet where marked minima in the He abundance are typically measured (Borrini *et al.*, 1981). The open field lines emerging from the equatorial region, although not evident in the potential extrapolation of Figure 3, are likely to exist due to the double/complex structure of the closed field line region. They outline further out the heliospheric current sheet and guide the very slow wind flowing in its proximity. The onset of slow wind in the streamer core was directly measured via Doppler dimming by Noci and Gavryuseva, 2007. The nascent solar wind was propagating along field lines, separating sub-streamers, in flux tubes characterized first by rapid expansion and subsequently by a narrowing of their cross-section before the wind reaches the critical point. The depletion of oxygen observed with UVCS in the streamer cores has been ascribed by Noci *et al.*, 1997 to this peculiar magnetic topology that has the effect of decreasing the wind speed in the corona, whilst the density is not affected. A speed reduction determines a reduced proton flux and, as a consequence, a depletion of the oxygen ions. Thus, adopting by analogy the same reasoning in the present case, we suggest that the wind flowing along the flux tubes emerging from the core of the streamer belt, due to their topology, slows down in such a way to influence locally the Coulomb drag, that is, the collisional coupling between helium ions and protons. This means that the reduced proton flux is dragging a reduced number of helium ions in the solar wind (*e.g.*, Geiss *et al.*, 1970, Wang 2008), giving origin to the low He abundance observed both in corona and in the heliosphere. The combination of the magnetic topology effect with the unusually slow wind conditions observed in 2009, gives origin to a much higher helium depletion in the interplanetary space than measured during the previous solar minima.

A similar geometry of the open field lines can be found in the regions immediately surrounding the streamer/coronal hole boundaries (Wang and Sheeley, 1990, Antonucci 2006), that induces the same effect of slowing down the local wind (Antonucci *et al.*, 2012). Moving away from the boundary the flux tube divergence becomes monotonic and the wind speed is progressively increasing with distance from the streamer boundary as the flux tube expansion factor decreases. Therefore, we expect a consequent increase of the coronal He abundance with heliolatitude. Indeed, this effect is observed in the latitudinal profiles of Figure 2 and in the coronal image of Figure 3, where along the open field lines surrounding the boundaries of the streamer belt the He abundance is increasing with distance from the regions where the magnetic field is closed.

A strong helium depletion is also observed in the closed field regions where the plasma is mainly confined (Figure 3). In this case, however, the low abundance likely arises from physical processes different from inefficient Coulomb drag, to be ascribed, for instance, to gravitational settling in plasma confined in closed magnetic field regions (Li *et al.*, 1998), or other processes acting in determining the elemental composition in corona, such as wave particle interaction as described by Rakowski, C. E. and Laming, J. M. 2012 and Laming 2012.

The global images of He II in the solar atmosphere out to 3 R<sub>☉</sub> demonstrate that the He abundance in the corona is modulated by the topology of the magnetic field lines and, from the very low values attained in the equatorial region, peaks at the boundaries separating the quiescent streamers and the polar coronal holes where the solar wind speed is expected to increase. The extremely low coronal abundance of the helium ions in the solar equatorial region causes the anomalously low helium abundance measured in the heliosphere during the minimum activity of Cycle 23.

### **Online content**

Any Methods, including any statements of data availability and Nature Research reporting summaries, along with any additional references and Source Data files, are available in the online version of the paper at <https://doi.org/XXXXX>.

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### **References:**

1. Fineschi, S. et al. Ultraviolet and Visible-light Coronagraphic Imager (UVCI) for HERSCHEL (Helium Resonance Scattering in Corona & HELiosphere). *Proc. SPIE* **4853**, 162-171 (2003).
2. Romoli, M. et al. The HERSCHEL/SCORE Visible and UV Coronagraph. *Proc. of the Second Solar Orbiter Workshop, ESA-SP* **641**, 79.1-79.5 (2007).
3. Auchère, F. et al. HECOR: HELium CORonagraphy aboard the Herschel sounding rocket. *Proc. SPIE* **6689**, 66890A-1-66890A-11 (2007).
4. Howard, R. A. et al. The SECCHI Experiment on the STEREO Mission. *American Geophysical Union, Spring Meeting 2007*, Abstr. id.SH33A-01 (2007).
5. Hansteen, V. & Velli, M. Solar Wind Models from the Chromosphere to 1 AU. *Space Sci. Rev.* **172**, 89-121 (2012).
6. Schwenn, R. et al. First View of the Extended Green-Line Emission Corona At Solar Activity Minimum Using the Lasco-C1 Coronagraph on SOHO. *Sol. Phys.* **175**, 667-684 (1997).
7. Noci, G. et al. The quiescent corona and slow solar wind. *Fifth SOHO Workshop, ESA SP* **404**, 75-84 (1997).
8. Raymond, J.C. et al. Composition of Coronal Streamers from the SOHO Ultraviolet Coronagraph Spectrometer. *Sol. Phys.* **175**, 645-665 (1997).

9. Withbroe, G. L. et al. Probing the solar wind acceleration region using spectroscopic techniques. *Space Sci. Rev.* **33**, 17-52 (1982).
10. Kasper, J. C. et al. Evolution of the Relationships between Helium Abundance, Minor Ion Charge State, and Solar Wind Speed over the Solar Cycle. *Astrophys. J.* **745**, 162-168 (2012).
11. Borrini, G. et al. Solar wind helium and hydrogen structure near the heliospheric current sheet - A signal of coronal streamers at 1 AU. *J. Geophys. Res.* **86**, 4565-4573 (1981).
12. Noci, G. & Gavryuseva E. Plasma Outflows in Coronal Streamers. *Astrophys. J.* **658**, L63-L66 (2007).
13. Geiss, J., Hirt, P. & Leutwyler, H. On Acceleration and Motion of Ions in Corona and Solar Wind. *Sol. Phys.* **12**, 458-483 (1970).
14. Wang, Y.-M. Relating the Solar Wind Helium Abundance to the Coronal Magnetic Field. *Astrophys. J.* **683**, 499-509 (2008).
15. Wang, Y.-M. & Sheeley, N.R. Jr. Solar wind speed and coronal flux-tube expansion. *Astrophys. J.* **355**, 726-732 (1990).
16. Antonucci, E. Wind in the Solar Corona: Dynamics and Composition. *Space Sci. Rev.* **124**, 35-50 (2006).
17. Antonucci, E, Abbo, L. & Telloni, D. UVCS Observations of Temperature and Velocity Profiles in Coronal Holes. *Space Sci. Rev.* **172**, 5-22 (2012).
18. Grevesse, N. & Sauval, A.J. Standard Solar Composition. *Space Sci. Rev.* **85**, 161-174 (1998).
19. Li, J. Physical Structure of a Coronal Streamer on the Closed-Field Region as Observed from UVCS/SOHO and SXT/Yohkoh. *Astrophys. J.* **506**, 431-438 (1998).
20. Rakowski, C. E. & Laming, J. M. On the Origin of the Slow Speed Solar Wind: Helium Abundance Variations. *Astrophys. J.* **754**, 65-75 (2012).
21. Laming, J. M., Non-WKB Models of the FIP Effect: The Role of Slow-Mode Waves. *Astrophys. J.* **744**, 115-128 (2012).

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### **Author Contributions**

All authors contributed to the discussion, proposing and planning of observations, data interpretation and writing of this manuscript. J.D.M is Principal Investigator of the HERSCHEL sounding rocket. E.A is Co-Principal Investigator and led development of SCORE with assistance from S.F, M.R., G.M., M.F., F.L., AMM, M.P., and L.Z.. F.A. led the development of HECOR with assistance from F.R., J-P.M., and J-C.L.. J.S.N was HERSCHEL Project Scientist and led development of HEIT with assistance from J.L., J.-P.W., and D.W. DT developed the codes for the analysis of the SCORE data and the cross-check with the UVCS data. G.R., L.A., J.M.L., N.B., C.G., A.C., assisted in analyzing data. J.K.K., and L.G. performed the UVCS observations. E.A would also like to acknowledge A. Gherardi, L. Gori, G. Noci, E. Pace, D. Paganini, D. Gardiol, D. Loreggia, V. Da Deppo, M.G. Pelizzo, G. Naletto, P. Nicolosi, and G. Tondello for their contribution in the development of SCORE.

### **Author Information**

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**Figure 1. Global images of He II emission in the solar atmosphere out to  $3 R_{\odot}$  in the frame of the visible light polarized emission of the corona out to  $6 R_{\odot}$ .** Panels a and b are, respectively, the photometric images obtained in the SCORE H I Ly- $\alpha$  and He II channels from 1.5 to 2.2  $R_{\odot}$ . The white dots in panel a) indicate the location of the coordinated SOHO UVCS observations. Panel c is the photometric image obtained in the HECOR He II from 1.28 to 3  $R_{\odot}$ . The stray light-corrected photometric image from the EIT He II channel is included inside the He II channel coronagraph images in panels b and c. Panel d is an illustration of the global morphology on 14 Sept. 2009 achieved by applying a radial filter - smoothed over  $20^{\circ}$  polar angle segments - to a composite image consisting of the EIT He II channel inside 1.28  $R_{\odot}$ , the HECOR He II channel from 1.28 to 2.3  $R_{\odot}$  and the LASCO C2 polarized brightness (pB) image at greater coronal heights. The box denoted by the dotted lines in panel d outlines the FOV of panels a, b & c and that of Figure 3.

**Figure 2. Polar profiles of the He abundance.** Polar profiles of coronal quantities derived from SCORE measurements, at the west limb, at 1.7 (panel a), 1.9 (panel b) and 2.1 (panel c) solar radii above the Sun's surface; the heliocentric latitude is expressed in degrees, counterclockwise from the north pole. The helium abundance (red dots) is compared with the H I and He II intensities (black and blue dots, respectively). The error bars (smaller than the symbols for the H I intensity) refer to 1-sigma uncertainties. The horizontal dashed lines represent previous estimations of the He abundance: at the edge of quiescent equatorial streamers during the minimum of cycle 22 (green line, Raymond et al., 1997), in the central region of equatorial streamers (blue line, Raymond et al., 1997), inferred for the convection zone (red line, Grevesse & Sauval, 1998).

**Figure 3. Magnetic topology of the solar corona in the region where the He abundance is measured.** Extrapolated potential field lines overlaid on the composite enhanced He II image of Figure 1(d) (grayscale). The field lines are colored according to the expansion factor (closed field lines are in white). The helium abundance is over plotted in red scale. The three blue dashed arcs mark the locations of the polar profiles of Figure 2.

## Methods

### **Background:**

The first attempt for a direct measurement of the helium abundance in the corona was obtained with the CHASE (Coronal Helium Abundance Experiment) experiment on board Spacelab 2 (Patchett *et al.*, 1981). The value derived at 1.15  $R_{\odot}$  was 7.9%, consistent with the photospheric values (Gabriel *et al.*, 1995). Unfortunately, these measurements were strongly affected by a stray light level larger than expected. More recently, Raymond *et al.*, (1997) have used UVCS/SOHO observations of the 1085 Å He II Balmer line at 1.5  $R_{\odot}$  and derived an upper limit of 4.8% for the coronal helium abundance for the case of quiescent streamers. Similar observations of the He II Balmer line with SUMER/SOHO yielded a value of 5% (Laming and Feldman, 2003). Besides the inherent uncertainties in the measurements, another explanation for this spread in the abundance values is the existence of temporal and spatial variations. For example, oxygen, another high FIP element, has been shown to be depleted in the core of streamers (Kohl *et al.*, 1997). Considering this possibility and the observed in-situ variations with solar wind properties, instead of localized spectroscopic measurements, we developed a suite of imaging coronagraphs to obtain a global map of the coronal helium abundance in the acceleration region of the solar wind.

HERSCHEL combines, extends, and refines the capabilities of the successful SOHO EIT, LASCO, and UVCS instruments (Delaboudinière 1995, Brueckner 1995, Kohl 1995). SCORE utilizes the same telescope optics for each wavelength and is the prototype for the Solar Orbiter METIS instrument (Fineschi *et al.* 2012, Antonucci *et al.*, 2020 in press). HeCOR served as a prototype for the Full Sun Imager on board Solar Orbiter (Auchère *et al.*, 2005; Rochus *et al.*, in press)

### **HERSCHEL Calibration:**

A collimator capable of projecting a parallel beam of light in the visible, in the VUV (120 nm) and two band passes in the EUV (17 nm and 30 nm) was assembled from NRL test equipment used in the Skylab, SOHO and STEREO orbital missions (see Defise 1999 for description of prototype). The light output of this collimator was calibrated using NIST-traceable photodiodes from International Radiation Detectors (IRD). Characterization of the stray light performance of both coronagraphs and a good end-to-end throughput calibration of HECOR and the SCORE visible & He II channels was achieved with this test setup. The laboratory end-to-end throughput calibration of the SCORE H I channel was problematic, so the throughput projection constructed from component calibrations was validated by the SOHO UVCS H Ly- $\alpha$  made in the coordinated joint observation program for the HERSCHEL flight. The relevant absolute calibrations are HECOR =  $5.9 \times 10^9$  ph cm<sup>-2</sup> sr<sup>-1</sup> DN<sup>-1</sup> px<sup>-1</sup>; SCORE H I =  $4.3 \times 10^8$  ph cm<sup>-2</sup> sr<sup>-1</sup> DN<sup>-1</sup> px<sup>-1</sup>; and SCORE He II =  $8.4 \times 10^8$  ph cm<sup>-2</sup> sr<sup>-1</sup> DN<sup>-1</sup> px<sup>-1</sup>.

Observations from each of the HERSCHEL instruments were compromised by in-flight anomalies. The thin Aluminum filter blocking visible light from the HECOR detector developed a pinhole. The impact of this HECOR anomaly was minimized in post-flight image analysis. The optical alignment of SCORE moved during launch resulting in a relative misalignment of the external and internal occulter. The impact of the SCORE anomaly was a total loss of the visible light channel. In the SCORE H I (UV) and He II (EUV) channels the image of the east half (heliocentric coordinates) of the corona was lost but the west half was largely unaffected.

### He abundance derivation:

The Helium abundance is deduced from the H I and He II line intensity ratio and the intensity of the resonantly scattered H and He lines can be expressed as

$$I_{ion} = hB_{12}^{ion} \int_0^{\infty} n_{ion} \int_{\Omega} p(\theta) I_{\odot} f(v_{ion}, T_{ion}, P_{\odot ion}) d\Omega ds$$

where  $h$  is the Planck's constant,  $B_{12}^{ion}$  is the Einstein's coefficient for absorption,  $n_{ion}$  is the ion number density,  $p(\theta)$  accounts for the anisotropy of the scattering,  $I_{\odot}$  is the total intensity of the chromospheric exciting line and  $f(v_{ion}, T_{ion}, P_{\odot ion})$  is a function of the ion velocity, temperature and chromospheric profile. In the case of the HI line emission, the chromospheric photons are scattered by neutral hydrogen atoms. Since according to the LASCO C2 and C3 images, in the days immediately preceding and following the rocket launch the corona shows persistent features at a same latitude implying a roughly cylindrical symmetry, we assume that the observed emission primarily comes from the plane of the sky. Hence, the line intensity ratio can be expressed as:

$$\frac{I_{He}}{I_H} = A_{He} \frac{N_{He^+}/N_{He}}{N_{H^0}/N_H} \frac{B_{12}^{He}}{B_{12}^H} \frac{I_{\odot He} f(v_{He}, T_{He}, P_{\odot He})}{I_{\odot H} f(v_H, T_H, P_{\odot H})}$$

Ionization balance and transition rates are taken from Arnaud & Rothenflug, 1985, Elwert 1952, and Gabriel & Jordan 1972, respectively. A comparison of the contribution functions (given by the product between the ionization equilibrium  $R_i$  and the collisional excitation rate coefficient of the atomic transition  $C_{12}$ ) of the H I 121.6 nm and He II 30.4 nm lines obtained on the basis of the atomic parameters adopted in the present analysis and those derived by using the CHIANTI atomic data base (Dere et al., 2009) shows no significant differences. The intensity profile of the on-disk Lyman- $\alpha$  H I 121.6 nm spectral line has been derived by Lemaire *et al.*, 2005. This full Sun Lyman- $\alpha$  intensity profile has been scaled to the 121.6 nm radiance on September 14, 2009, provided by the Solar Stellar Irradiance Comparison Experiment (SOLSTICE) on board the Solar Radiation and Climate Experiment (SORCE) spacecraft:  $I_{ex,121.6} = 5.323 \times 10^{15} \text{ ph cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ . The He II disk profile is assumed to be Gaussian with a FWHM of 0.01 nm (e.g., Doschek *et al.*, 1974, Brosius 1996). This profile has been scaled to the  $I_{ex,30.4} = 1.390 \times 10^{14} \text{ ph cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$  solar irradiance deduced from SORCE SOLSTICE Lyman- $\alpha$  irradiance using the empirical relationship by Auchere (2005). Considering the lack of active regions at the time of flight, we assumed a constant intensity and shape of the chromospheric H and He II profiles across the solar disk. The coronal H absorbing profiles are derived from the neutral hydrogen kinetic temperature given by Antonucci *et al.*, 2005, the same value is used for the He ion kinetic temperature.

In order to deduce the helium abundance from the He II and HI line intensity ratio, it is necessary to determine the contributions to the He II emission, observed with SCORE, of other lines falling in the imaging telescope passband (approximately 1 nm wide), determined by the multilayer coating and filter. In particular, the light from the Si XI 30.3 nm line makes an important contribution wherever there is 1.5 MK plasma in the line of sight.

The approach adopted to remove the Si XI intensity contamination does not require information on the electron temperature of the coronal plasma. The intensity measured in the He channel of SCORE is primarily composed of two contributions. A component, dominant at lower heights, is due to the Si XI 30.3 nm emission produced via collisions of the silicon ions with free electrons, which is decreasing with heliodistance as  $n_e^2$ . At higher heights the dominant contribution is due to the He II 30.4 nm line, formed via resonant scattering of the disk radiation by coronal helium ions, decreasing as  $n_e$ . The level where the Si XI line becomes negligible is clearly outlined in the data by a change of slope; that is, a well-defined knee is present in the radial profile of the observed  $I_{\text{He,SCORE}}$ . It can be proved that the Si XI contribution is indeed negligible above the knee, by computing the ratio of the coronal polarized brightness,  $pB$ , a quantity proportional to electron density, and the intensity measured in the SCORE He channel. The fact that this curve is substantially flat, implies that both quantities are proportional to electron density; hence, above the knee the signal in the He channel is entirely due to the He II 30.4 nm emission by resonance scattering. The polarized brightness,  $pB$ , is obtained from the data of the Mark IV K-coronagraph of the High Altitude Observatory at Mauna Loa Solar Observatory, on September 15, 2009.

The He channel intensity measured above the knee has been fitted with a combination of two power laws and then the fit has been extrapolated down to the inner limit of the SCORE field of view. Since the curve obtained in this way is representative of the radial profile of the He II line intensity, the Si XI contribution at lower heights can be isolated and thus accurately removed.

Information on the electron temperature  $T_e$  is however needed in order to estimate the coronal helium abundance and it can be derived by comparing the SCORE observations with a model corona for the H I and He II line emission valid at the minimum of solar activity. The coronal electron density determined on the basis of the van de Hulst inversion of the polarized brightness  $pB$ , measured with the Mark IV coronagraph between 1.14 and 2.86  $R_\odot$ , and SoHO/LASCO/C2 above 2  $R$ , is close to the density profile by Gibson1999. For this reason, the hydrostatic electron temperature profile deduced by Gibson1999 from the ideal gas law has been considered as a first basis in the synthesis of the H I and He II line intensity.

In order to take into account that the He abundance in corona was measured with SCORE in September 2009, during the deepest, long-lasting solar activity minimum of the space era, when freeze-in coronal temperatures deduced on the basis of charge-state ratios in the heliosphere were anomalously low (Zhao and Fisk, 2010), we have derived the coronal He/H abundance, from the ratio of the He and H intensities in two cases: 1) in the assumption of typical coronal temperatures of a solar minimum quiescent streamer (e.g., Gibson *et al.*, 1999), and 2) by decreasing these temperatures by the maximum drop (20%) found in the freeze-in temperatures (Kasper *et al.*, 2012), that can be reasonably ascribed to an approximately equatorial source of the solar wind measured with the in-situ instruments at L1. However, the difference between the abundance derived accounting for the drop in freeze-in temperatures and that obtained for typical coronal temperature values remains well within the errors estimated for the abundance and reported in Figure 2. In the latitude range across the solar equator considered in the analysis, the expansion speed of the corona is less than 70  $\text{km s}^{-1}$  - as inferred by applying Doppler dimming techniques (Withbroe *et al.*, 1982, Noci *et al.*, 1987) to the SCORE HI data - thus ensuring that the coronal dynamics only marginally affects the He abundance results. Analyses of the coordinated SOHO

UVCS observations of O VI are consistent with the expansion rate derived for the hydrogen component.

### **Comparison with context data:**

The Figure 1d image is a composite of HECOR observations and those obtained simultaneously by EIT/SOHO. At the edge of the EIT field of view there is a significant background created by light scattered from the bright solar disk by the first-generation multilayer optics used in EIT. Therefore, to make a useful comparison between EIT and HECOR an important correction of the EIT image in the figure is de-convolution using the PSF (Point Spread Function) as described by Auchère and Artzner, 2004 and Auchère 2000. Co-alignment in the figure is achieved strictly on the basis of pointing information (i.e., without a priori assumptions on the identity of the observed structures of the two instruments to obtain an alignment via cross-correlation). There is a very good correspondence between structure observed in the outer part of the EIT field and the inner part of the field of HECOR. This alignment is particularly clear at the edges of the streamers. We also note the continuation of plumes observed with EIT above the solar North Pole to about  $1.7 R_{\odot}$  in the HECOR field of view. This agreement between HECOR and EIT is expected because the two instruments have very similar passbands.

The field of view in Figure 1d is extended beyond HECOR with the image obtained by SOHO LASCO C2 visible light coronagraph. The correspondence between features observed in HECOR and LASCO (as well as the SCORE He II and LASCO) is visibly poorer than that between HECOR and EIT. The plumes observed by HECOR extend into the field of C2, but there are plumes visible in C2 above the north pole with no counterpart in HECOR. This may be due, at least in part, to the low signal to noise ratio over the poles in the HECOR data. Visible extensions of the streamers above the western boundary in the HECOR and SCORE He II images align with the brightest parts of streamers in C2. However, the detailed structure within each streamer is very different in the HERSCHEL He II and SOHO visible light images. Furthermore, depletion in the region between streamers is much more pronounced in HECOR and SCORE He II than in C2.

LASCO C2 observes Thomson scattering of visible light photospheric radiation by free electrons in the corona. The intensity measured by C2 is proportional to the integral of the electron density on the line of sight. However, the intensity measured by HECOR is the integral over the line of sight of a function depending on the electron density, but also several other parameters including the temperature of the helium ions, abundance, etc.. Thus, any differences between the HECOR and C2 images are an indication the coronal intensity variations observed by HECOR is not entirely due to changes in total coronal density.

### **Data Availability**

The imaging data that support the plots within this paper and other findings of this study are available from NSA Goddard Coordinated Data Analysis Workshop (CDAW) Data Center ([cdaw.gsfc.nasa.gov](http://cdaw.gsfc.nasa.gov)) or from the corresponding author on reasonable request. The data from Figure 2 within the main text are provided as Source Data files.

### **Code Availability**

All relevant codes utilized during this study are available from the corresponding author on reasonable request.

### **References for the Methods section**

22. Patchett, B. et al. The Coronal Helium Abundance Experiment on Spacelab 2. *Space Sci. Rev.* **29**, 431-437 (1981).
23. Gabriel, A. H. et al. Spacelab 2 measurement of the solar coronal helium abundance. *Adv. Space Res.* **15**, 63-67 (1995).
24. Laming, J.M. & Feldman, U. The Solar Helium Abundance in the Outer Corona Determined from Observations with SUMER/SOHO. *Astrophys. J.* **546**, 552-558 (2003)
25. Kohl, J.L. et al. First Results from the SOHO Ultraviolet Coronagraph Spectrometer. *Solar Phys.* **175**, 613-644 (1997).
26. Delaboudinière, J.-P. et al. EIT: Extreme-Ultraviolet Imaging Telescope for the SOHO Mission. *Sol. Phys.* **162**, 291-312 (1995).
27. Brueckner, G.E. et al. The Large Angle Spectroscopic Coronagraph (LASCO). *Sol. Phys.* **162**, 357-402 (1995).
28. Kohl, J.L. et al. The Ultraviolet Coronagraph Spectrometer for the Solar and Heliospheric Observatory. *Sol. Phys.* **162**, 313-356 (1995).
29. Fineschi, S. et al. METIS: a novel coronagraph design for the Solar Orbiter mission. *Proc SPIE* **8443**, 84433H-1 - 84433H-13 (2012).
30. Antonucci, E. et al. Metis: The Solar Orbiter visible light and ultraviolet coronal imager. *Astron. & Astrophys.* in press (2020).
31. Auchère, F. et al. Innovative designs for the imaging suite on Solar Orbiter. *Proc. SPIE* **5901**, 590115-1- 590115-7 (2005).
32. Rochus, P. et al. The Extreme Ultraviolet Imager on Solar Orbiter. *Astron. & Astrophys.* in press (2020)
33. Defise, J.M. Analyse des performances instrumentales du télescope spatial EIT. *Ph.D. thesis, Université de Liège.* (1999).
34. Dere, K.P. et al. CHIANTI - an atomic database for emission lines. IX. Ionization rates, recombination rates, ionization equilibria for the elements hydrogen through zinc and updated atomic data. *Astron. & Astrophys.* **498**, 915-929 (2009).
35. Arnaud, M., & Rothenflug, R. An updated evaluation of recombination and ionization rates. *Astron. & Astrophys. Suppl. Ser.* **60**, 425-457 (1985).
36. Elwert, G. Über die Ionisations- und Rekombinationsprozesse in einem Plasma und die Ionisationsformel der Sonnenkorona. *Z. Naturforschung*, **7A**, 432-439 (1952)
37. Gabriel, A. H., & Jordan, C. Case Studies in Atomic Collision Physics, Vol. 2, ed. McDaniel & McDowell, North-Holland, Amsterdam, (1972).

38. Lemaire, P. et al. Variation of the full Sun hydrogen Lyman profiles through solar cycle 23. *Adv. Space Res.* **35**, 384-387 (2005).
39. Doschek, G. A., Behring, W. E. & Feldman, U. The Widths of the Solar he I and he II Lines at 584, 537, and 304 Å. *Astrophys. J.* **190**, L141-L142 (1974).
40. Brosius, J.W. Measuring Active and Quiet-Sun Coronal Plasma Properties with Extreme-Ultraviolet Spectra from SERTS. *Astrophys. J. Suppl.* **106**, 143-164 (1996)
41. Auchère, F. Effect of the H I Ly $\alpha$  Chromospheric Flux Anisotropy on the Total Intensity of the Resonantly Scattered Coronal Radiation. *Astrophys. J.* **622**, 737-743 (2005).
42. Antonucci, E., Abbo, L., & Doderò, M. A., Slow wind and magnetic topology in the solar minimum corona in 1996-1997. *Astron. & Astrophys.* **435**, 699-711 (2005).
43. Zhao, L. & Fisk, L. The Behavior of the Heliospheric Magnetic Field and the Solar Wind during the Unusual Solar Minimum between Cycles 23 and 24. *SHINE 2010 Proceedings of the conference, 26-30 July* (2010).
44. Gibson, S. et al. Solar minimum streamer densities and temperatures using Whole Sun Month coordinated data sets. *J. of Geophys. Res.* **104**, 9691-9700 (1999).
45. Withbroe, G.L. et al. Probing the solar wind acceleration region using spectroscopic techniques *Space Sci. Rev.* **33**, 17-52 (1982).
46. Noci, G., Kohl, J. L., & Withbroe, G. L. Solar wind diagnostics from Doppler-enhanced scattering. *Astrophys. J.* **315**, 706-715 (1987).
47. Auchère, F. & Artzner, G.E. EIT Observations of the 15 November 1999 Mercury Transit. *Sol. Phys* **219**, 217-230 (2004).
48. Auchère, F., An Observational Study of Helium in the Solar Corona with the EIT Instrument on Board the SOHO Spacecraft. *PhD thesis Université Paris VI* (2000).