Investigating the Formation of the Helium Spectrum in the Solar Atmosphere

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Abstract:

We present the first results of coordinated observations with SOHO (Solar Heliospheric Observatory) and ground-based observatories aimed at investigating the mechanisms responsible for the formation of helium lines in the quiescent solar atmosphere. The observations described here were taken on 7–13 May 1997; the SOHO instruments involved were CDS, SUMER and EIT, while ground-based support was provided by the German Vacuum Tower Telescope on Tenerife (\textsc{He} I $\lambda$10830 and \textsc{Ca} II $\lambda$8498 spectra-spectroheliograms), Coimbra Solar Observatory (H\alpha spectroheliograms), and NASA/NSO Vacuum Tower Telescope on Kitt Peak (\textsc{Ca} II $\lambda$8542 spectra-spectroheliograms and polarimetry).

1. Introduction

We present a sample of data and some first results from a campaign of coordinated observations with SOHO (Solar Heliospheric Observatory: Domingo, Fleck, & Poland, 1995) and ground-based observatories; the main scientific objective was the problem of the formation of the helium spectrum in the quiescent solar atmosphere. The observations were taken on May, 7–13, 1997; the SOHO instruments involved were CDS (with both its spectrometers: NIS and GIS), SUMER and EIT, while ground-based support was provided by the German Vacuum Tower Telescope on Tenerife (VTT: \textsc{He} I $\lambda$10830 and \textsc{Ca} II $\lambda$8498 spectra-spectroheliograms), Coimbra Solar Observatory (H\alpha spectroheliograms), and NASA/NSO spectromagnetograph at the NSO Vacuum Tower Telescope on Kitt Peak (KPVT: \textsc{Ca} II $\lambda$8542 spectra-spectroheliograms and polarimetry).

Observations from these SOHO and ground-based instruments provide diagnostics covering a wide range of temperatures in the solar atmosphere, from the chromosphere to the corona. Such a data set can effectively test the different possible mechanisms of formation. For a discussion of the current status of the debate on the formation of the helium spectrum, we refer to, e.g., Andretta & Jones (1997) and Jordan et al. (1993).

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Figure 1. Intensities of some of the lines observed with CDS/NIS in a sample quiet Sun raster scan obtained during the May 7–13 campaign.

2. Observations

Much of the controversy about the solar helium spectrum stems from the intrinsically multi-level, non-LTE processes by which it is formed. The influence of local physical quantities such as temperature and density is mixed through radiative transfer in many interlocking, spectrally separated transitions to conditions in remote, geometrically complex regions of the atmosphere. This poses several theoretical and computational problems, but also makes observational studies rather difficult. In particular, the EUV helium spectrum has hardly been studied in detail, and almost never in connection with longer wavelength features. It is therefore important to establish the empirical properties of the helium lines as completely as possible.

The helium spectral features observed in this campaign were the first two \( \text{He} \, \text{i} \) resonance lines (\( \lambda584 \), with SUMER and CDS/NIS band 2, and \( \lambda557 \), CDS/NIS band 2), the triplet \( \text{He} \, \text{i} \) \( \lambda10830 \) line (VTT) and the \( \text{He} \, \text{II} \) Ly\( \alpha \) line at 304 \( \AA \) (CDS/NIS band 2, 2\textsuperscript{nd} order; CDS/GIS band 3; EIT).
2.1. EUV Observations

The EUV instruments aboard SOHO, particularly the Grazing Incidence Spectrometer (GIS) of CDS, can give information on the amount of EUV flux capable of photoionizing helium atoms and ions in the relevant spectral ranges (λ < 504 Å and λ < 228 Å for He I and He II respectively). In fact, photoionizations by EUV radiation followed by recombination cascades is a possible mechanism for exciting the solar helium spectrum.

In addition to coronal and helium lines, the transition region diagnostics available with the CDS and SUMER spectrographs can instead constrain alternative formation mechanisms based on collisional excitation taking place in the lower transition region. Some of the lines observed with the Normal Incidence Spectrometer (NIS) of CDS are shown in the set of images of Fig. 1. Other lines observed with CDS/NIS are Fe xvi λ360, Si x λ347 and λ356, Mg ix λ368, C iii+O ii λ539 and the O iv λ554 multiplet, while the C iii λ1176 multiplet was observed with SUMER.

The CDS/NIS intensity images for all the lines shown in Fig. 1 have been obtained from the simultaneous line profiles observed with the 2″ × 240″ slit. Each raster scan comprises 60 slit spectra, with a step size of 2″, thus covering
an area of $120'' \times 240''$. In the process of extracting the total intensities and velocities from the individual line profiles, it has been necessary for some lines to take into account line blends.

The CDS/GIS spectra were obtained with the $4'' \times 4''$ slit, for a total of $10 \times 20$ spectra in each raster, covering an area of $40'' \times 80''$ aligned with the center of the CDS/NIS field of view. The normal observing procedure was an alternating series of NIS and GIS scans.

During the CDS observations, SUMER was continuously observing with the $0.3'' \times 120''$ slit at the center of the CDS field of view, at $X = +700''$ (SOHO coordinates).

Finally, during each daily CDS and SUMER observing sequence, EIT obtained a sequence of full-disk, full-resolution images in all four of its bands (He ii $\lambda304$, Fe xv $\lambda284$, Fe xii $\lambda195$ and Fe ix–Fe x $\lambda171$).
Figure 4. As in Fig. 3, at a different location. The λ10830 line shifts are even more evident here.

2.2. Ground-Based Observations

The observations with the German Vacuum Tower Telescope on Tenerife (Spain) provide information on the link between the helium spectrum, using the He I λ10830 line, and the chromosphere, in this case with the λ8498 component of the Ca II IR triplet. The two lines were recorded strictly simultaneously. The slit of the spectrograph covered 94′′ and with a step size of 0.5′′ we scanned an area of 94′′ × 112′′ in normal conditions. The exposure times were 0.25 s and 5 s for the calcium and the helium line, respectively, thus, the spatial resolution especially of the helium spectra is seeing limited (≈ 1′′).

An example of the data taken on 12 May in a quiet Sun area is shown in Figure 2. In Figures 3 and 4, slit spectra from the same area scan show an interesting high velocity event in the λ10830 line. This area is marked in Figure 2 as well. Figures 3 and 4 also show representative profiles at other locations along the slit.

The observed line shifts, in excess of 20 km/s in some places (as in Fig. 4), seem to have the characteristics of a bipolar flow, with red- and blue-shifted profiles separated by a few arcseconds. Other examples, though somewhat less dramatic, can be found in our data set. These are probably events similar to
Figure 5. The field of view of KPVT.

those observed in the He I $\lambda$10830 line by, e.g., Muggle, Schmidt & Knölker (1997) or Penn & Jones (1997). However, in this case it is possible to notice (especially in Fig. 3) that the relatively deep chromospheric Ca II $\lambda$8498 line also shows a signature of the same flow.

Also note in Fig. 3 two very different Ca II line profiles (solid and dot-dashed lines), one of them showing a quite strong core emission with self-reversal qualitatively similar to the core emission in the Ca II H and K lines. Interestingly, the corresponding He I line profiles do not seem to change significantly.

The KPVT observations complement this information with spectropolarimetry in the $\lambda$8542 component of the same Ca II IR triplet. An example of data taken on 8 May 1997 is shown in Fig. 5. Like CDS and VTT, the KPVT images shown in that figure are actually obtained from spectra-spectroheliograms. The size of the area scanned by the slit was approximately $255'' \times 510''$, with a spatial pixel of about 1.1''. This data set is particularly interesting for it provides information on the magnetic field in the chromosphere.

Finally, observations were also made in the +0.5 Å wing of H$\alpha$, over a field of view that included the area covered by the CDS raster. These spectroheliograms, taken at the Coimbra Solar Observatory, will be used to correlate variable strength in the H$\alpha$ wing emission with changes in the other spectral lines observed, as a first step to determine if the corresponding chromospheric velocity fields correlate with those observed higher in the quiet Sun atmosphere in the various SOHO lines. While weather interfered with these observations for part of the May campaign, useful spectroheliograms were obtained during
each daily sequence of SOHO observations. We are digitizing these photographic images for coregistration with the He\textsc{i} \lambda 10830, \lambda 584 and \lambda 304 images.

3. A Preliminary Analysis and Interpretation of the EUV Data

Analysis of the data is in progress. However, some interesting aspects can be investigated with just a preliminary inspection of the CDS data. In particular, we study the empirical correlation between the two He\textsc{i} resonance lines, \lambda 584 and \lambda 537, since it can be a useful diagnostic for the structure of the atmosphere at the height of formation of those lines (Andretta & Jones 1997).

Because of its high elemental abundance, helium resonance lines can easily build up sufficient optical depth to make the transfer of the line radiation an important aspect of the physics of the problem. However, even at relatively high optical depths, the fraction of photons lost in a chain of resonant scattering processes may be small (the so-called effectively optically thin regime). In this case, the total intensity of the line is relatively little affected by the transfer of radiation. Each line has its limit optical depth, \( \tau^* \), beyond which the line itself becomes effectively optically thick.

An analysis of the multi-level non-LTE problem for He\textsc{i} reveals that the \lambda 537 line tends to leave the effectively optically thin regime more easily than
λ584. When that happens, the intensity ratio of the two lines changes rapidly with He i column depth. Moreover, in regions of partial ionization of hydrogen (such as in the chromosphere), the value of $\tau^*(\lambda 584)$ is also strongly influenced by the local plasma pressure via the column density of hydrogen atoms (which can absorb and degrade $\lambda 584$ photons).

In Fig. 6, the observed correlation $\lambda 584/\lambda 537$ is compared with computations in three different scenarios:

- The solid line represents the results obtained when the two He i lines are collisionally excited in a lower transition region that is effectively optically thin in both lines: $\tau(\text{TR}) < \tau^*(\lambda 584), \tau^*(\lambda 537)$. As density (and optical depth) increases, the computed ratio does not change very much.

- The dashed line represents the case of a lower transition region effectively optically thick in the $\lambda 537$ line but not in $\lambda 584$: $\tau^*(\lambda 537) < \tau(\text{TR}) < \tau^*(\lambda 584)$. A stronger variation of the line ratio results.

- Finally, the dotted line is the case of a pure recombination spectrum, which forms at optical depths in the resonance continuum of the order of unity, i.e. in the upper chromosphere. In this case, both lines are outside the optically thin regime, and thus changes in the ionization state of hydrogen, driven by pressure variations for instance, play a major role in determining their ratio.

Clearly this last scenario seems to be incompatible with the observations. Along with analysis based on other indirect tests (Andretta & Jones 1997, Andretta et al. 1997), it seems unlikely that the He i resonance spectrum in the quiescent solar atmosphere is formed exclusively from a photoionization-recombination process induced by coronal radiation.

We have mentioned in §2.1. how a more direct approach should involve the use of CDS/GIS spectra, which can in fact give a direct measure of the number of coronal photons capable of producing helium lines by recombination cascades. While we are working on this aspect, such an analysis requires a more accurate GIS calibration (both absolute and relative to the NIS spectrometer) than the one currently available.

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