Using the IRAP Solar Atmosphere Model & Observations to Investigate Helium Abundance in the Inner Heliosphere

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Abstract

Helium is a major constituent of the corona and solar wind & plays an important role in the energy budget of the corona & the acceleration of the solar wind. Helium abundance varies with the solar cycle and between the different types of fast and slow solar winds. The IRAP Solar Atmospheric Model (ISAM) is exploited to study the mechanisms that regulate Helium abundance in the source region of the fast and slow solar winds. We contrast numerical results with and without Helium included in the model. We find good agreements between alpha particle abundances in ISAM to observations and those results found in other studies. The differences in abundances are consistent with the solar cycle variation reported by Kasper et al. (2008).

Introduction & Project Aim

The solar wind is often divided into 2 groups, the fast wind originating from polar coronal holes, and a slow wind. The slow wind is itself divided by its source, that from active regions and an alvenic wind from the boundaries of coronal holes.

Whilst protons account for >90% of ions in the solar wind, Helium also plays a non-trivial role. Helium's abundance with respect to protons has been found to be 5±4% typically (Killie, et al., 2005).

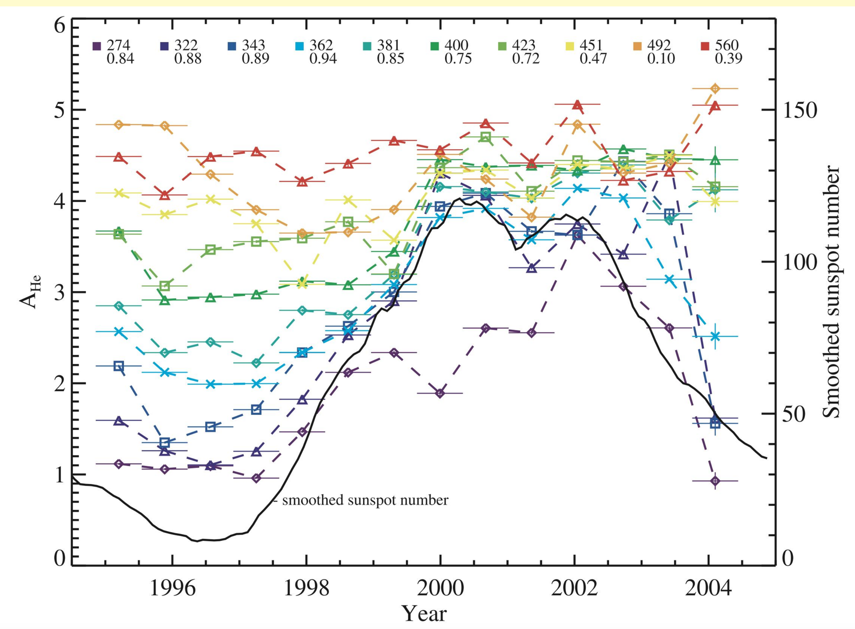

Figure 1 - Kasper et al, (2008) plot of the variation of Helium abundance observations over the Solar Cycle. Colours represent different solar wind speeds. The black line is the smoothed sunspot number.

When plotting Helium abundance in the slow solar wind(s) with the Solar Cycle, Kasper et al. (2008) found a variation between 1 at solar minimum to 5 at solar maximum. Moses et al. (2020) found that in equatorial regions, Helium is almost completely depleted. This could be explained by sampling one type of slow wind more than the other during each period. We aim to use ISAM to explain these differences in Helium abundance.

The IRAP Solar Atmosphere Model (ISAM)

We solve the transport equations of H, H^+ and e^- in order to obtain the bulk properties of the solar wind. For the heating we assume a phenomenological heating from Withbroe et al. (1988), characterised by an energy flux and a heating scale height. The latter is set to a great enough value in which to heat the solar wind beyond the sonic point, such that the energy deposited accelerates the solar wind rather than being preferably lost through downward heat conduction/radiative cooling. Heating high also reduces the pressure of the transition region and lowers the mass flux. The phenomenological heating is given by:

$$F_h = F_{B0}\left(\frac{A_0}{A}\right)\exp\left[-\frac{s-R_\odot}{H_f}\right]$$

Using the methodology set-out by Wang et al. (2016), the energy flux is set as proportional to the magnetic field strength at the base of the corona. The heating scale height is also set as inversely dependent to the expansion factor. Fast solar wind typically originates from tubes with low expansion factors given by:

$$f(r) = \frac{f_{max} e^{(r-R_1)/\sigma} + f_1}{e^{(r-R_1)/\sigma} + 1},$$

By varying the heating scale height and expansion factor in ISAM, we set up 3 solar wind scenarios to investigate the abundance and behaviour of Hydrogen, Helium and electrons from the chromosphere out to the solar wind.

ISAM Simulation of Fast Solar Wind

We first simulate just neutral Hydrogen, protons and electrons in ISAM to test whether the model is capable of reproducing observations and analytical models. Figure 2 shows the resulting temperature, density and velocity profiles of protons.

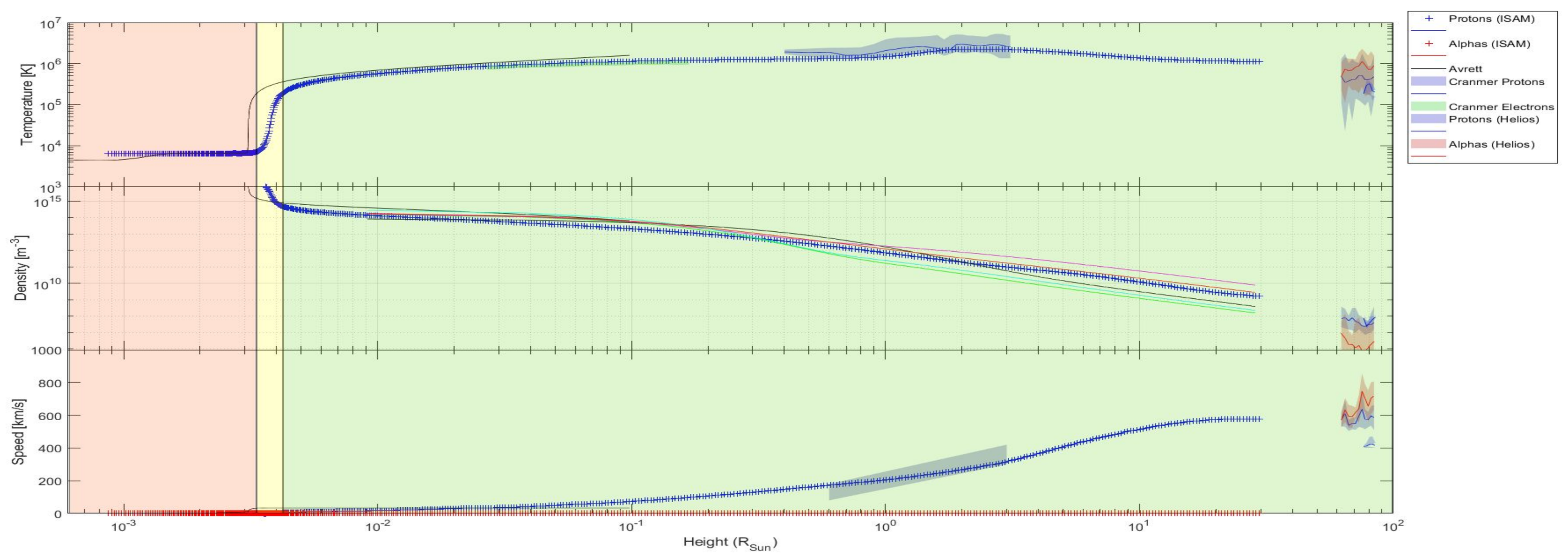

Figure 2 - Fast solar wind ISAM simulation of neutron hydrogen, protons and electrons. The temperature, density & velocity of protons is shown.

We find a good match with both the analytical profile provided in black (Avrett et al, 2008) and UVCS observations from Cranmer et al. (2009). Whilst the ISAM profile end before the presented Helios and PSP observations, the trajectories match well with their values. Whilst the transition region (TR) is slightly further from the Sun in the simulation, it is not outside of a typical observed location for it.

Including Helium in ISAM Simulations

We now include Helium in our ISAM simulations. As the abundance of Helium is great enough to significantly influence the properties of protons in the simulation, we run Helium alongside Hydrogen and electrons and allow them to interact in the model.

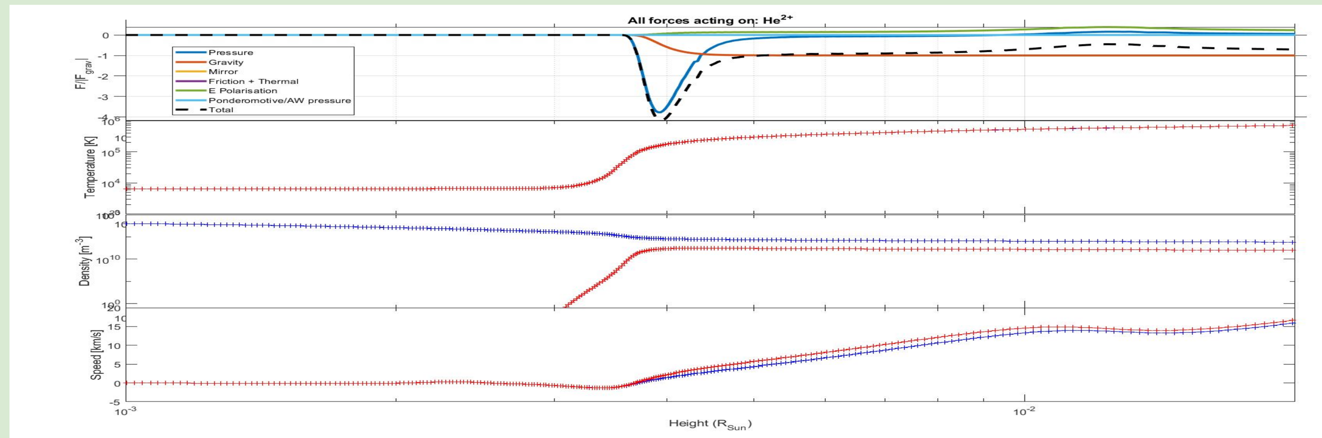

Figure 3 - Forces applying to alpha particles in ISAM model with distance from the Sun. Temperature, density & velocity of protons & alphas is also shown similarly to Figure 2.

A simulation of the upper chromosphere, transition region & lower corona in the fast wind is shown in Figure 3. As expected, we see similar temperature and density in the corona for the two species. Alpha particles are mostly governed by pressure in the TR but gravity in the lower corona. The ponderomotive force is not applied in this case.

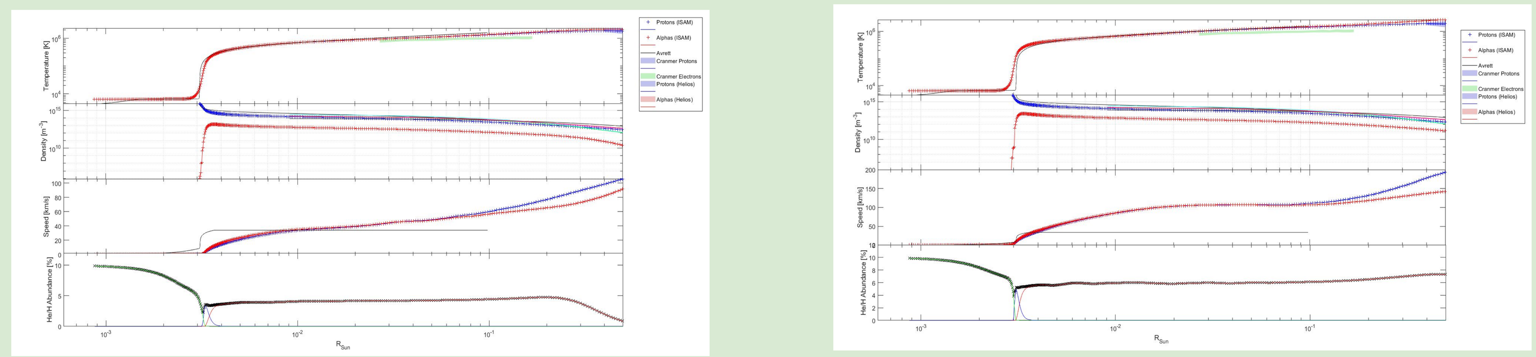

Figure 4 - ISAM simulations of Helium, Hydrogen & electrons combined for, left: slow solar wind from coronal hole boundaries & right: slow solar wind from active regions.

Slow wind solutions are shown in Figure 4. Despite there being no ponderomotive force applied, we find alpha particle abundances of around 5% consistent with previous observations (Killie et al., 2008), suggesting diffusion is important for setting alpha particle abundances in the solar wind. The higher abundances for the active region wind can partly account for the differences from Kasper et al. (2005).

Conclusions & Future Work

- The first He simulations show that ISAM can be used to model the properties of H & He neutrals & ions in the solar wind, corona & transition region.
- Consistent with Killie et al. (2005) and Kasper et al., (2008) we are able to simulate Helium abundances of 2-5% in the corona & solar wind for each type of solar wind, these abundances are driven by purely diffusion processes in the current simulations => we have not yet looked into wave-particle interactions (ponderomotive force).
- Future work will be to extent the simulations outwards to compare with Solar Orbiter and Parker Solar Probe observations directly.