Coordinated Analysis of
The Interstellar Focusing Cone at 1 AU
by an ISSI Team

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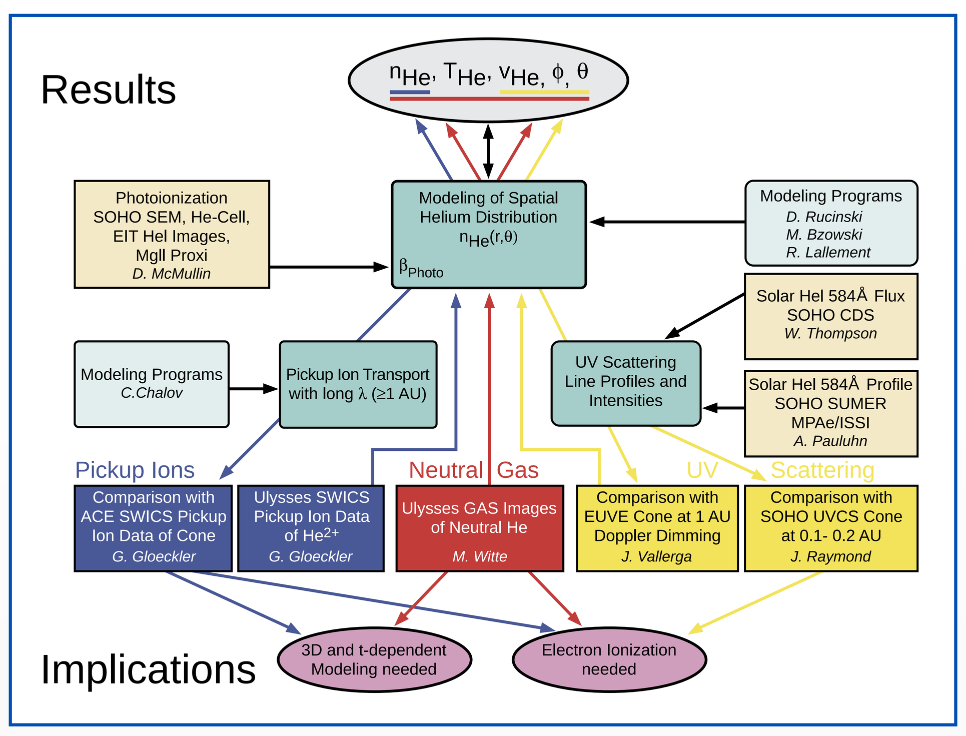
Introduction:

Interstellar neutral gas penetrates into the inner heliosphere as a neutral wind due to the relative motion between the sun and the local interstellar medium. Through the interplay between this wind, its ionization, and the sun's gravitation, a characteristic flow pattern and density structure are formed with gravitational focusing on the downwind side. Utilizing backscattering of solar UV *(Fahr, 1974; Weller and Meier, 1974; Lallement, 1996)*, pickup ion *(Möbius et al., 1995; Gloeckler et al., 1997; Gloeckler and Geiss, 2001)* and direct neutral gas observations *(Witte et al., 1996)*, the physical parameters of H and He as well as abundances of N, O and Ne can be derived. However, the parameters obtained from different observation sets have varied greatly in the past *(Dalaudier et al., 1984; Möbius, 1993)*, and the error bars have been substantial.

While the abundance of H and several other elements are significantly depleted through charge exchange in the heliospheric interface region, He enters the heliosphere unimpeded. He penetrates closest to the sun to well inside 1 AU, and it was the first element that could be observed simultaneously by all three methods. We have used the simultaneous availability of direct neutral atoms with Ulysses GAS, pickup ions with Ulysses and ACE SWICS, as well as UV observations of the cone close to the sun with SOHO UVCS and at 1 AU with EUVE over the past few years for a combined observation campaign (SOHO JOP 129) and analysis effort. The ionization environment, the solar illumination and the solar wind conditions were monitored simultaneously by ACE, SOHO and WIND, information that had to be inferred in the past.

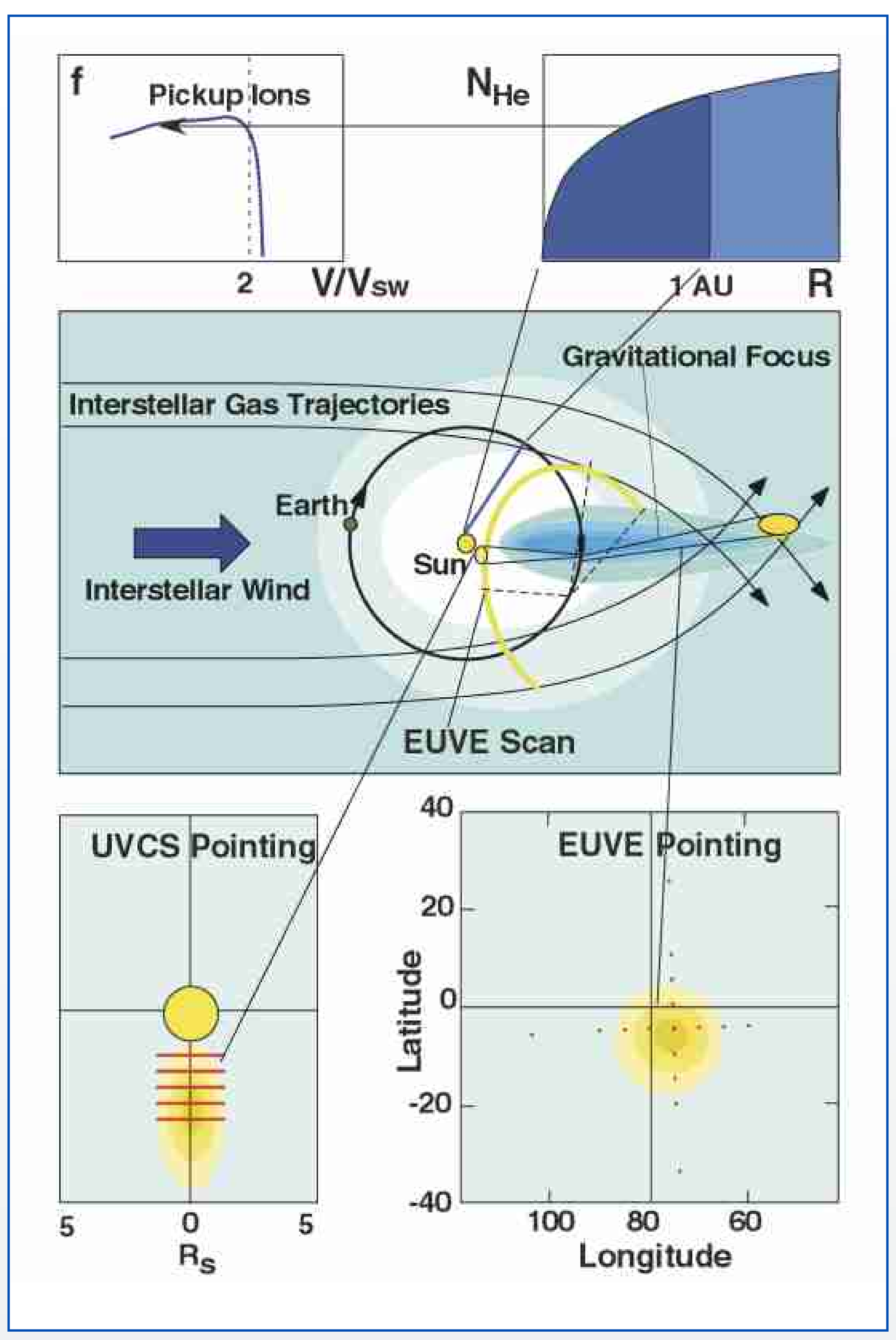
The two figures below show how these observations are combined with modeling to derive a consistent set of interstellar He parameters and which key regions of the He distribution are observed by the different methods. The color-coding indicates the major contribution of each method to the individual parameters.

Combined Analysis of Interstellar Helium



Rectangles indicate primary data sets that have been used (blue: pickup ions; red: neutral gas; yellow: UV scattering; beige: ancillary data on ionization and illumination). Rounded rectangles indicate modeling input and modeling parameters. Ellipses contain the results and the implications from the comparison of the different methods. The colored bars indicate the main sources of these results.

Diagnostics of Interstellar Helium with Pickup Ions and UV Backscattering



The pickup ion phase space density f as a function of V/Vsw reflects a radial cut of the He density for each point on the Earth's orbit. Pickup ion observations with ACE SWICS provide a contiguous 360° distribution in the ecliptic plane every year. They are long time averaged because of strong temporal variations due to transport effects.

UV backscattering provides line-of-sight integrals along the viewing direction. EUVE views the cone radially outward, i.e. with emphasis on slightly outside 1 AU. In its scanning mode EUVE provides also a lateral cut through the cone. Using the Earth's exosphere as an absorption cell, this observation is very sensitive to the bulk velocity of He. UVCS provides observations of the cone very close to the sun (0.1 - 0.2 AU), where ionization effects are most important and solar activity becomes apparent.

Main Questions:

- What is a consistent set of physical parameters for the interstellar He?
- What processes have made the results so variable in the past?
- Can the influencing processes be constrained by observations and modeling so that each of the three methods can be used in order to provide long term observations?

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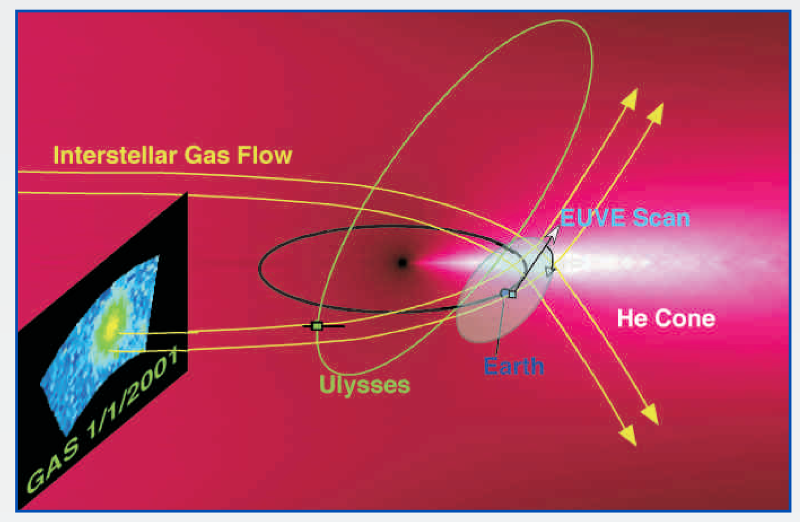
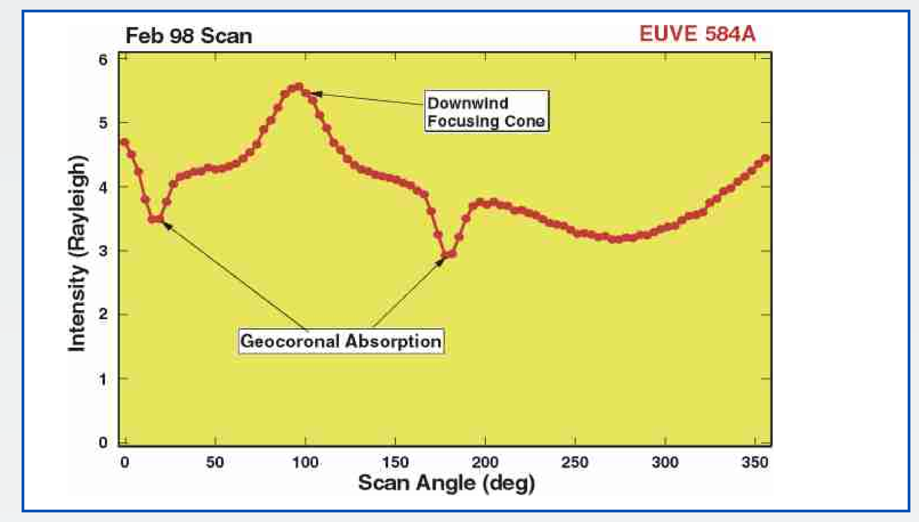
Direct Viewing of Interstellar Helium with Ulysses GAS



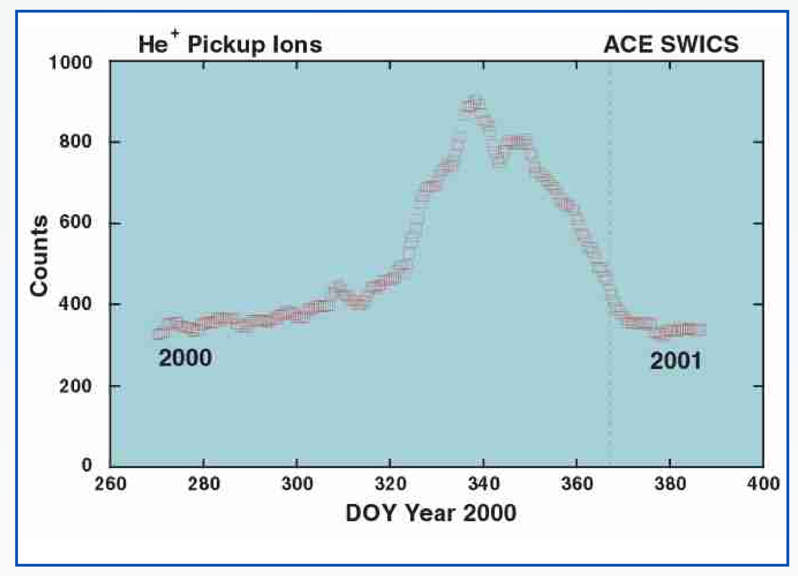
Interstellar He distribution (color coded), as modeled by J. Raymond, based on a hot model of the gas; typical location of Ulysses during the neutral He observations together with a sample of a sky image of the He flow; and a scan geometry for the He I 584 Å line glow through the focusing cone with EUVE from an October location.

Scan of the Helium Cone with EUVE in 1998



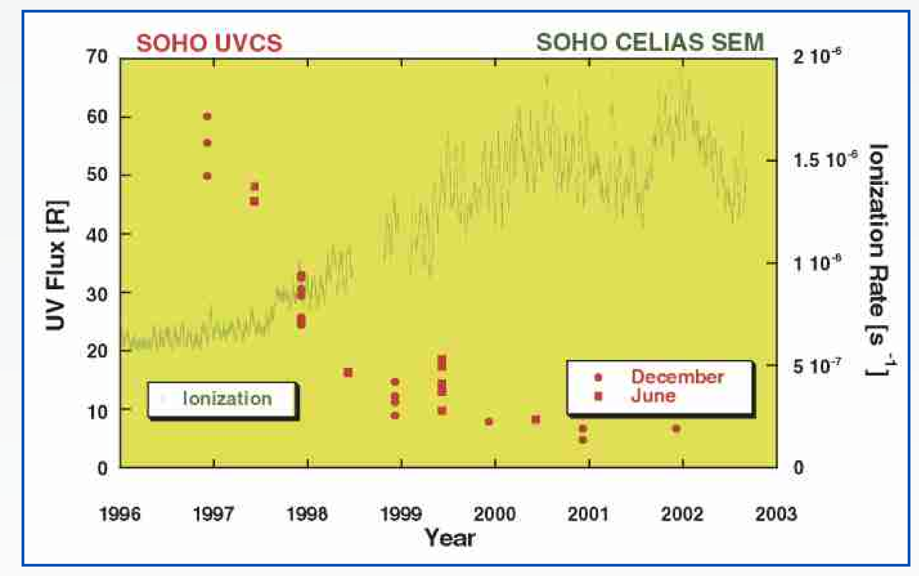
The flux increase in the center represents the cone. The second increase reflects the Earth's exospheric glow. The two dips are caused by resonant absorption of the He line by the exosphere in the directions where the velocity of the interstellar gas relative to the Earth is zero. The exact location of these features are used to deduce the He flow velocity.

ACE SWICS Pickup Ion Fluxes during one Helium Cone Traversal



The count rates have been averaged over 15.5 days to filter out the strong short-term fluctuations of the pickup ion fluxes. During this solar maximum crossing the cone still exhibits approximately a 3:1 density ratio from 1 AU.

Solar Cycle Variation of the Helium Cone Together with EUV Ionization



Intensity of the He I 584 Å glow of the focusing cone at 0.1 - 0.2 AU distance from the sun as taken with SOHO UVCS during June and December, 1996 through 2002. It is apparent that the He cone is strongly depleted as the ionization rate increases towards maximum solar activity.

Results:

- A set of physical parameters for interstellar neutral He has been compiled, based mainly on observations with the Ulysses Gas instrument: $N_{He} = 0.014\text{-}0.015 \pm 0.002\ cm^{-3}$; $T_{He} = 6500 \pm 400$ K; $v_b = 26.4 \pm 0.5$ km/s; $\lambda = 74.6°$; $\beta = -5.2°$ *(Witte et al., 1996; Witte et al., 2002).*
- The interstellar gas density is determined very accurately with He^{2+} pickup ions with Ulysses SWICS without resorting to an absolute calibration: $N_{He} = 0.015 \pm 0.002\ cm^{-3}$ *(Gloeckler et al., 1997; Gloeckler and Geiss, 2002)*. Pickup ions and solar wind He^{2+}, the main producer of pickups ions, are observed with the same instrument. Uncertainties in the charge exchange cross sections are the main potential source of errors. Both, neutral gas and pickup ion observations return the same value within a reasonable error bar of 10-15%.
- By employing the Earth's exosphere as a He absorption cell, EUVE has determined the bulk flow velocity independently to $v_b = 25.4 \pm 0.6$ km/s *(Flynn et al., 1998; Lallement, 2002)*. Within error bars, this result is compatible with the value from Ulysses Gas.
- All methods find the location of the cone, i.e the flow direction, within a narrow error band.
- The physical parameters, as found with all these methods, are consistent with the flow parameters and temperature derived for the average local interstellar medium from UV line absorption in nearby star spectra. *(Bertin et al., 1993; Lallement et al., 1997)*
- Using these parameters in modeling, the UV scattering observations of both EUVE and UVCS can be reproduced *(Lallement, 2002)*, if additional ionization is added to the measured photo ionization *(Judge et al., 1997)*.
- The pickup ion observations of the cone with ACE are compatible with these parameters *(Gloeckler and Geiss, 2001; Gloeckler and Geiss, 2002)*.
- The cone in the inner heliosphere is extremely variable with the solar cycle *(Michels et al., 2002; Lallement, 2002)*. At 0.1 - 0.2 AU it almost disappeared during solar maximum.

Implications:

- Neutral gas observations return the most accurate results on the interstellar gas distribution. The density is strongly supported by He^{2+} pickup ion results and the flow velocity by UV Doppler dimming.
- The following observations can only be reconciled with the physical parameters of He, if a substantial additional ionization, most likely electron impact, is included:
  - He densities and their solar cycle variation in the cone close to the sun
  - Neutral He fluxes on indirect orbits close to the sun
  - He^{+} pickup ion fluxes and spectra at 1 AU
- Poor knowledge of illumination and ionization have led to the widely varying results in the past. Great improvements have been achieved with all three methods.
- Neutral gas and pickup ion observations at different locations in the heliosphere can only be made consistent, if a latitude dependent ionization is assumed.
- In the future, improved observations and modeling of the interstellar gas need to include the inherently 3D and time-variable nature of the heliosphere.