The large-scale structure of the solar wind: flux conservation, radial scalings, Mach numbers, and critical distances

Daniel Verscharen[1,2], Stuart D. Bale[3,4,5], and Marco Velli[6]

1: Mullard Space Science Laboratory, University College London; 2: Space Science Center, University of New Hampshire; 3: Physics Department and Space Sciences Laboratory, UC Berkeley; 4: The Blackett Laboratory, Imperial College London; 5: School of Physics and Astronomy, Queen Mary University of London; 6: Department of Earth, Planetary, and Space Sciences, UC Los Angeles

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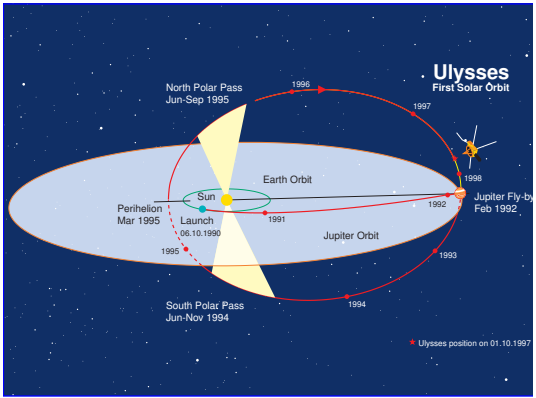
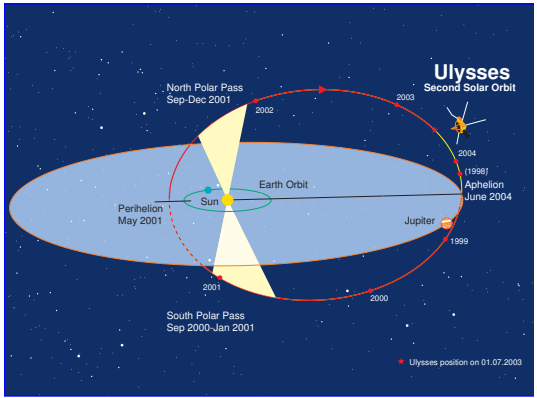
@DVerscharen @dverscharen

The global structure of the solar wind

Ulysses gives us a perspective on latitudinal and solar-cycle dependencies



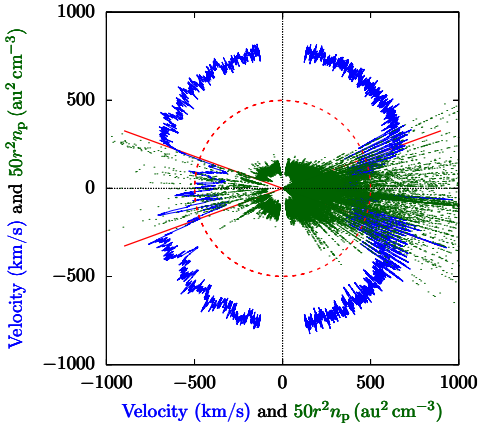


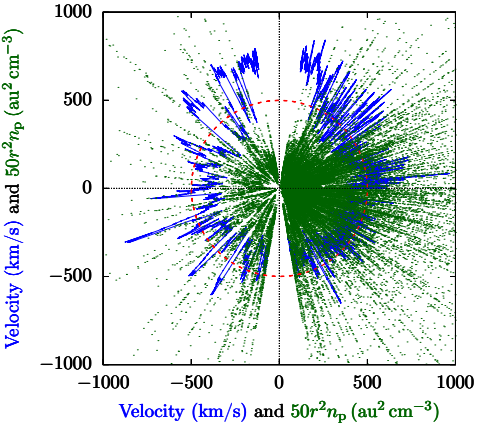
(ESA)

Latitudinal dependence is convoluted with radial dependence.

The global structure of the solar wind

The famous polar plots of the solar-wind speed





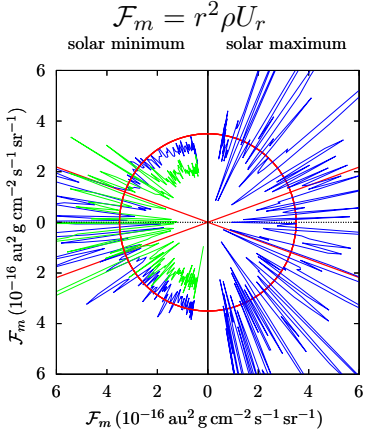
(Verscharen et al., 2019)

Latitudinal dependence is convoluted with radial dependence.

Conserved fluxes are independent of heliocentric distance

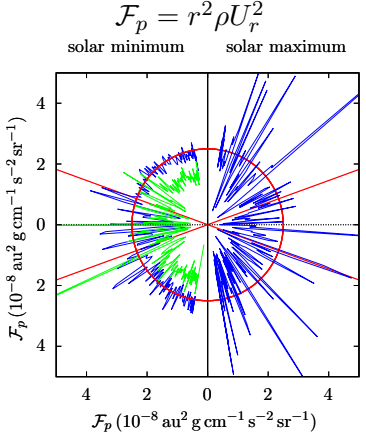
Ulysses observations of mass flux $\mathcal{F}_m$ and kinetic momentum flux $\mathcal{F}_p$

$\mathcal{F}_m = r^2 \rho U_r$



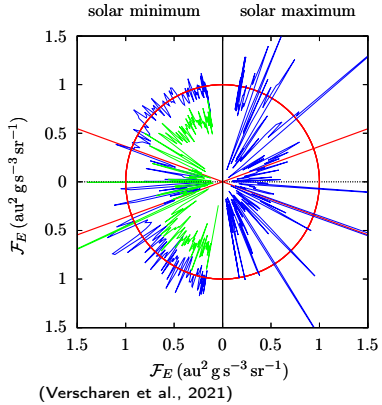
(Verscharen et al., 2021)

$\mathcal{F}_p = r^2 \rho U_r^2$



Conserved fluxes are independent of heliocentric distance

Ulysses observations of energy flux $\mathcal{F}_E$

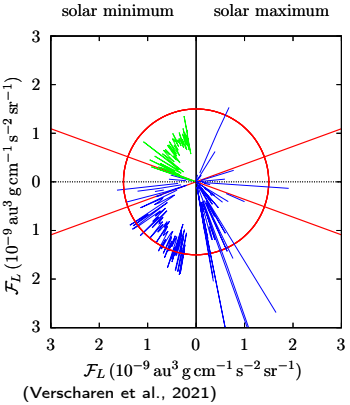


(Verscharen et al., 2021)

$$\mathcal{F}_E = r^2 \rho U_r \left(\frac{\boldsymbol{U}^2}{2} + \frac{\gamma}{\gamma - 1} \frac{P + p}{\rho} - \frac{GM_\odot}{r} - \frac{r B_r B_\phi}{4\pi \rho U_r} \Omega_\odot \sin\theta \right)$$

Conserved fluxes are independent of heliocentric distance

Ulysses observations of angular-momentum flux $\mathcal{F}_L$



(Verscharen et al., 2021)

$$\mathcal{F}_L = r^3 \rho U_r U_\phi - r^3 \frac{B_r B_\phi}{4\pi}$$

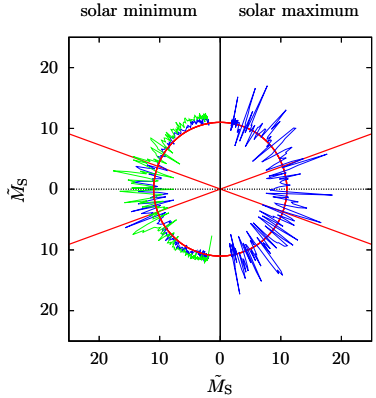
SWOOPS ion solar-wind flow directions have long-term systematic errors of up to about 2 degrees, making it difficult to determine $\mathcal{F}_L$ accurately.

Scalings of global solar-wind parameters

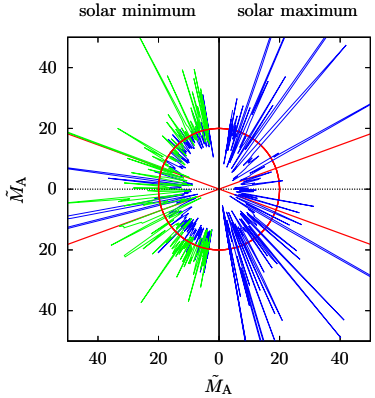
Ulysses observations of the scaled sonic ($\tilde{M}_\mathrm{S}$) and Alfvénic ($\tilde{M}_\mathrm{A}$) Mach numbers

Scaled to 1 au:

$$\tilde{M}_\mathrm{S} = U/c_\mathrm{S}$$



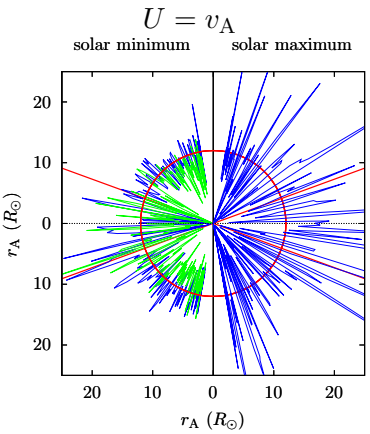
$$\tilde{M}_\mathrm{A} = U/v_\mathrm{A}$$

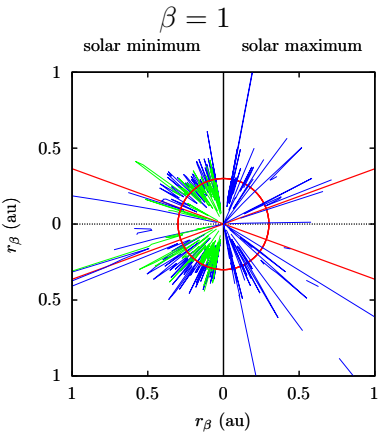


(Verscharen et al., 2021)

Scalings of global solar-wind parameters

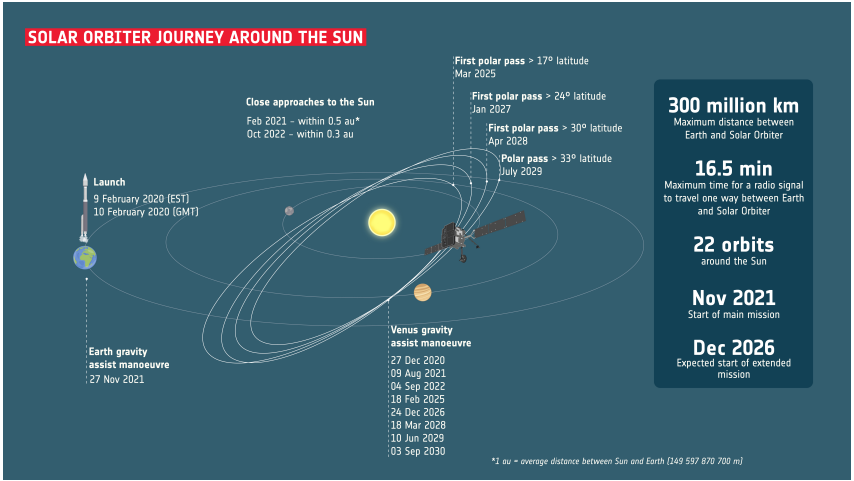
Ulysses observations of the Alfvén surface r_{A} and the $\beta = 1$ surface r_β





(Verscharen et al., 2021)

Solar Orbiter's orbit is bringing modern instrumentation close to the Sun and out of the ecliptic

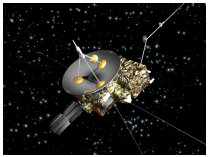


Conclusions

- Long-term measurements of conserved fluxes allow us to explore the global structure of the solar wind independent of heliocentric distance.
- Scaling laws provide the heliolatitudinal and solar-cycle dependence of the scaled Alfvénic and sonic Mach numbers as well as the Alfvén and $\beta = 1$ radii.
- Our results serve as predictions for observations with *Parker Solar Probe* and *Solar Orbiter*.

(Credit: ESA)

@DVerscharen @dverscharen



(Credit: ESA)

Literature

Daniel Verscharen, Kristopher G. Klein, and Bennett A. Maruca. The multi-scale nature of the solar wind. *Living Reviews in Solar Physics*, 16(1):5, December 2019. doi: 10.1007/s41116-019-0021-0.

Daniel Verscharen, Stuart D. Bale, and Marco Velli. Flux conservation, radial scalings, Mach numbers, and critical distances in the solar wind: magnetohydrodynamics and Ulysses observations. *Mon. Not. R. Astron. Soc.*, 506(4):4993–5004, October 2021. doi: 10.1093/mnras/stab2051.