New 3D solar wind speed and density models based on interplanetary scintillation observations

C. Porowski, M. Bzowski

M. Tokumaru

Heliosphere and LISM investigations - general overview

Boundaries of the heliosphere and the Local InterStellar Medium (LISM):

-difficult to investigate (no light emission, optically thin medium at short distance - astrophysical methods are useless)

-Voyagers – first point measurements *in situ* – but no other dedicated spacecraft to probe directly the heliopause and LISM

Indirect methods of investigations

Derivative (secondary) populations

-created due to charge exchange interaction between the Local Interstellar Medium (**LISM**) and Solar Wind (**SW)**

-*secondary ISN atoms*

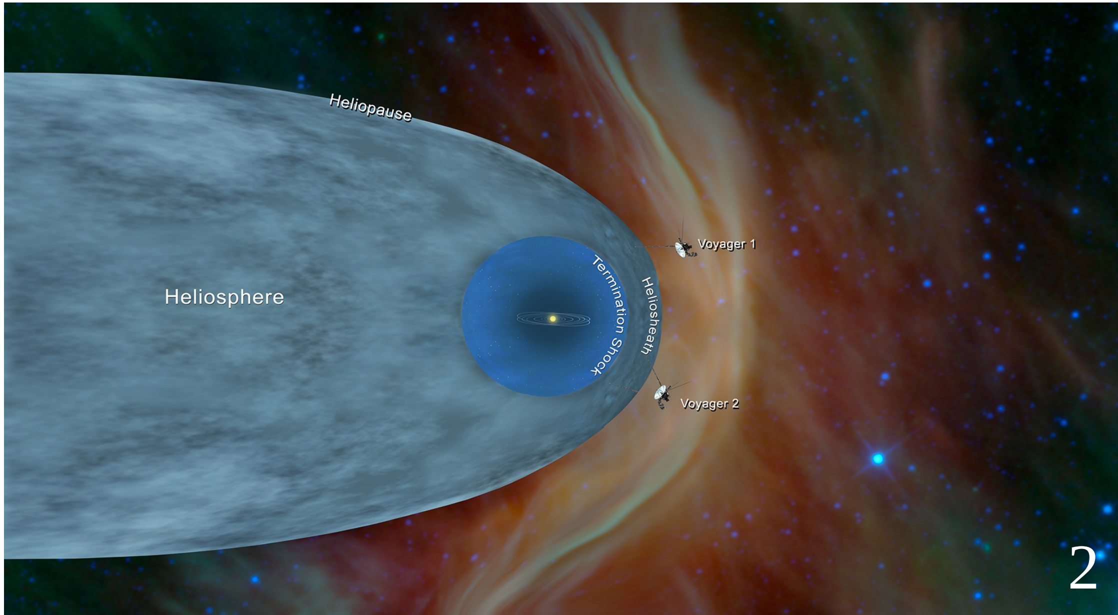
-*pickup ions (**PUIs**)*

-*energetic Neutral Atoms (**ENAs**)*

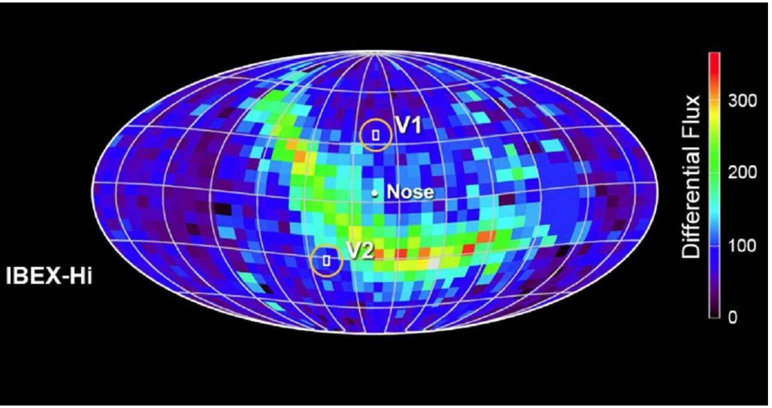
ISNeutral H atoms

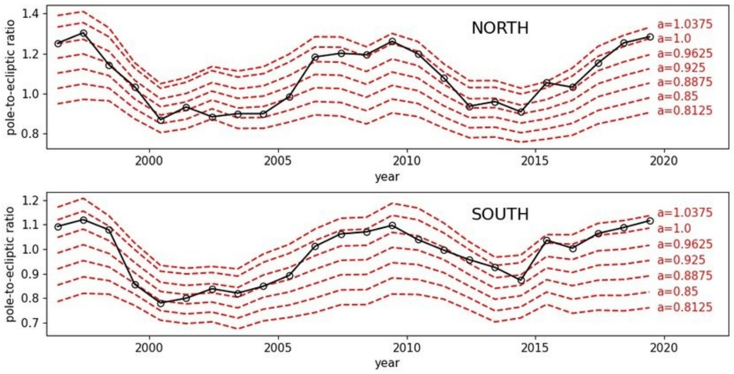
(Lyman-α helioglow)

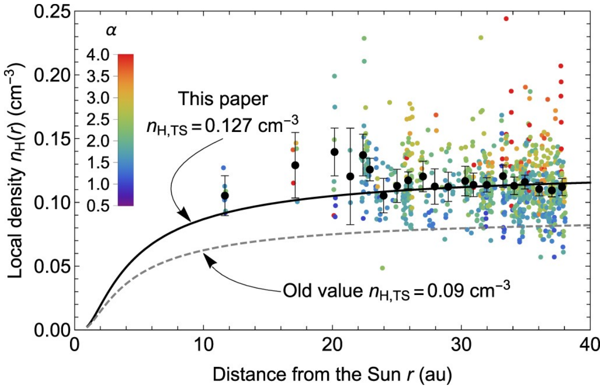
Data interpretation rely on the SW structure knowledge



Importance of the knowledge of the SW structure







Some of the most important results:

IBEX ribbon (unexpected feature) and 3D map of the heliosphere

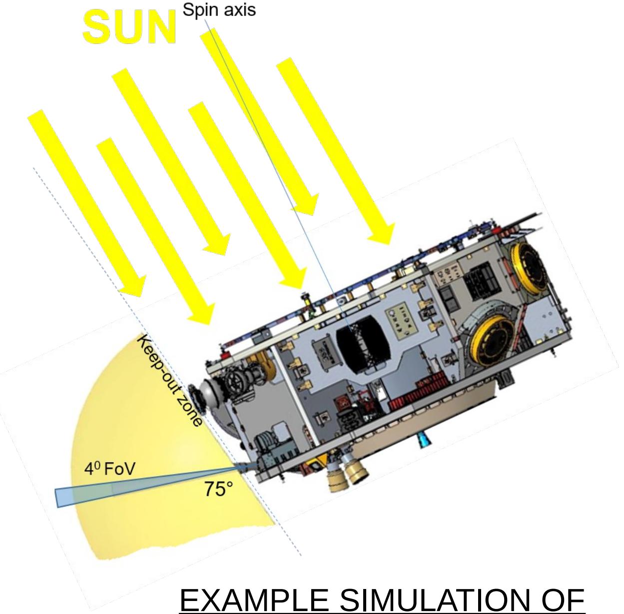
Time-dependent heliolatitudinal anisotropy of FUV/EUV – huge imapct on helioglow interpretation! (EUV: 10 to 121 nm, FUV: 122 to 200 nm)

Profile of local density of the interstellar neutral hydrogen

VLISM: speed = 25.9 km/s, T = 6150 K (through ISN helium observations)

Knowledge of the SW 3D structure is crucial to study the LISM and close vicinity of the Sun

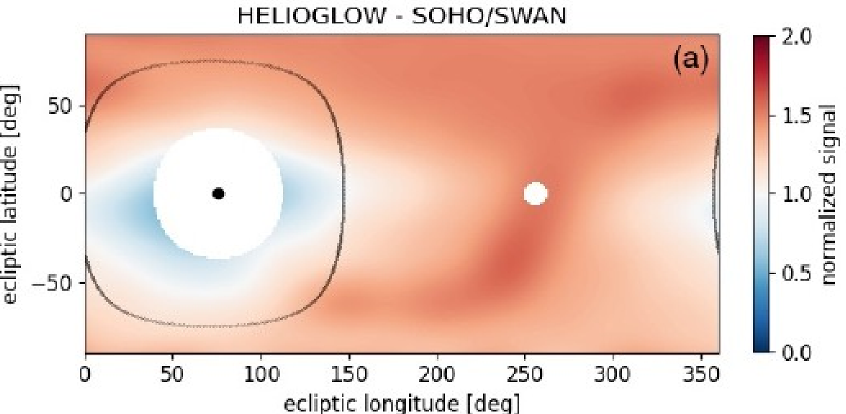
Sounding SW structure: GLOWS instrument on IMAP/NASA mission

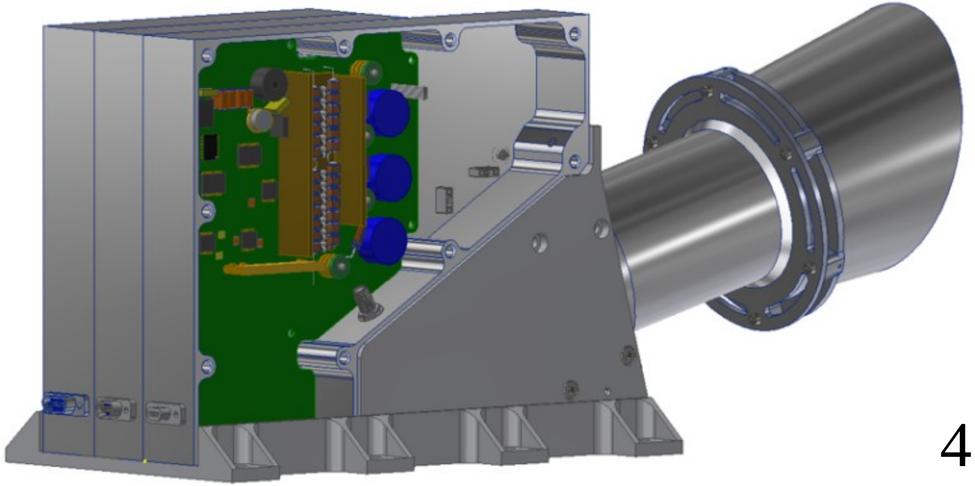


<u>to be launched in 2025</u>
fully designed and assembled by SRC Warsaw group
aim: measuring of the helioglow distribution
expected result: determination of the heliolatitudinal structure of the solar wind

Not only data but also SIMULATIONS are needed
Comprehensive suite for modelling neutral atoms in heliosphere
WawHelioIon, WawHelioUV, WTPM, WawHelioGlow

<u>EXAMPLE SIMULATION OF WawHelioGlow</u>

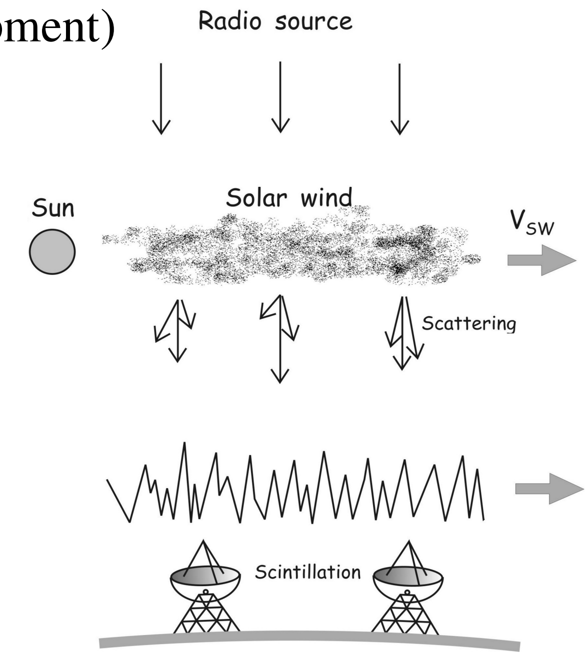




Sounding the SW structure: Interplanetary Scintillations (IPS)

Continuous data collection since 1985

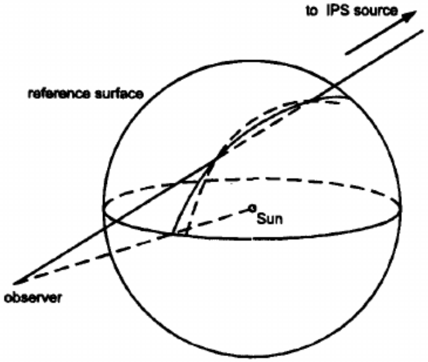
- performed by group led by *M. Tokumaru, ISEE,* 名古屋大学 Nagoya University
- 15-20 sources daily at $f = 327$ MHz
- antennas - up to 2010: 4, now: 3
- collection: continuously since 1985 with a gap in 2010 (upgrade of the equipment)
- data freely available online via ftp/http
- **it is the base of our model**



Solar Wind (SW): electron density fluctuations

- their relative values depend on the SW expansion speed
- they scatter the radio waves of point-like radio sources (observed intensity scintillates)
- relation speed-density: $\Delta N_e \propto V^{\alpha}$ (the faster the wind, the larger the fractional density fluctuations)
- frozen-in hypothesis
- uniform momentum flux among different speed flows

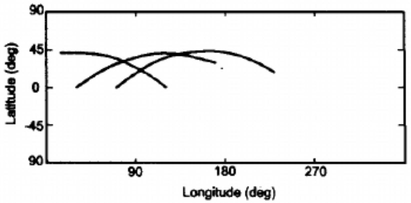
Interplanetary scintillations (IPS)

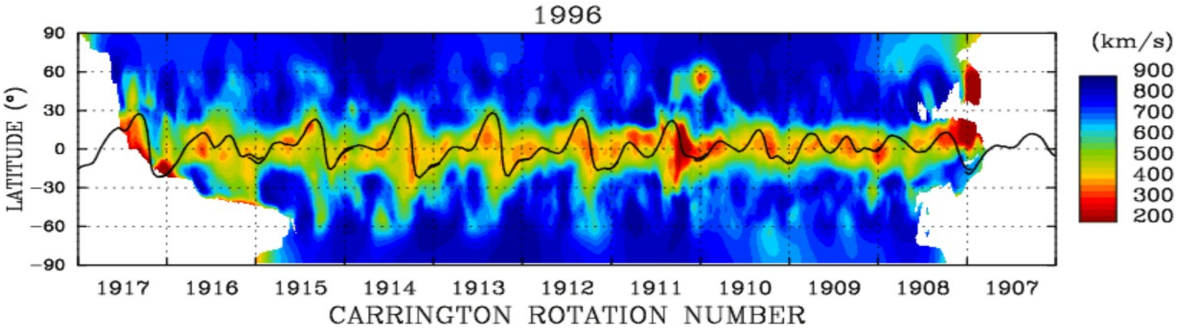


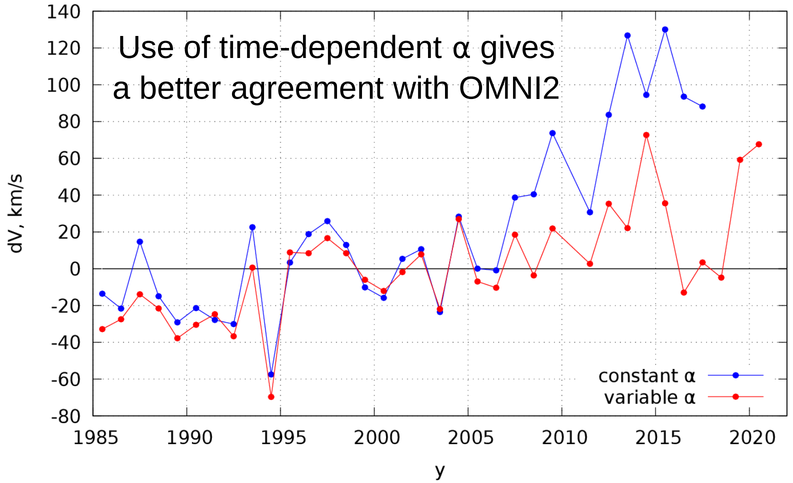
Data interpretation

- Line Of Sight (**LOS**) integration effect disturbes the measured SW speed
- removing of **LOS** effect *via* Computer Assisted Tomography (**CAT**)
- **CAT rely on** the relation speed-density: $\Delta N_e \propto V^{\alpha}$
- **α** is time dependent due to secular changes of SW properties (Tokumaru 2021)
- outcome of **CAT**: Carrington Speed Maps

(*the maps are projected onto a 1x1 degree mesh on a sphere*):



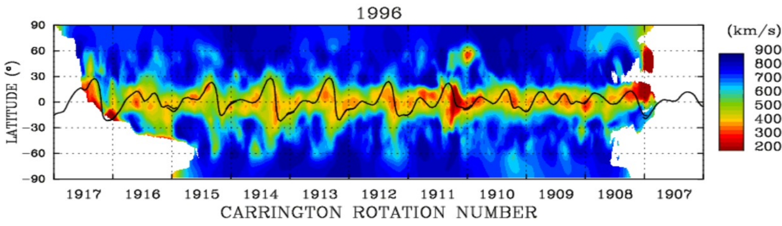




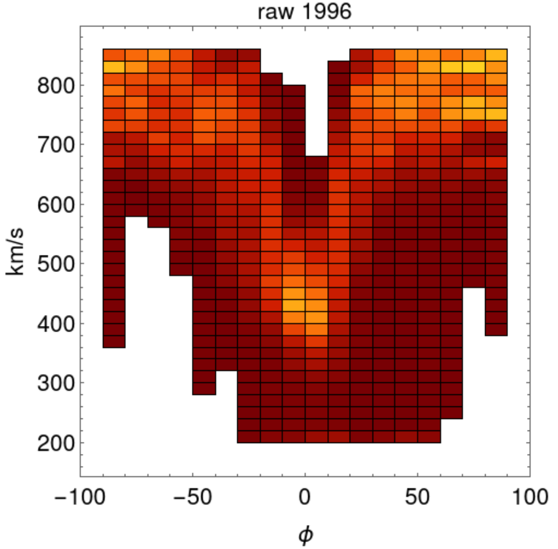
Modelling of profiles: preprocessing of the Carrington Maps

Averaging of the Carrington Maps

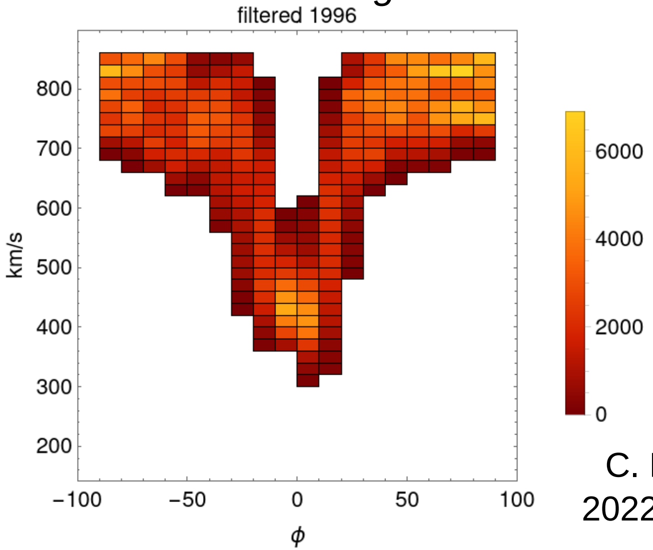
- aim – latitudinal average profiles: elimination of longitude
- extensive **background appears and biases** the average profiles
- the background is **filtered** before averaging (*see plots below*)
- filtering – **statistical tools used**
- mean correction for bias is characteristic
- time resolution: Carrington Rotations



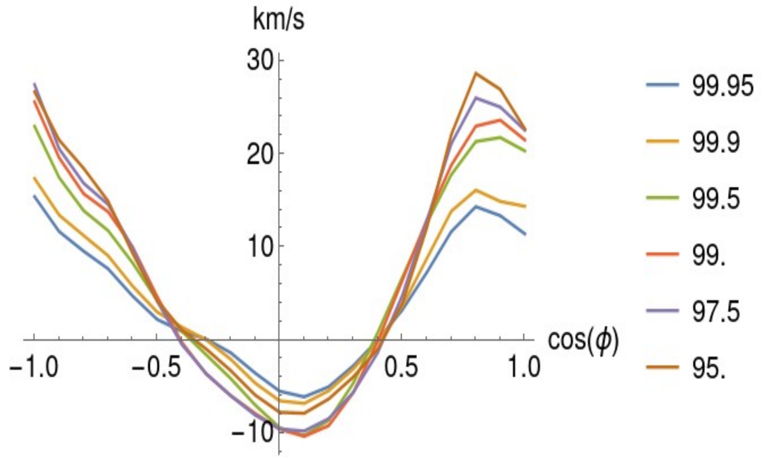
before filtering



after filtering



MEAN CORRECTION



C. Porowski et al., 2022ApJS..259....2P

Model formulation

Model based on Legendre polynomials

Domain: $z = \cos(\phi)$

Model to fit: $$V(z) = \sum_{i=1}^{N} Q_i P_i(z)$$

Derivatives at the poles: $$\left.\frac{dV}{dz}\right|_{z=\pm 1} = 0$$

Why to use Legendre polynomials:

- axially symmetrical problem
- flexible: no arbitrary assumption on the shape of the profile
- fitting done for the entire latitude range simultaneously
- we are able to describe the mean profile shape accurately

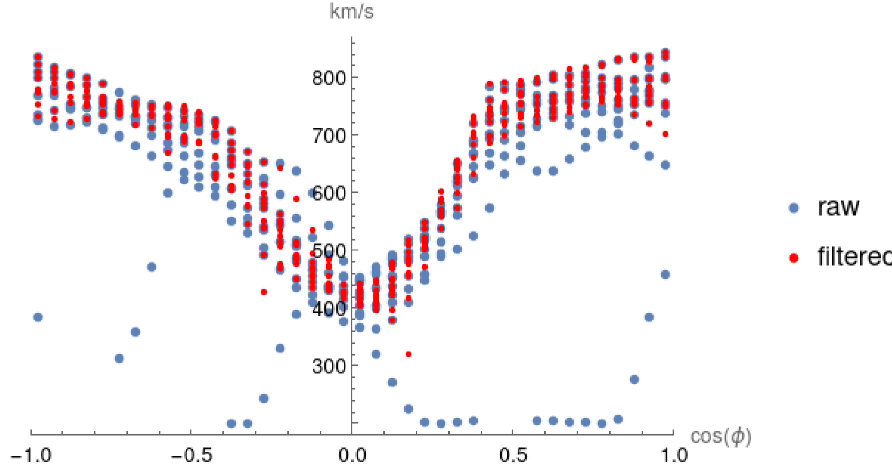
Fitting:

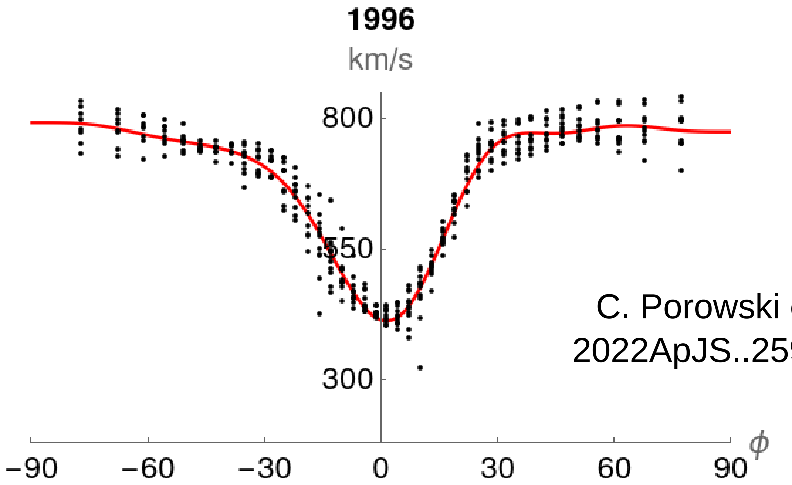
* Legendre order set empirically to 20

* Each year fitted individually

* Fitted model parameters Q_i: let’s treat them as time series

after filtering and binning





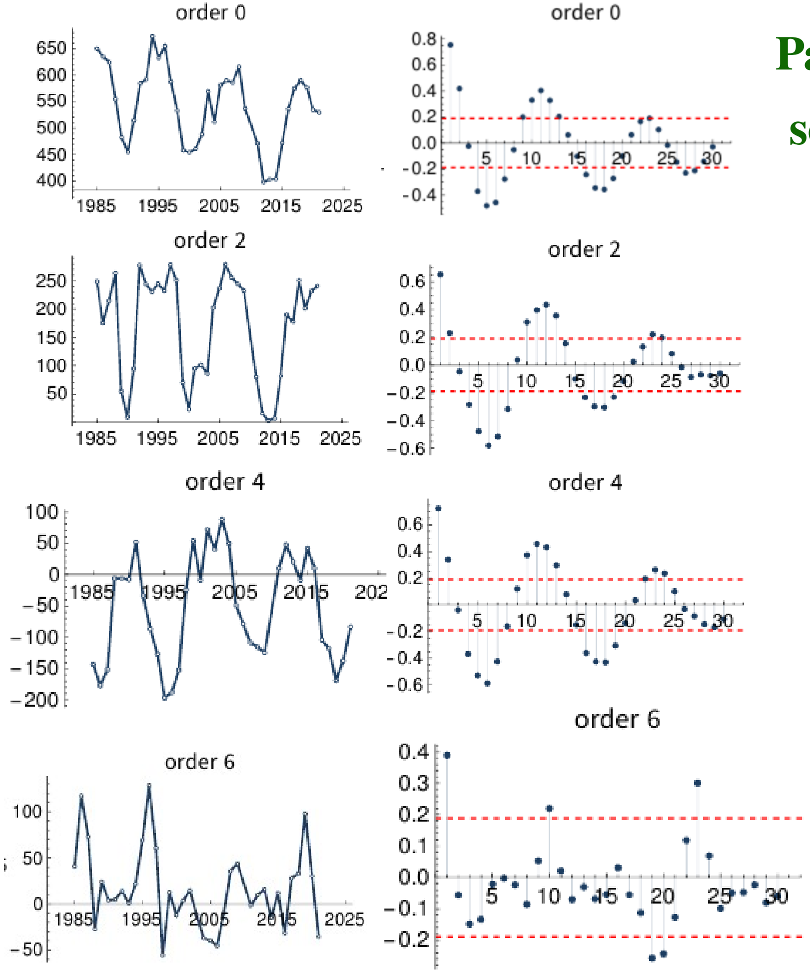
C. Porowski et al., 2022ApJS..259....2P

PROPERTIES OF MODEL Q_i`s

SYMMETRIC Q_i

three first: 11 years seasonality dominates

starting from 4-th other periodicities appear

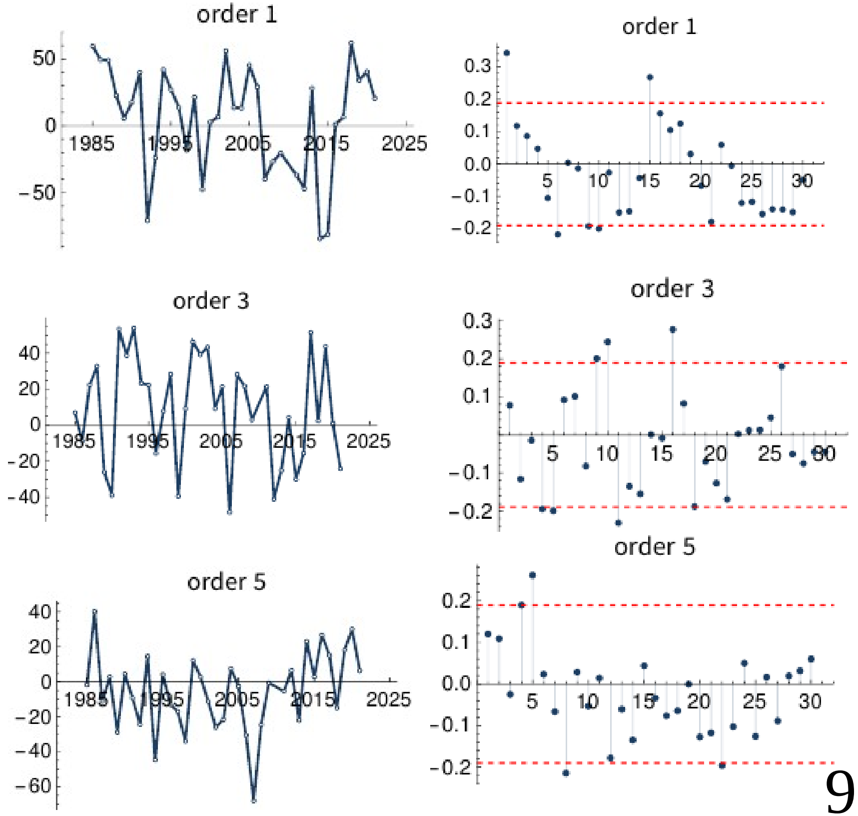


Parameters Q_i follow the solar cycles like proxies

We try to use it empirically

ASYMMETRIC Q_i

Pure periodic specificity



PROPERTIES OF PROXIES

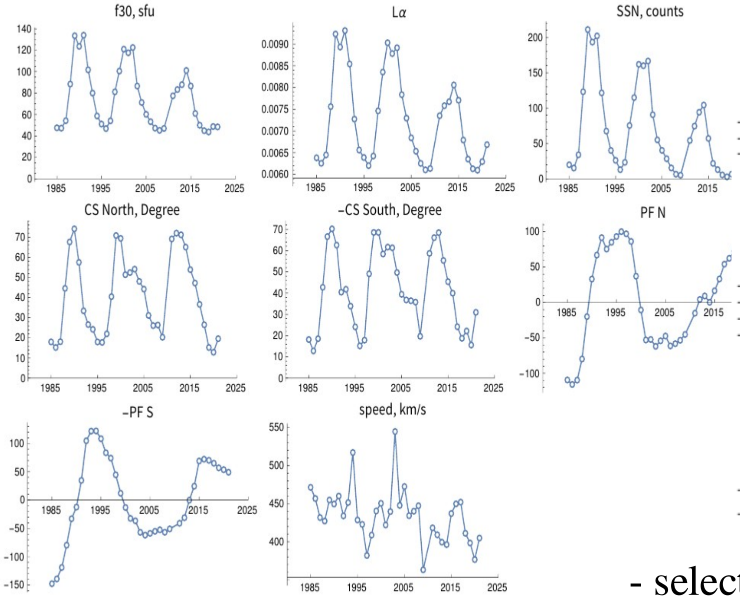
Proxies taken into account

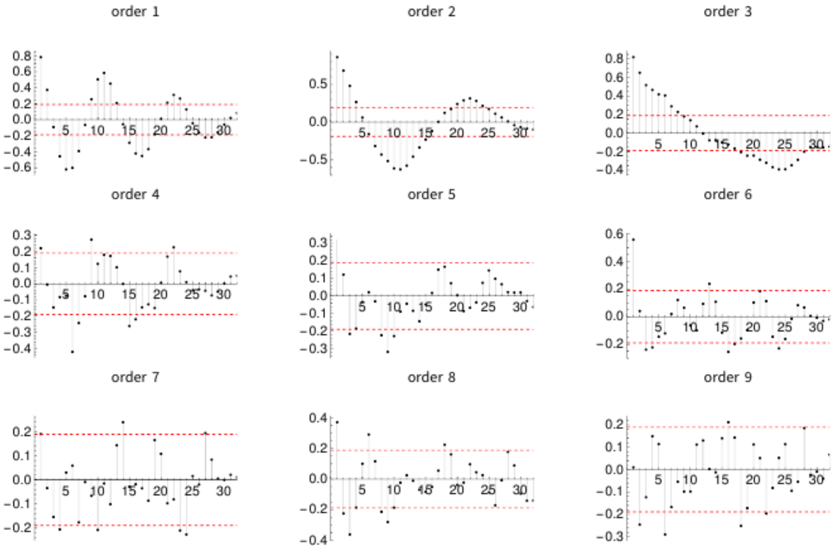
- radio flux at 30 cm

  radio flux at 10.7 cm
- solar irradiance in Ly-α line
- modified sunspot number
- current sheet tilt angle (N, S)

  $\mathrm{MgII}_{c/w}$ ratio (Bremen)
- polar field strength (N, S)
- speed

  density





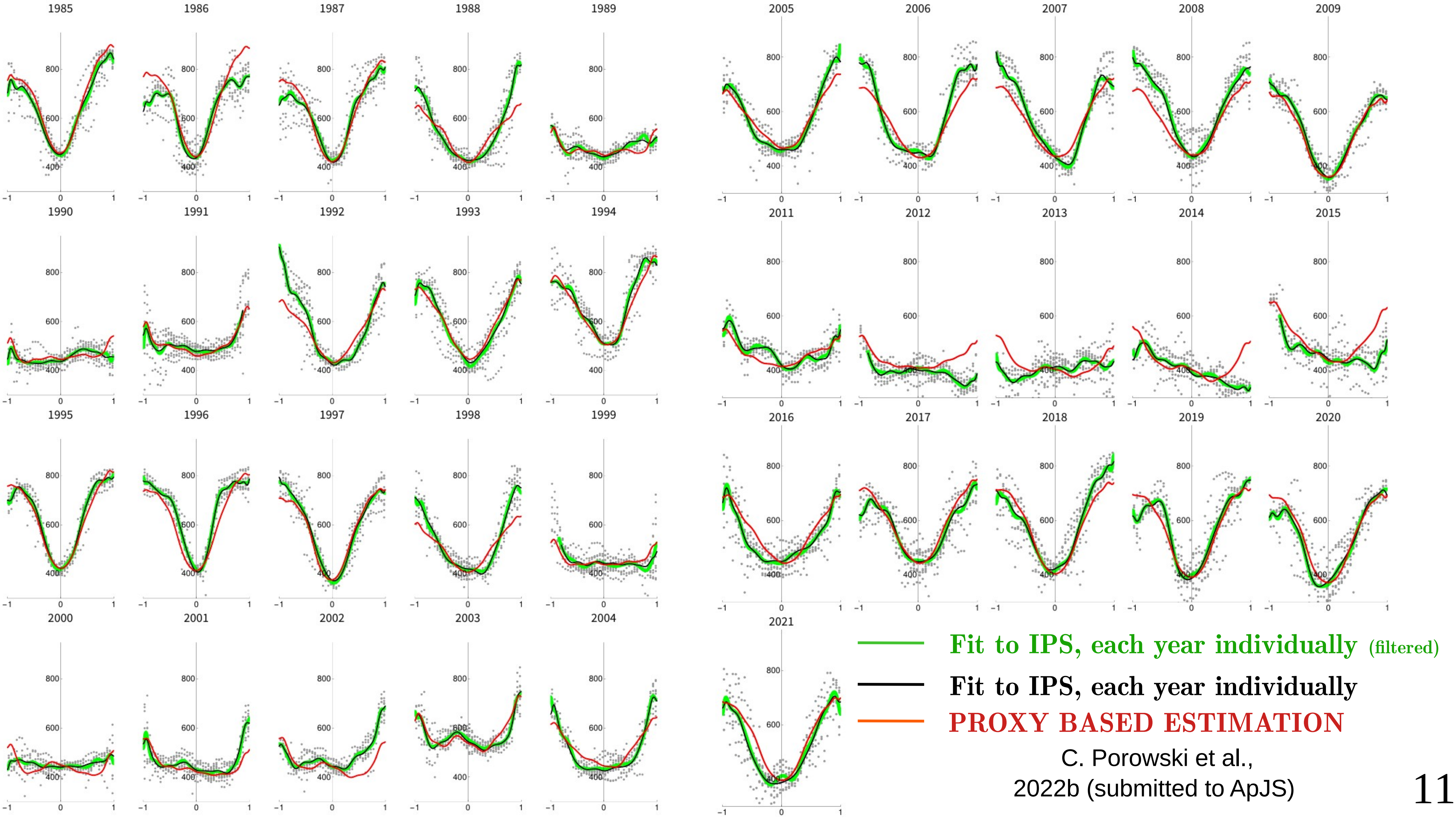
- selection empirically improved
- selected proxies are easily available
- ACF: commonly known seasonalities as expected

Strategy:

We separate the Q_i and proxy variabilities into uncorrelated channels

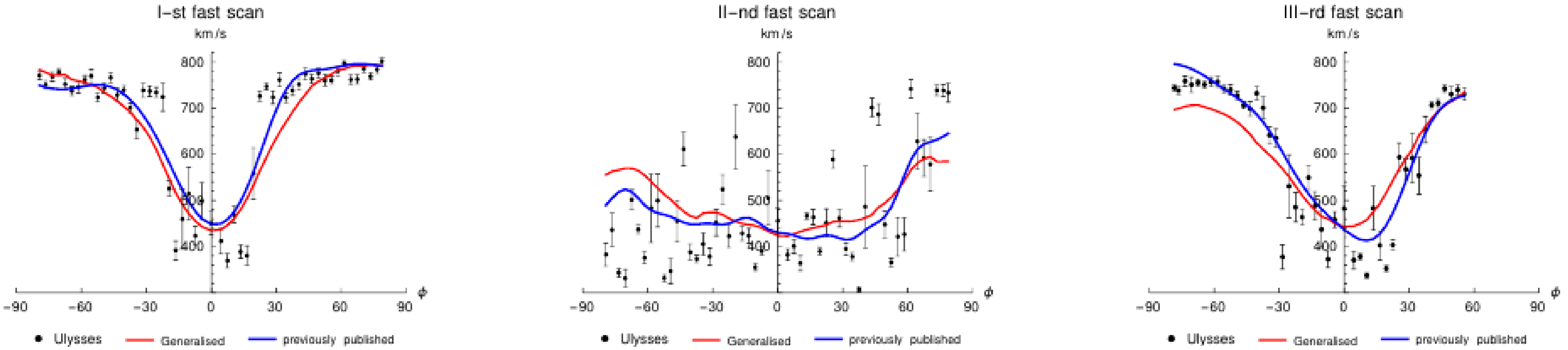
Next we look for general dependence between the Q_i and proxies to express one by another (fit to all years)

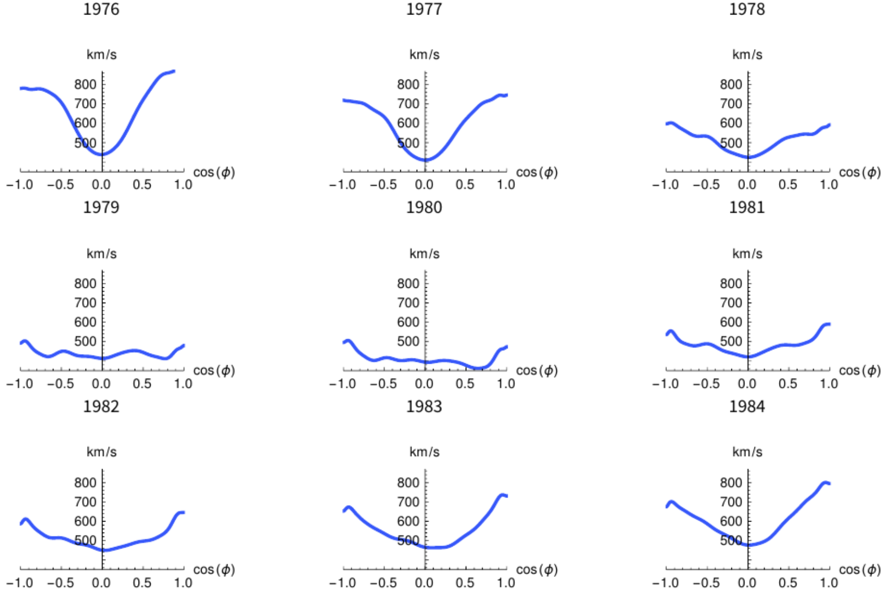
$$PC_i^{SWmodel}(t) = c_i + \sum_{j=1}^{n} M_{ij}\, PC_j^{proxy}(t),$$



C. Porowski et al.,
2022b (submitted to ApJS)

Results: comparison with Ulysses and prediction





Prediction before IPS era-preliminary!
(1976-1984, and **2010**)

C. Porowski et al.,
2022b (submitted to ApJS)

Conclusions

<u>The new SW speed and density model characteristics:</u>

- is a part of **WawHelIon 3DSW** model
- model parameters (Q_i) confirm reported correlations with proxies and periodicities in SW
- reconstruction of SW profiles *via* proxies
- proper reproduction of Ulysses measurements
- may be used to predict SW speed structure in past/future
- model is applicable to filling gaps in SW **speed and density**
- a potential tool for testing of SW creation models
- opened questions are still ahead (*higher temporal resolution, response for the changing physical parameters of SW, etc., work in progress*)

Different authors provide hints: correlations, periodicities in SW, our model synthesises empirically these properties into a whole piece

Thank you for your attention

The new SW speed and density model characteristics:

- is a part of **WawHelIon 3DSW** model
- model parameters (Q_i) confirm reported correlations with proxies and periodicities in SW
- reconstruction of SW profiles *via* proxies
- proper reproduction of Ulysses measurements
- may be used to predict SW speed structure in past/future
- model is applicable to filling gaps in SW **speed and density**
- a potential tool for testing of SW creation models
- opened questions are still ahead

Results: residuals

$$PC_i^{SWmodel}(t) = c_i + \sum_{j=1}^{n} M_{ij}\, PC_j^{proxy}(t),$$

- in equatorial area of the Sun the fit seems fine
- the higher heliolatitudes the larger spread
- the spread does not depend on profile representation
- the spread is due to poor temporal resolution which do not follow dynamic changes of SW profiles

WHY SPREAD INCREASES TOWARDS THE POLES?

EXAMPLE PLOTS EXPLAIN IT

changing to maximum | middle of minimum