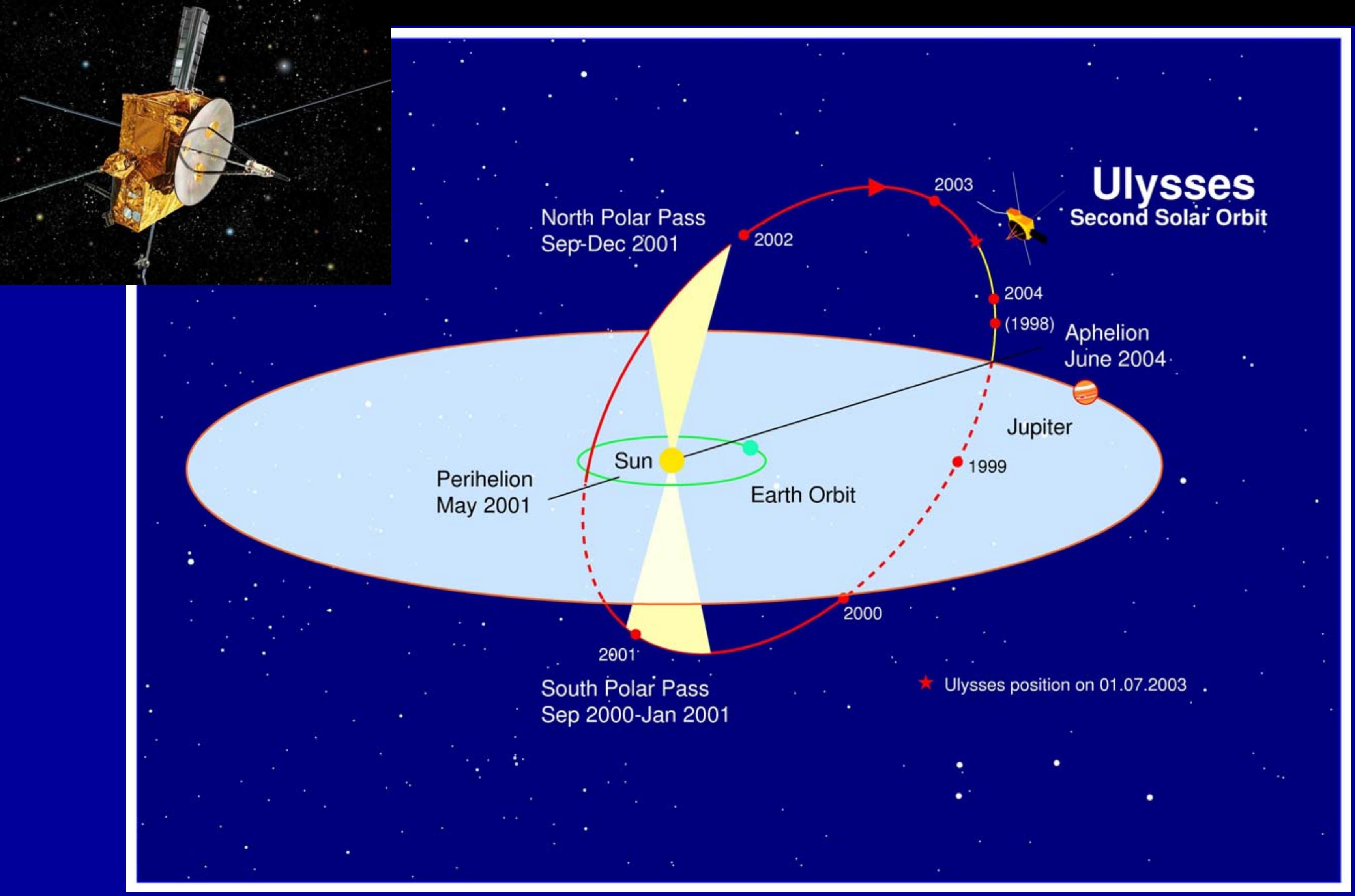
Ulysses in the 21st Century

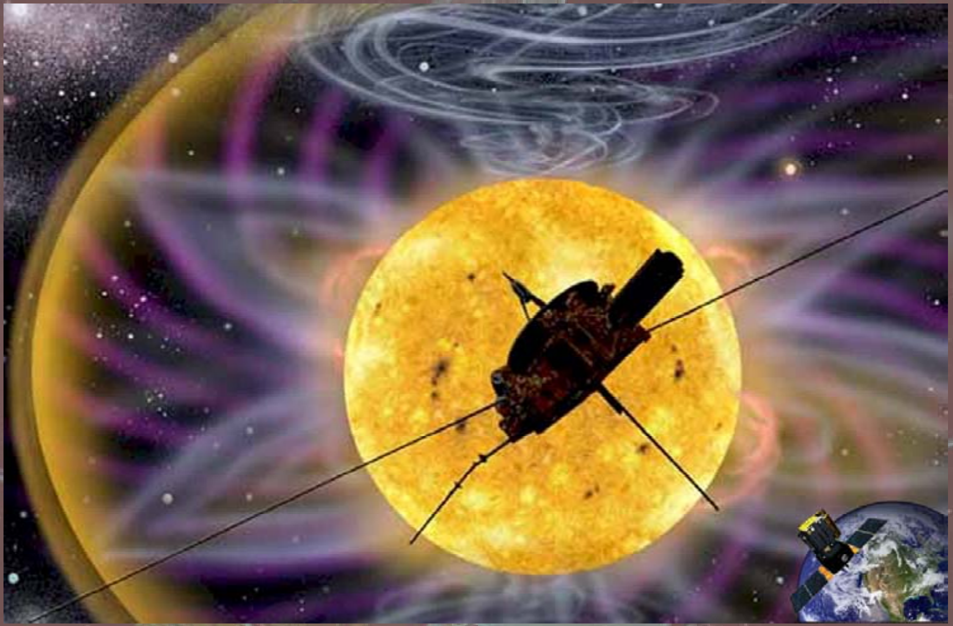
Steve Suess, NSSTC

(with thanks to Richard Marsden, ESA Project Scientist)

- Introduction to the Ulysses Mission
- Overview of orbits 1 & 2
- The 3rd orbit, 2004-2008 :
  - Transport of particles and dust in latitude
  - Composition throughout the heliosphere
  - Collaboration with other missions
- The spacecraft, power, communications, ..., nutation



The original objective: *"Investigate for the first time as a function of heliographic latitude the properties of the solar wind, the structure of the Sun/wind interface, the heliospheric magnetic field, solar radio bursts and plasma waves, solar X-rays, solar and galactic cosmic rays, and both interstellar and interplanetary neutral gas and dust."*

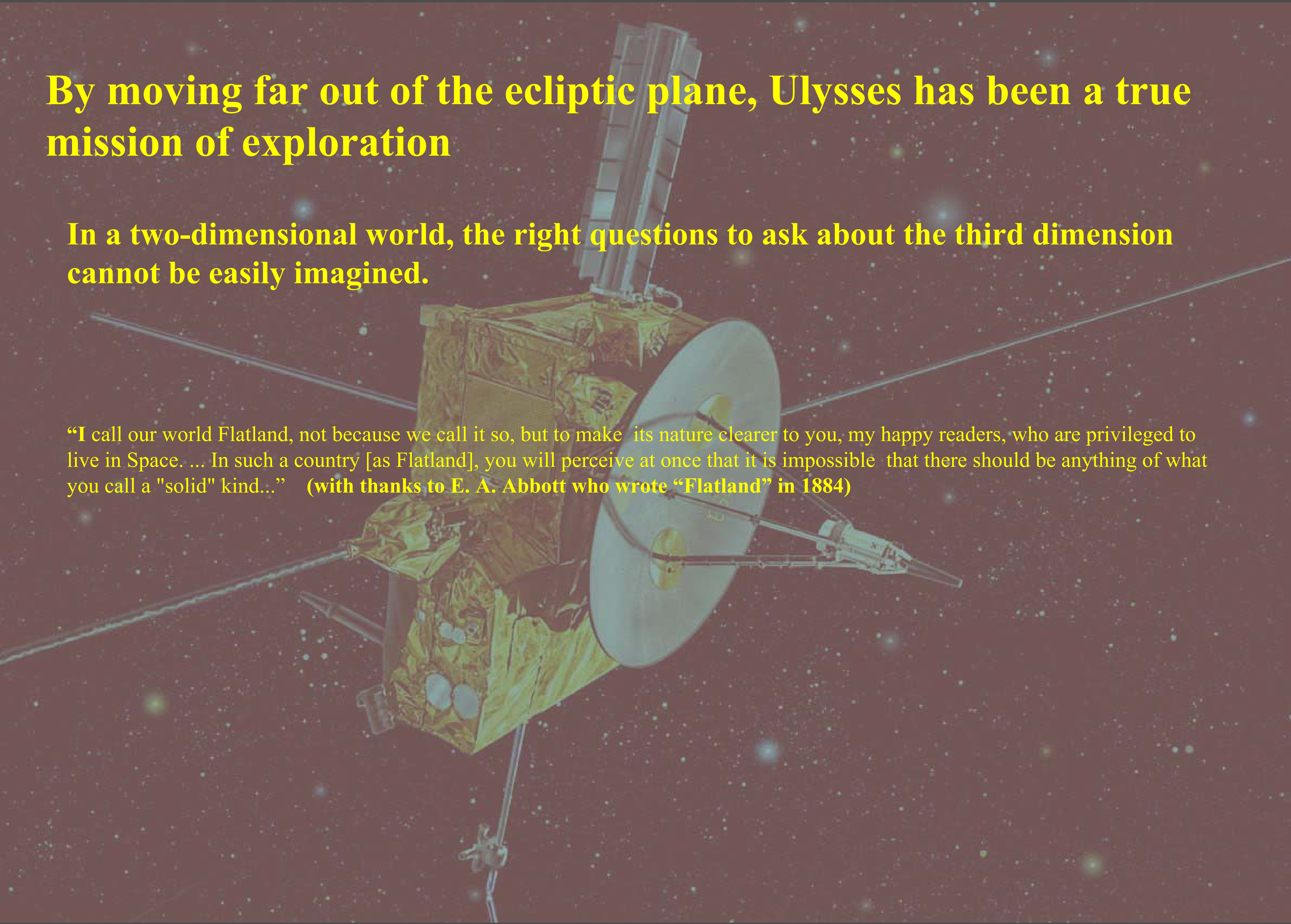


Ten experiments measure *in situ* fields and particles, dust, UV, X-rays, and gamma rays. With these experiments and its polar orbit, Ulysses has met the original objective and gone on to make fundamental contributions and discoveries related to the 3D heliosphere and also to the Sun, Jupiter, the local interstellar medium (LISM), the Milky Way, and the origins of gamma ray bursts. Ulysses science has evolved to become broad based and its success has made it the touchstone for global heliospheric studies. Ulysses has even come to support the NASA and International Living With a Star programs through its help in developing 3D models of heliospheric dynamics.

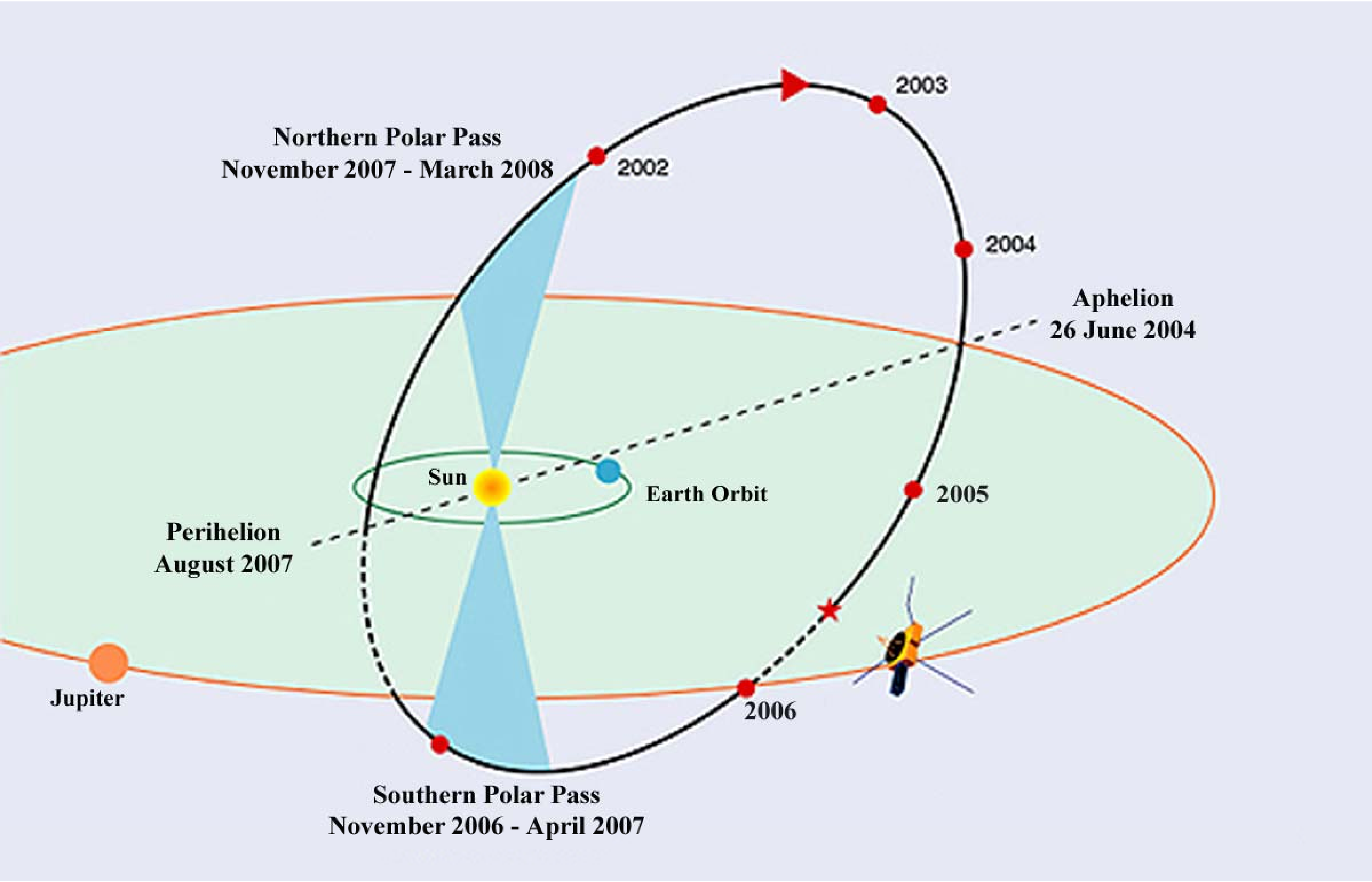
By moving far out of the ecliptic plane, Ulysses has been a true mission of exploration

In a two-dimensional world, the right questions to ask about the third dimension cannot be easily imagined.

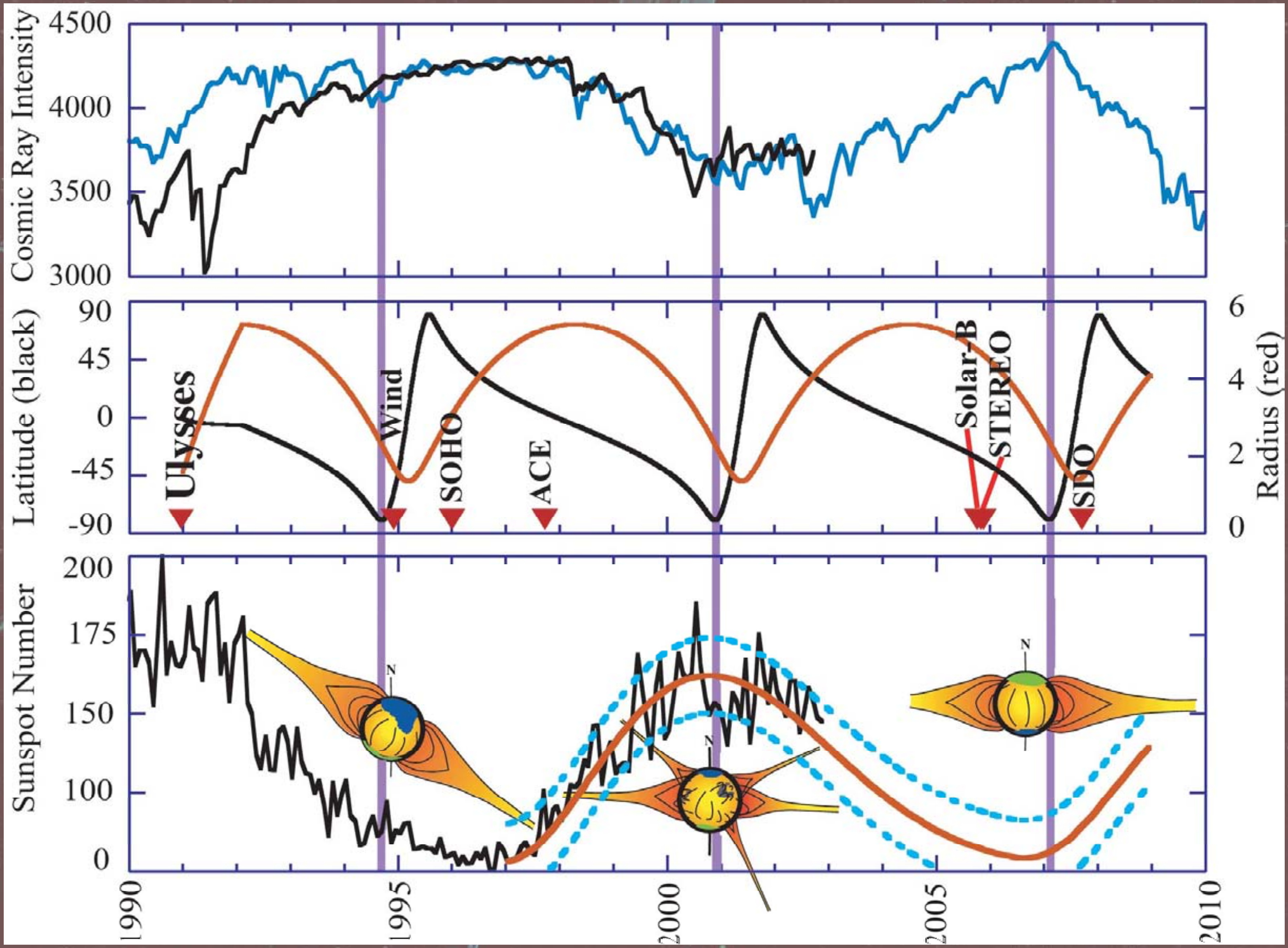
“I call our world Flatland, not because we call it so, but to make its nature clearer to you, my happy readers, who are privileged to live in Space. ... In such a country [as Flatland], you will perceive at once that it is impossible that there should be anything of what you call a "solid" kind...” **(with thanks to E. A. Abbott who wrote “Flatland” in 1884)**

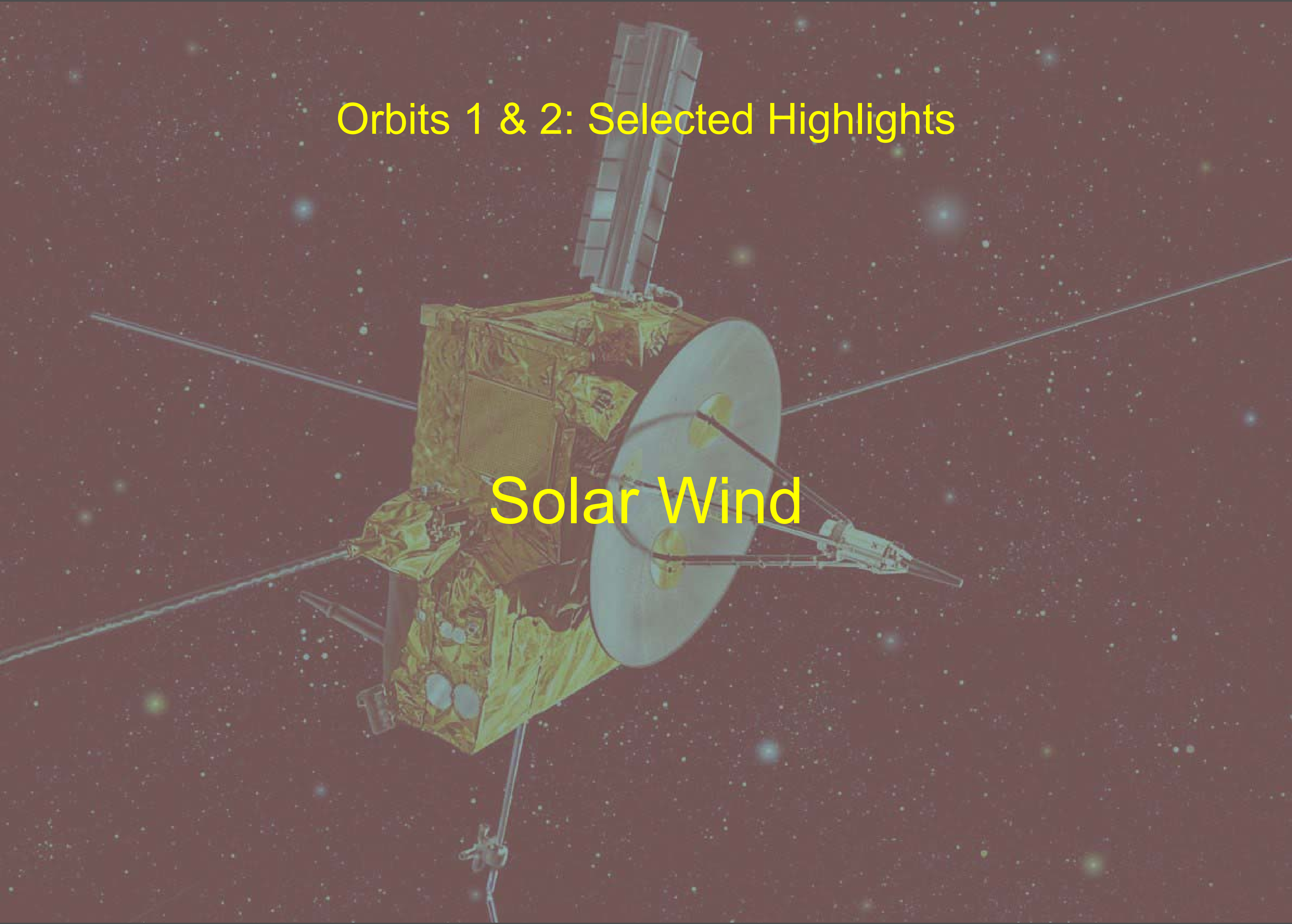


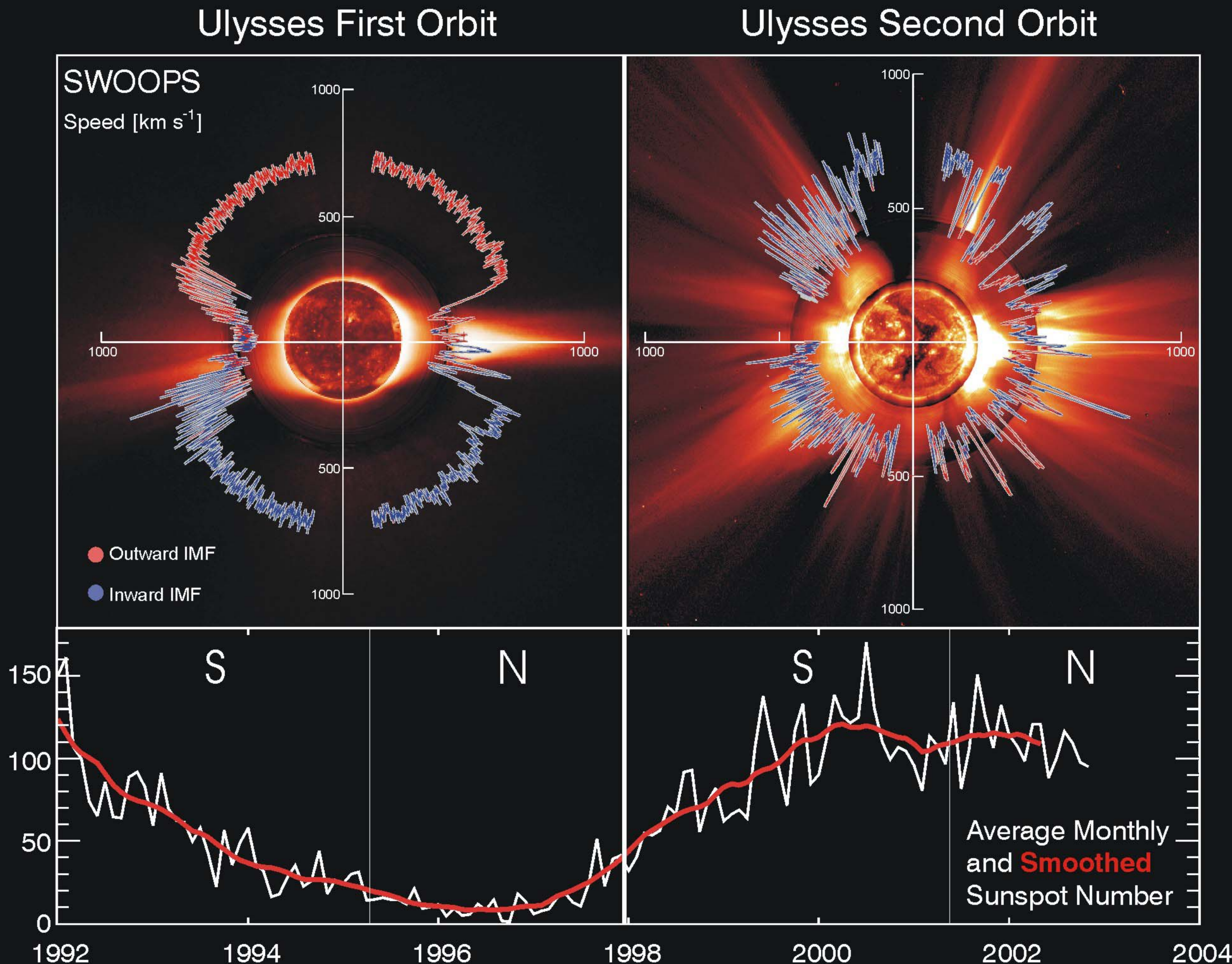
“Ulysses Full Cycle” orbit



Top Panel: Black - CR intensity from the Climax, Colorado monitor. Blue - Climax data shifted to the right by 22 years, the length of the “Hale” (full) solar magnetic cycle. The 11 year solar cycle modulation is not the same in the two halves of the magnetic cycle due to **VxB** drifts of the particles.



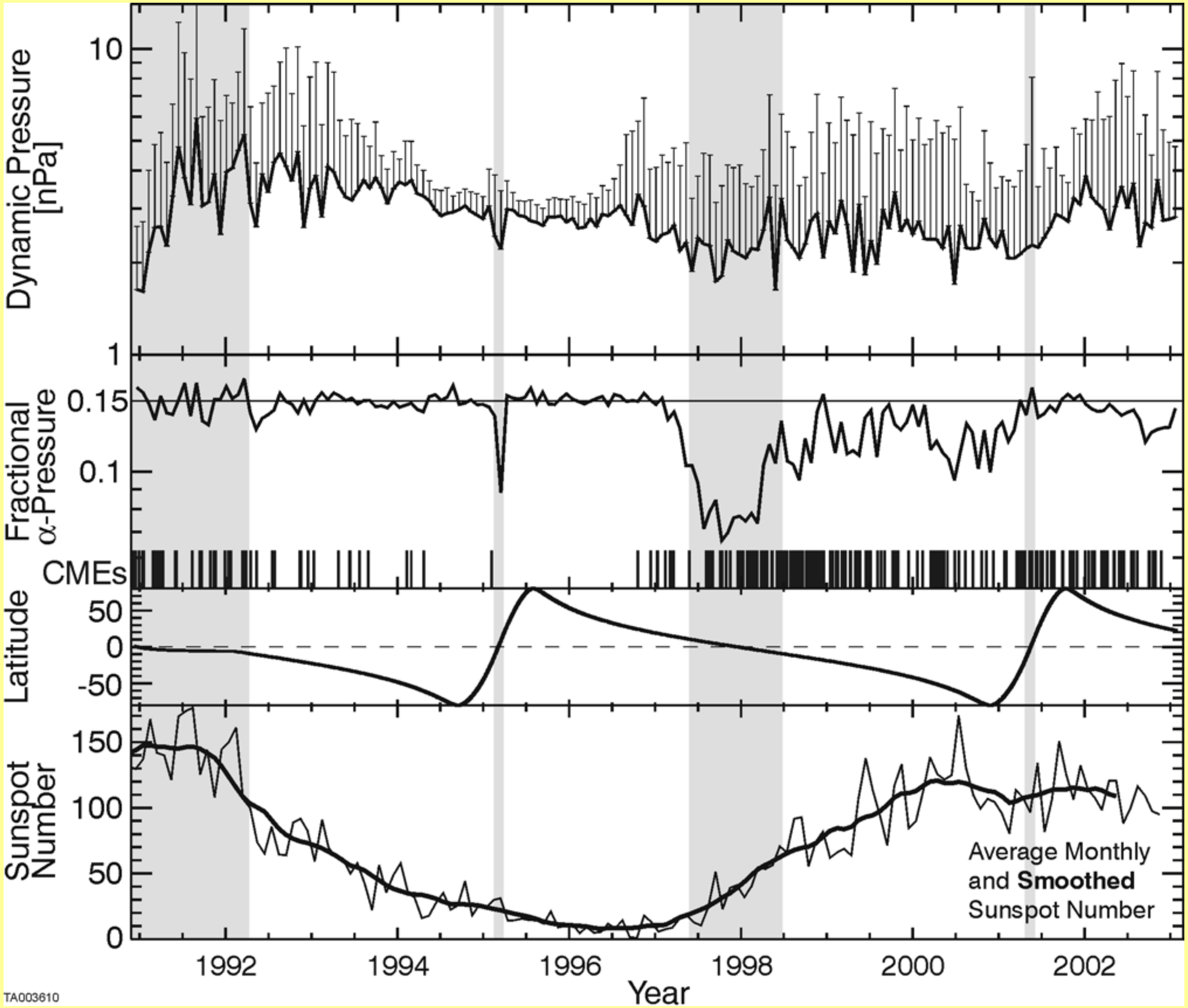

Orbits 1 & 2: Selected Highlights
Solar Wind



TA003573R

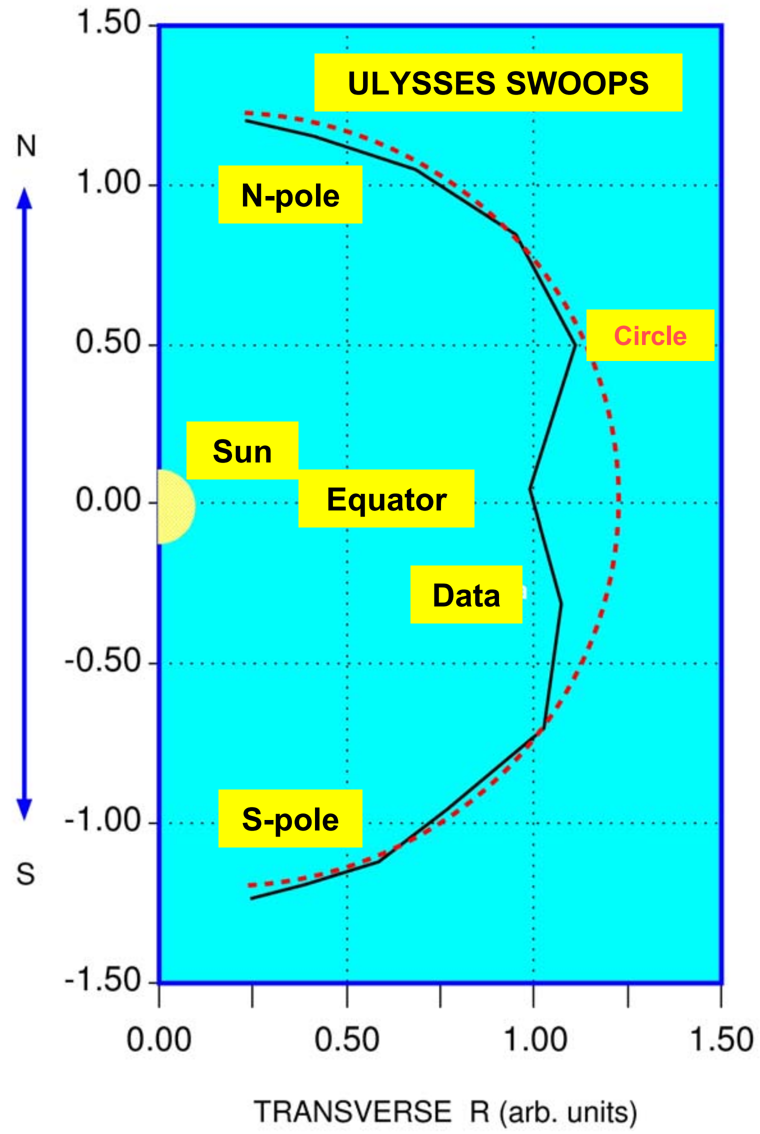
McComas et al., *Geophys. Res. Lett.*, 2003.

Solar Wind Dynamic Pressure

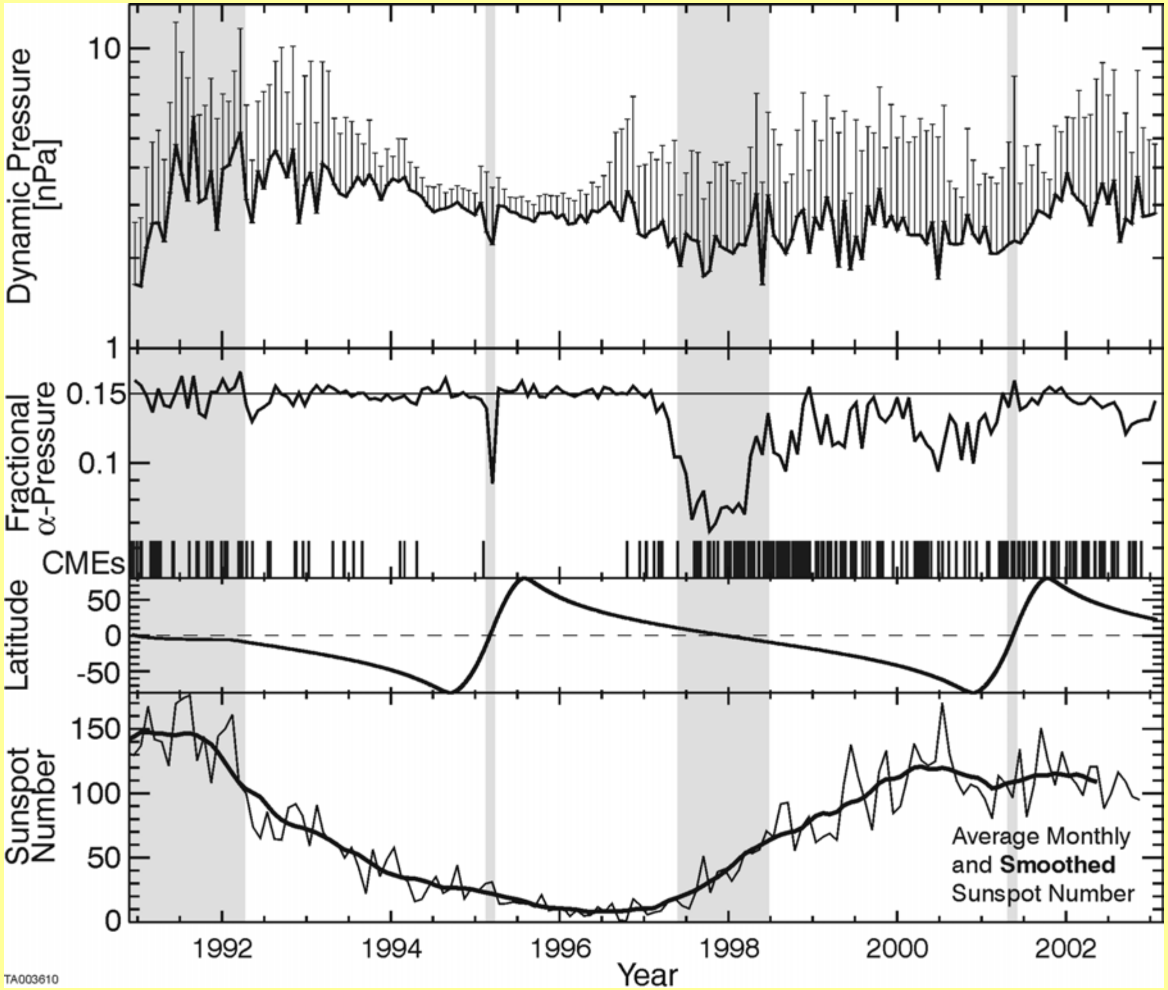


McComas et al., GRL, 2003

THE SHAPE OF THE HELIOSPHERE IN 1995, INFERRED FROM ULYSSES SOLAR WIND PLASMA MEASUREMENTS



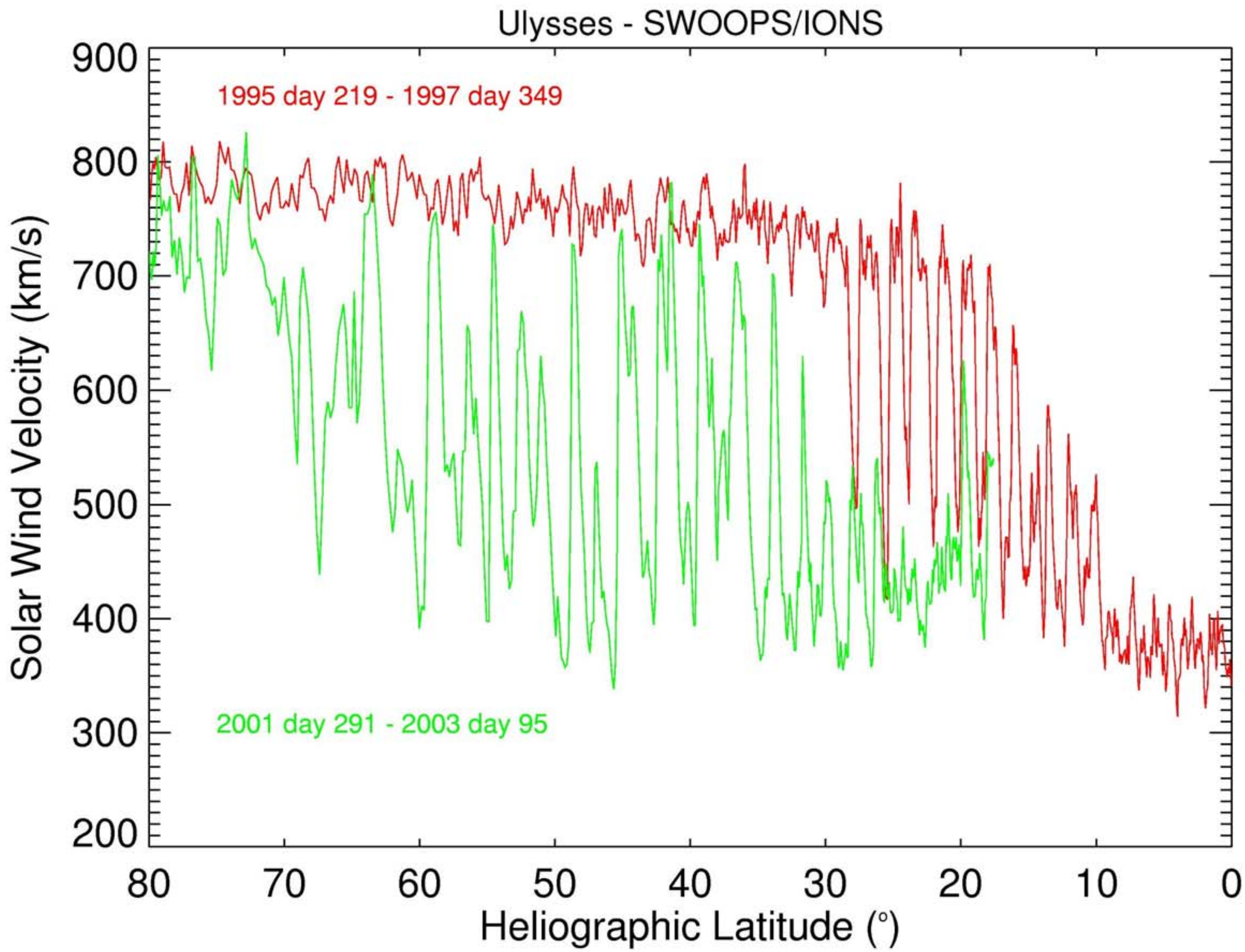
Solar Wind Dynamic Pressure



The dynamic pressure at the 2000-2001 solar maximum was much lower than at the 1992 solar maximum.

Was the heliospheric termination shock moving inwards and closer around 2002-2003?

McComas et al., GRL, 2003

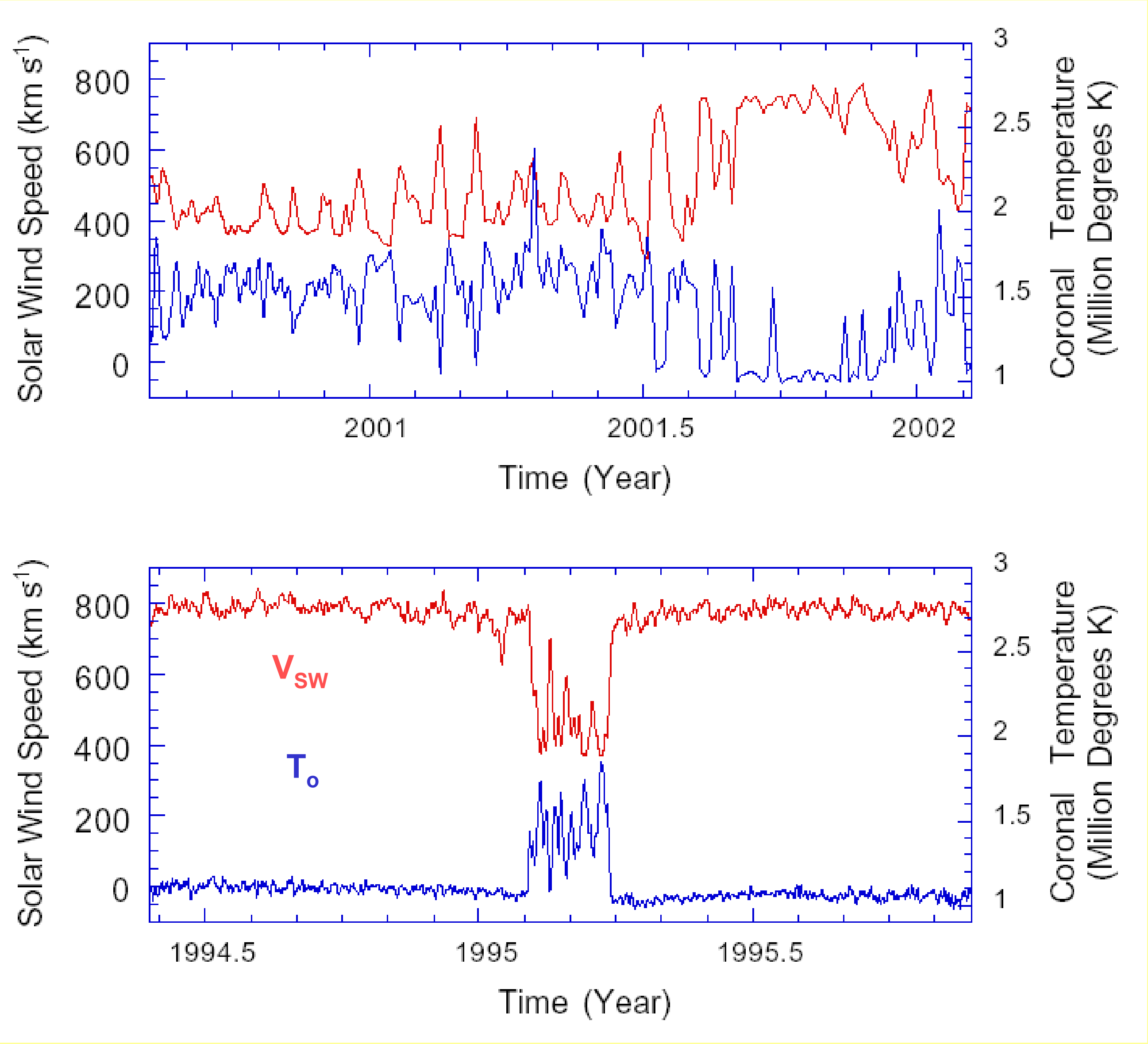


The peak solar wind speeds in 2001-2003 display the *same latitudinal gradient* that the fast wind showed in 1995-1997.

Insights into solar wind origin

Solar Maximum

Solar Minimum



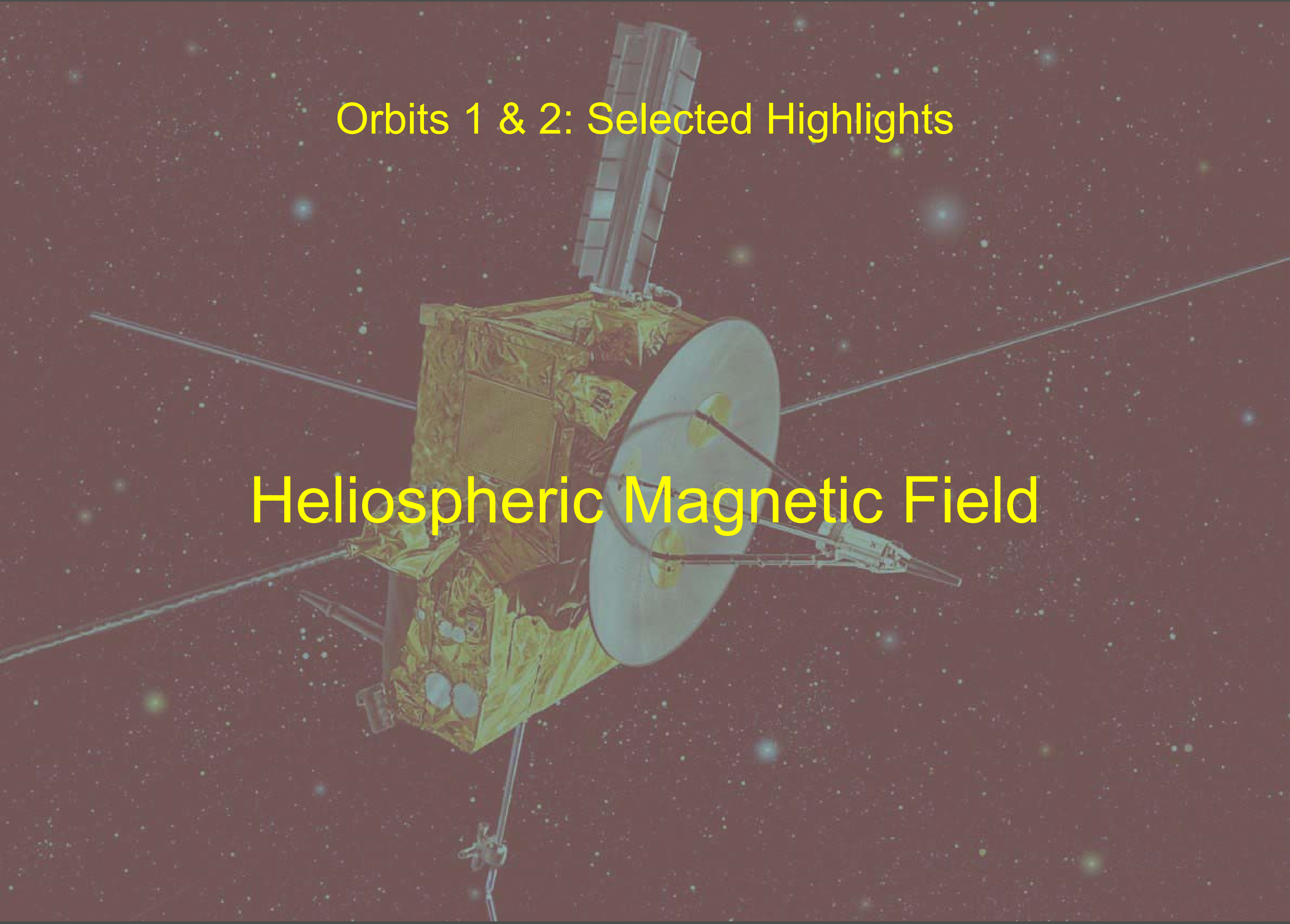
After Gloeckler et al., JGR, 2003

Solar Wind Summary

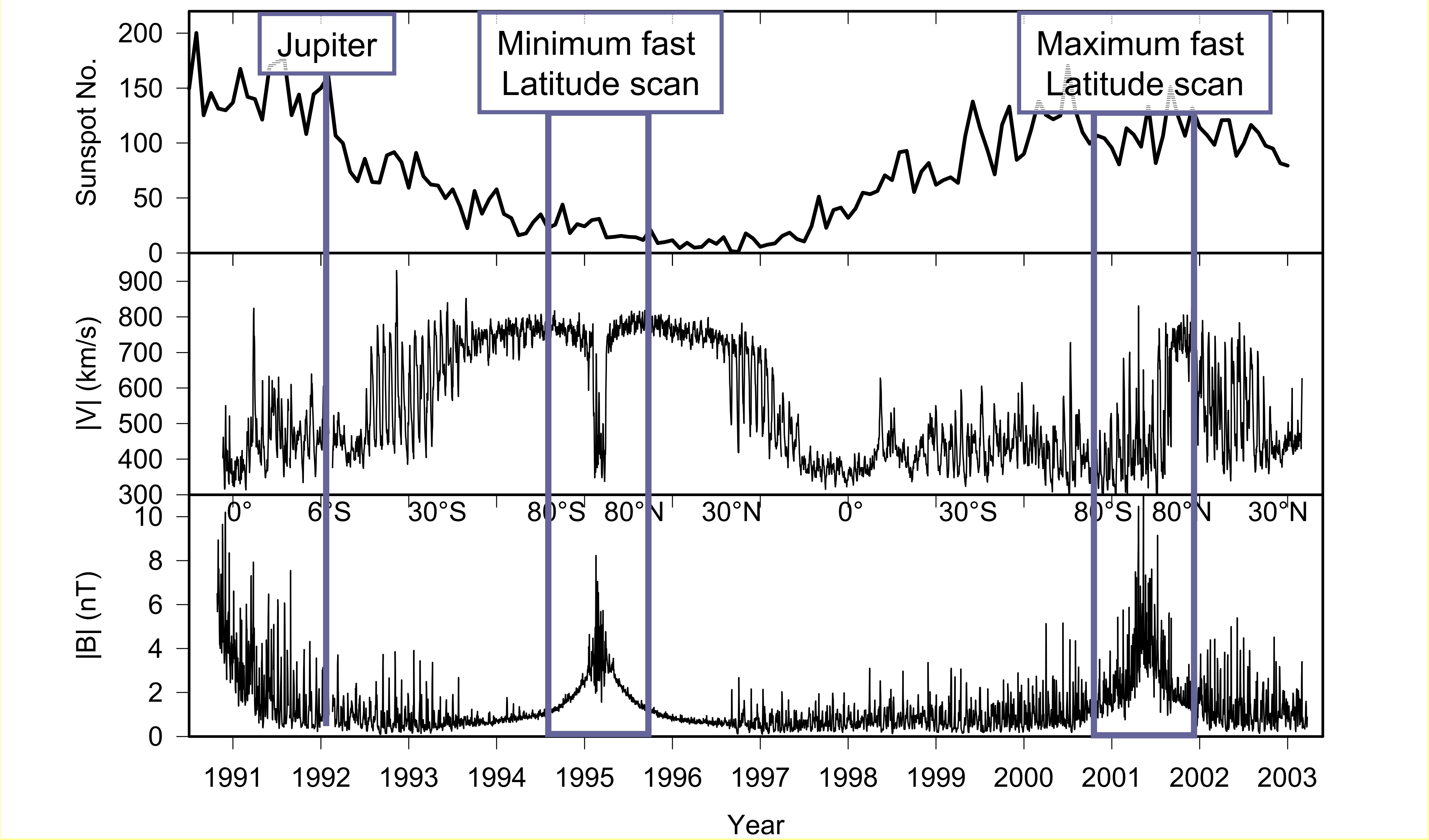
- Minimum vs. Maximum:
  - Min: simple bimodal structure
  - Max: variable flows at all latitudes (CH, CME); highly inclined streamer belt; peak speeds show same latitudinal dependence as at max => physical rotation is important
- Dynamic pressure $m_p(n_p v_p^2 + 4n_\alpha v_\alpha^2)$:
  - Large variation (factor ~2) seen 1991-2001
  - Pressure at recent solar max lower than 1991 => smaller heliosphere? Voyager TS encounter?
- Solar wind origin:
  - $V^2_{SW} \sim 1/T_{O^{7+}/O^{6+}}$
  - Reconnection between open field lines and coronal loops
  - large loops in streamer belt: slow SW
  - smaller loops in CH: fast SW

Orbits 1 & 2: Selected Highlights

Heliospheric Magnetic Field

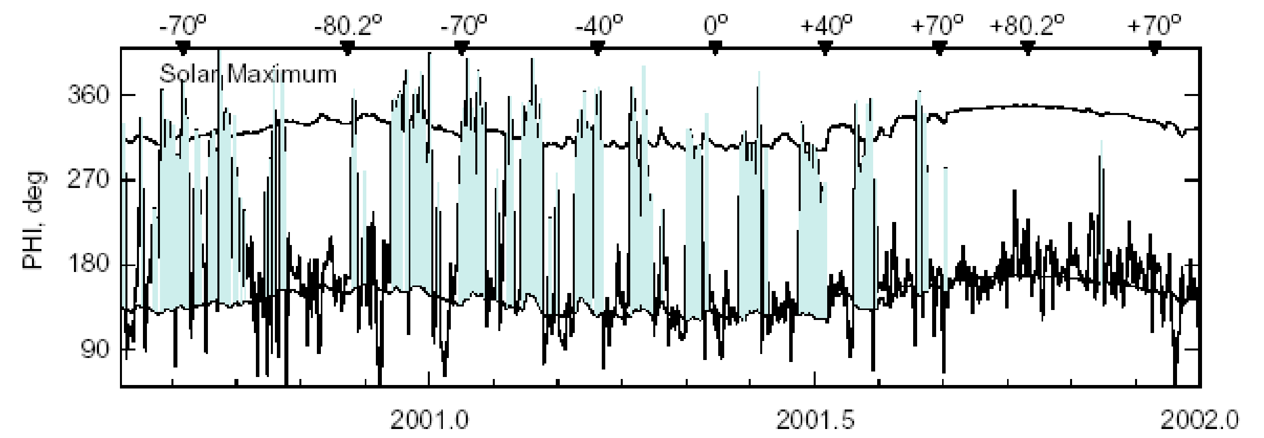


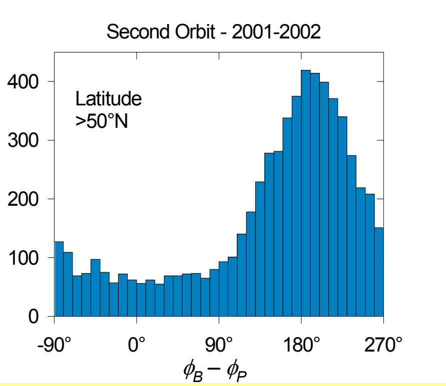
Magnetic Field Overview

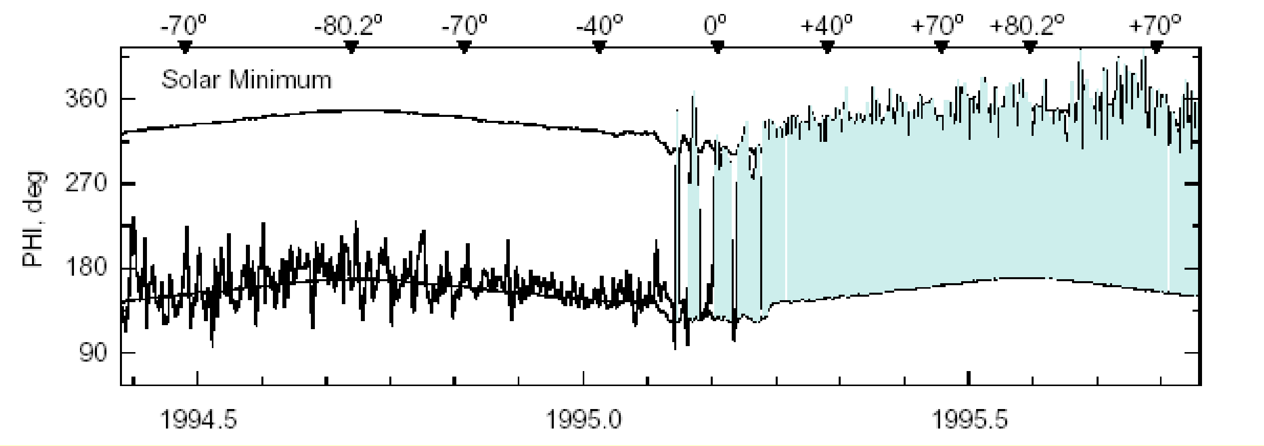


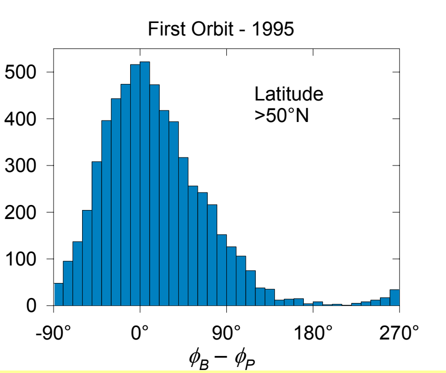
Horbury et al., 2003

Heliospheric magnetic field spiral angle









Smith et al., 2003

Spiral angles in the southern, *versus* the northern, hemisphere

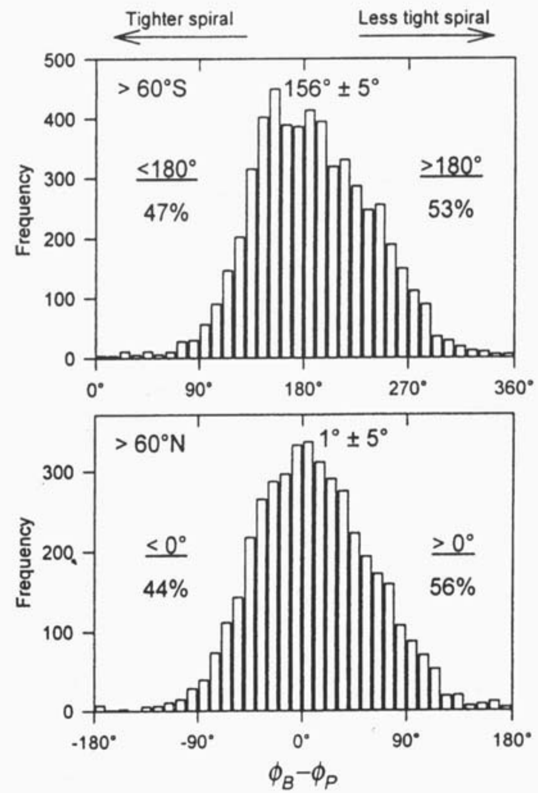
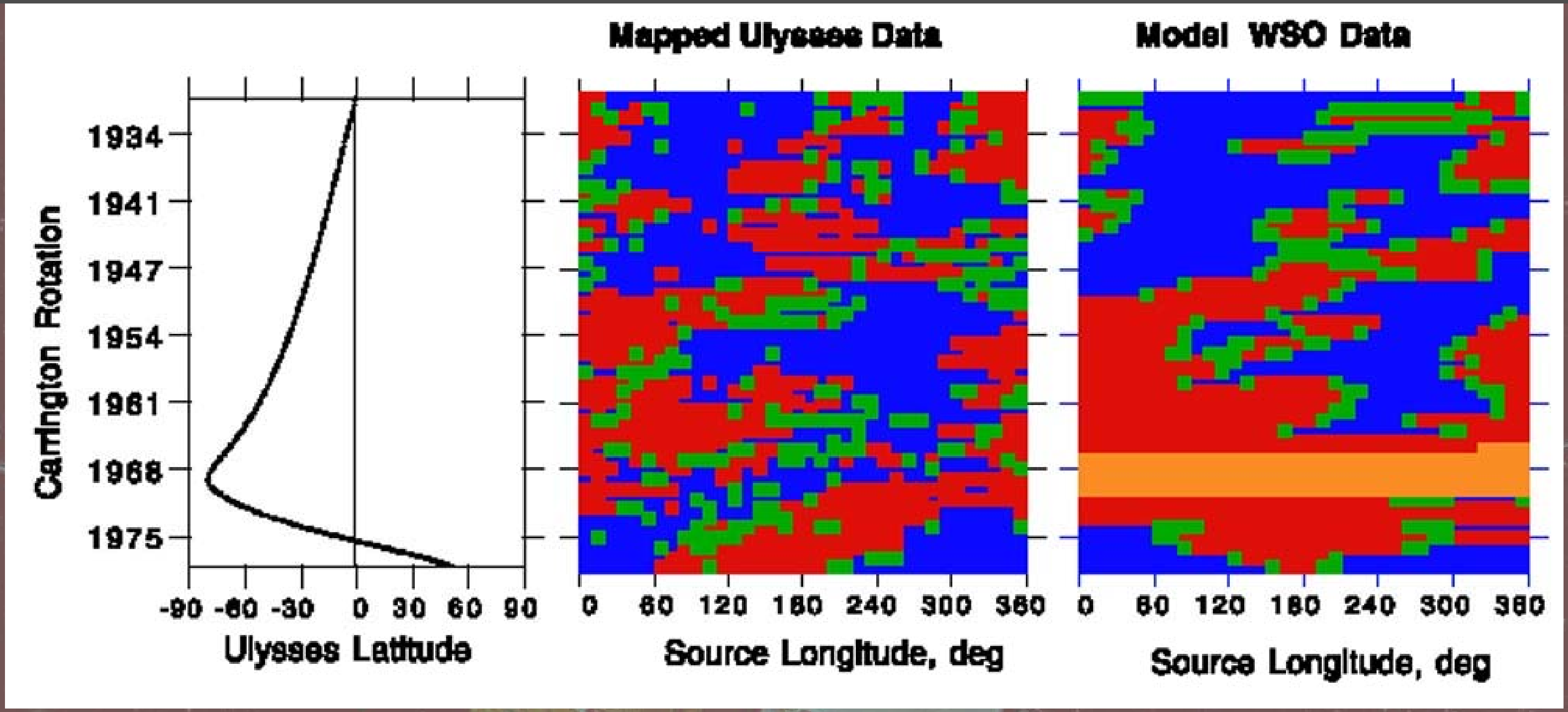


Figure 2.33. Histograms of the direction of the high-latitude HMF (ϕ_B) relative to the expected Parker spiral angle (ϕ_P) (from Forsyth *et al.*, 1996).

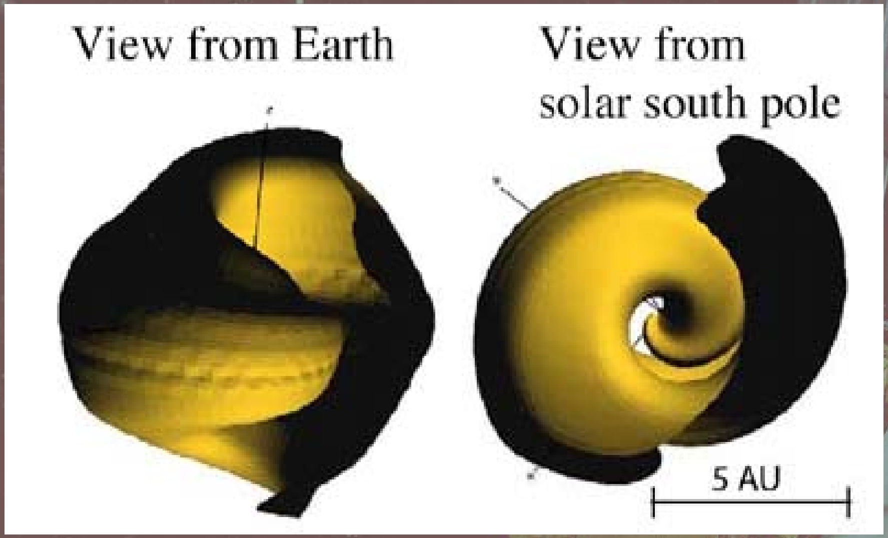


(left) Ulysses' latitude vs. Carrington rotation.

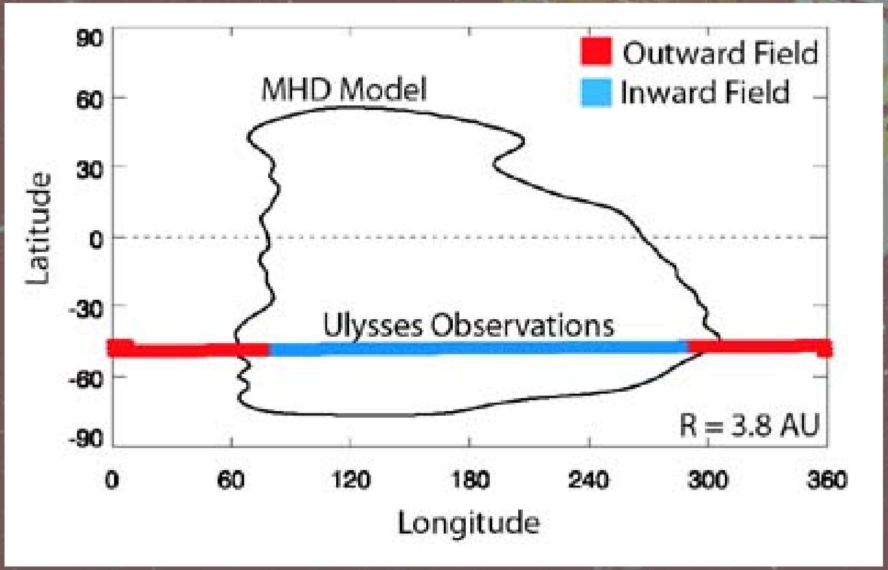
(middle) Magnetic polarity of the HMF at Ulysses, mapped back onto Carrington rotation and longitude on a 2.5 solar radii source surface.

(right) The magnetic polarity expected at the Ulysses' footpoint on the source surface using the WSO potential-field source surface model. Red (blue) denotes outward (inward) field and orange denotes implied outward field.

[Neugebauer et al., 2002]



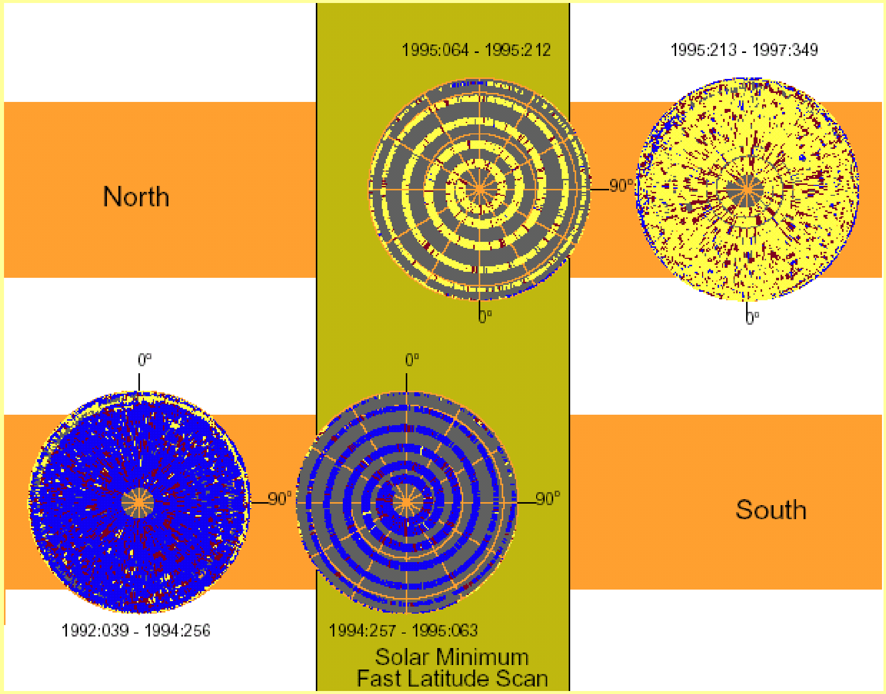
3D surface plot of the HCS for CR1961 - April 2000.

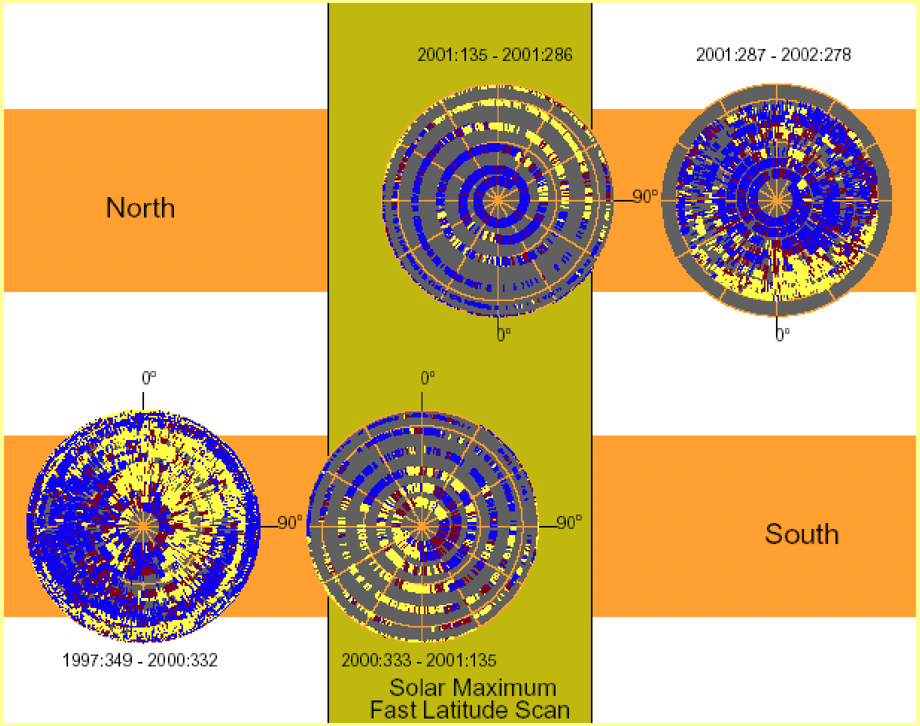


Cut through the HCS at 3.8 AU and comparison with Ulysses.

[Riley et al., 2002]

Polarity distribution - the view from above the poles



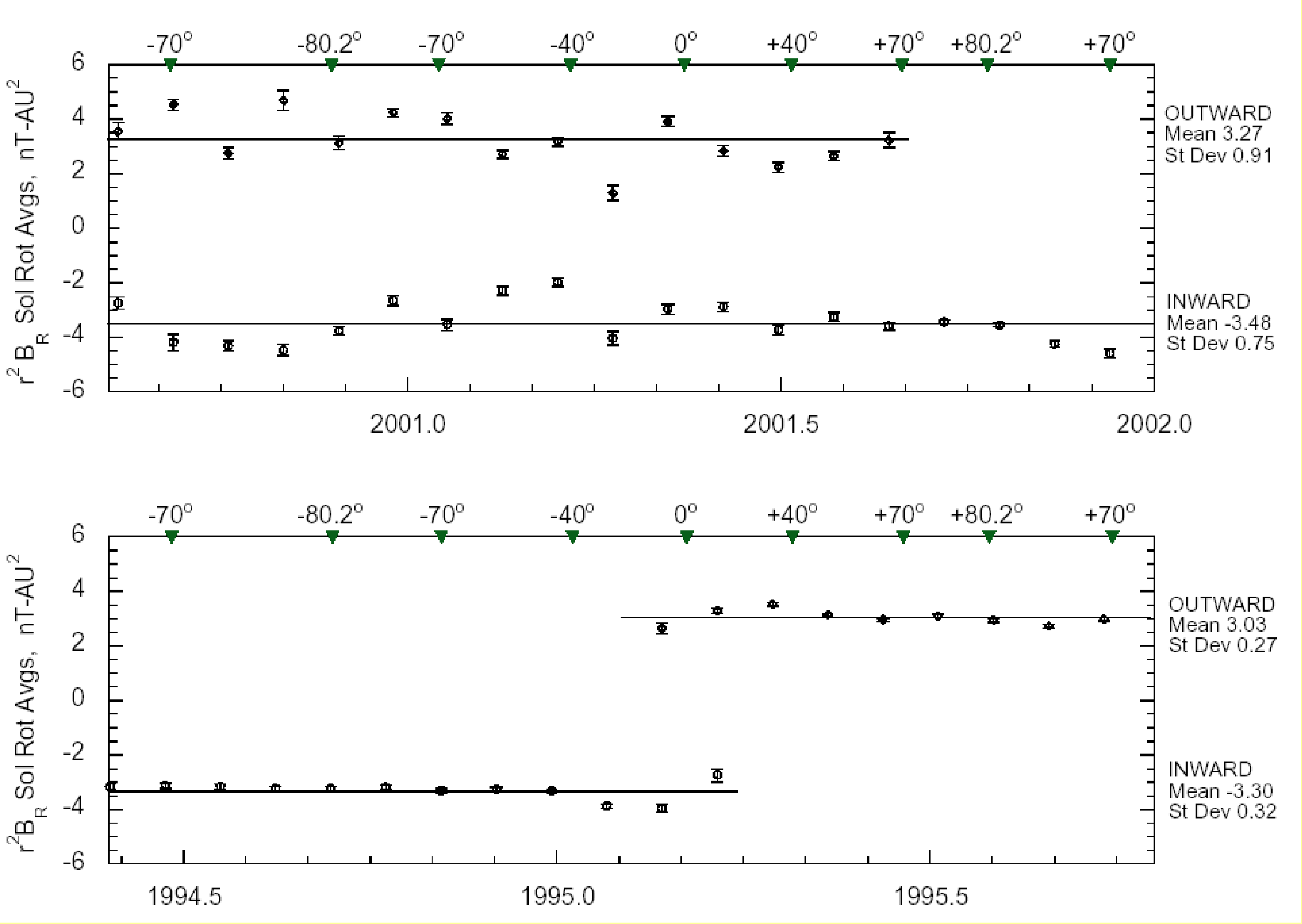


Jones and Balogh, Ann. Geophys. (in press), 2003

Heliospheric magnetic field open flux (r^2B_R)

Solar Maximum

Solar Minimum

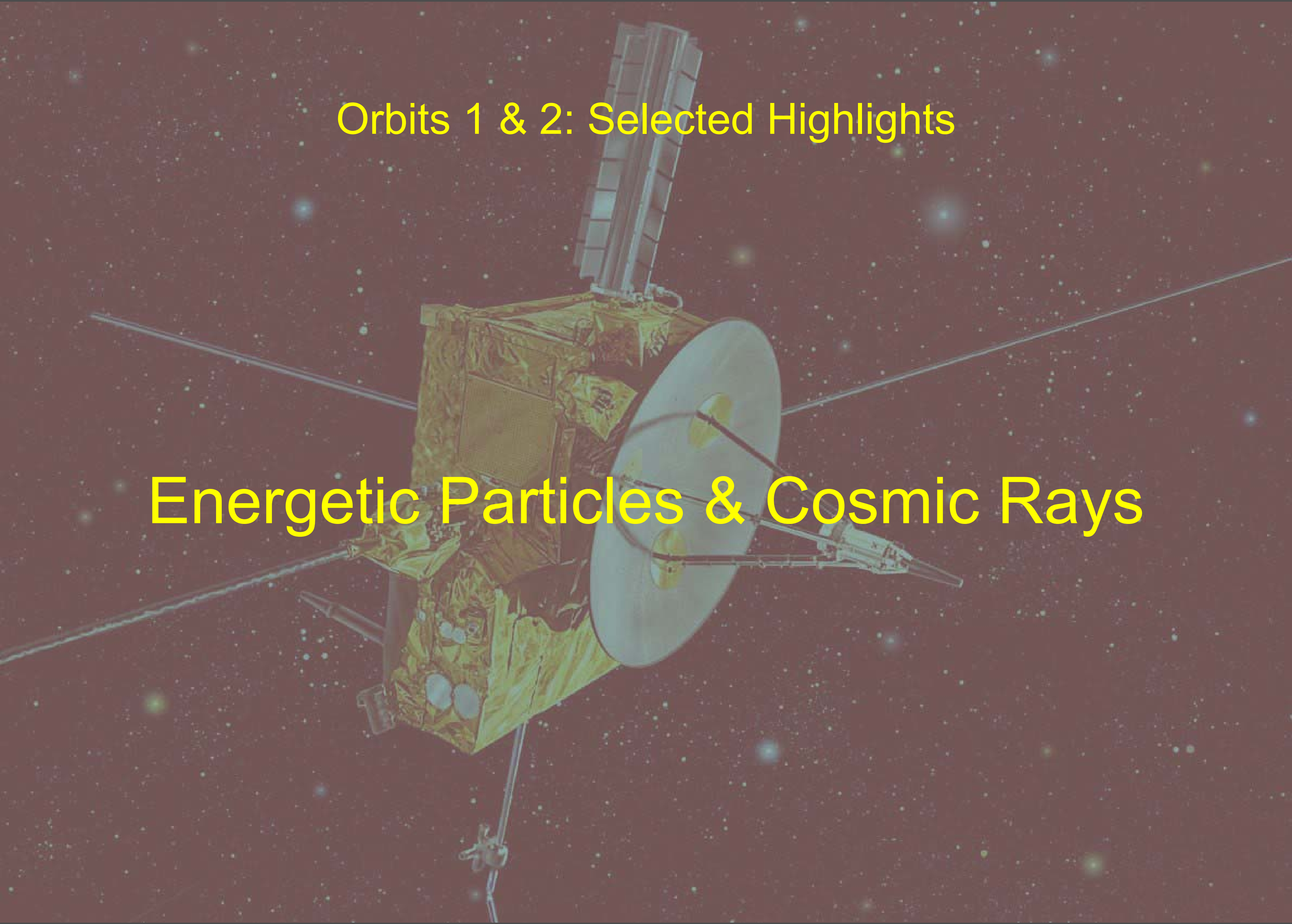


Smith et al., 2003

Magnetic Field Summary

- Spiral angle:
  - Minimum: dipole-like structure
  - Maximum: alternating polarities extend to high latitudes; non-random pattern => dipole-like character still dominates; dipole axis ~ equatorial
  - “New” northern polarity seen in 2001
- Open flux ($R^2 B_R$):
  - Independent of latitude at minimum and maximum
  - Mean open flux is ~ equal at minimum and maximum

Orbits 1 & 2: Selected Highlights

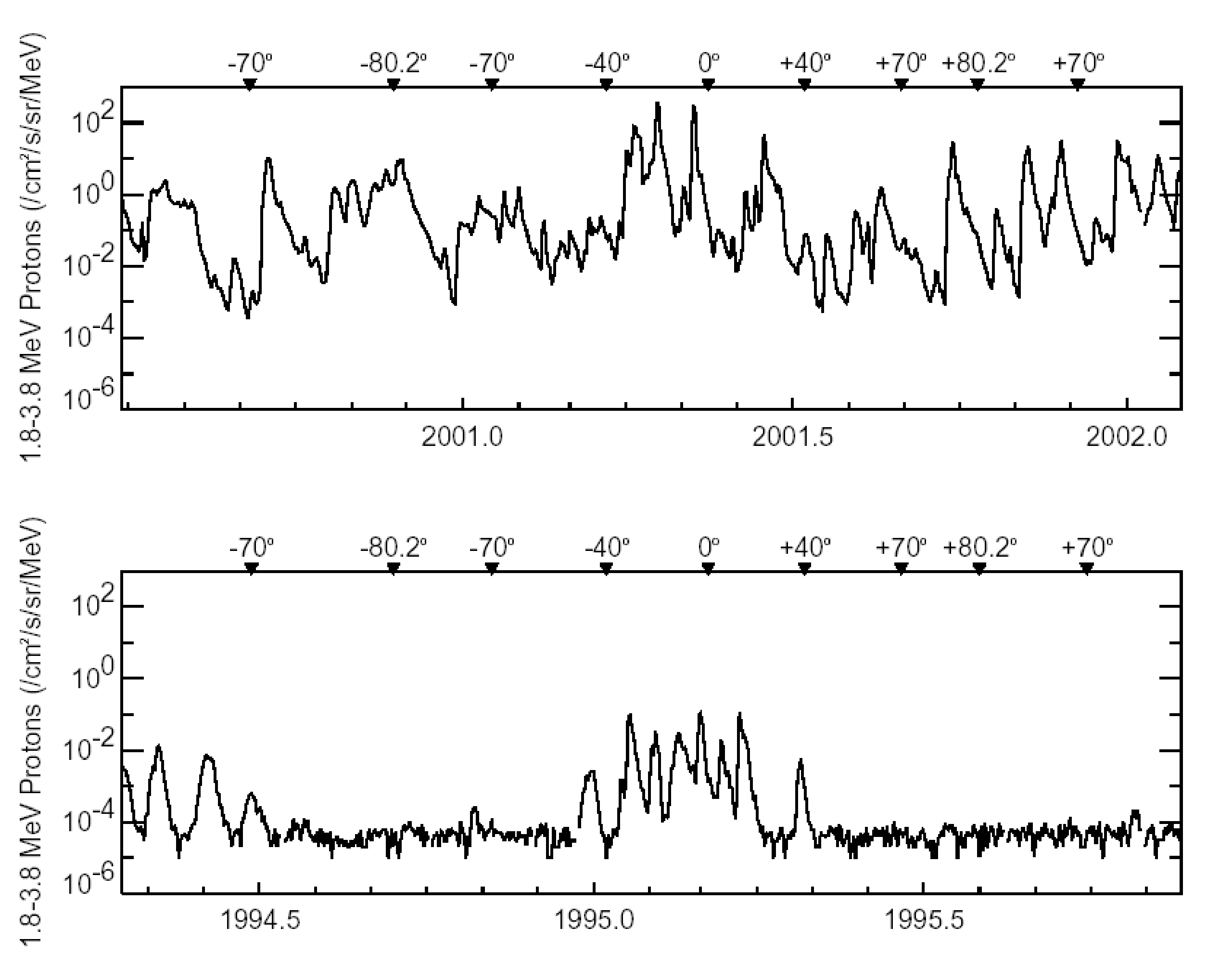


Energetic Particles & Cosmic Rays

Energetic particles at high latitudes (1)

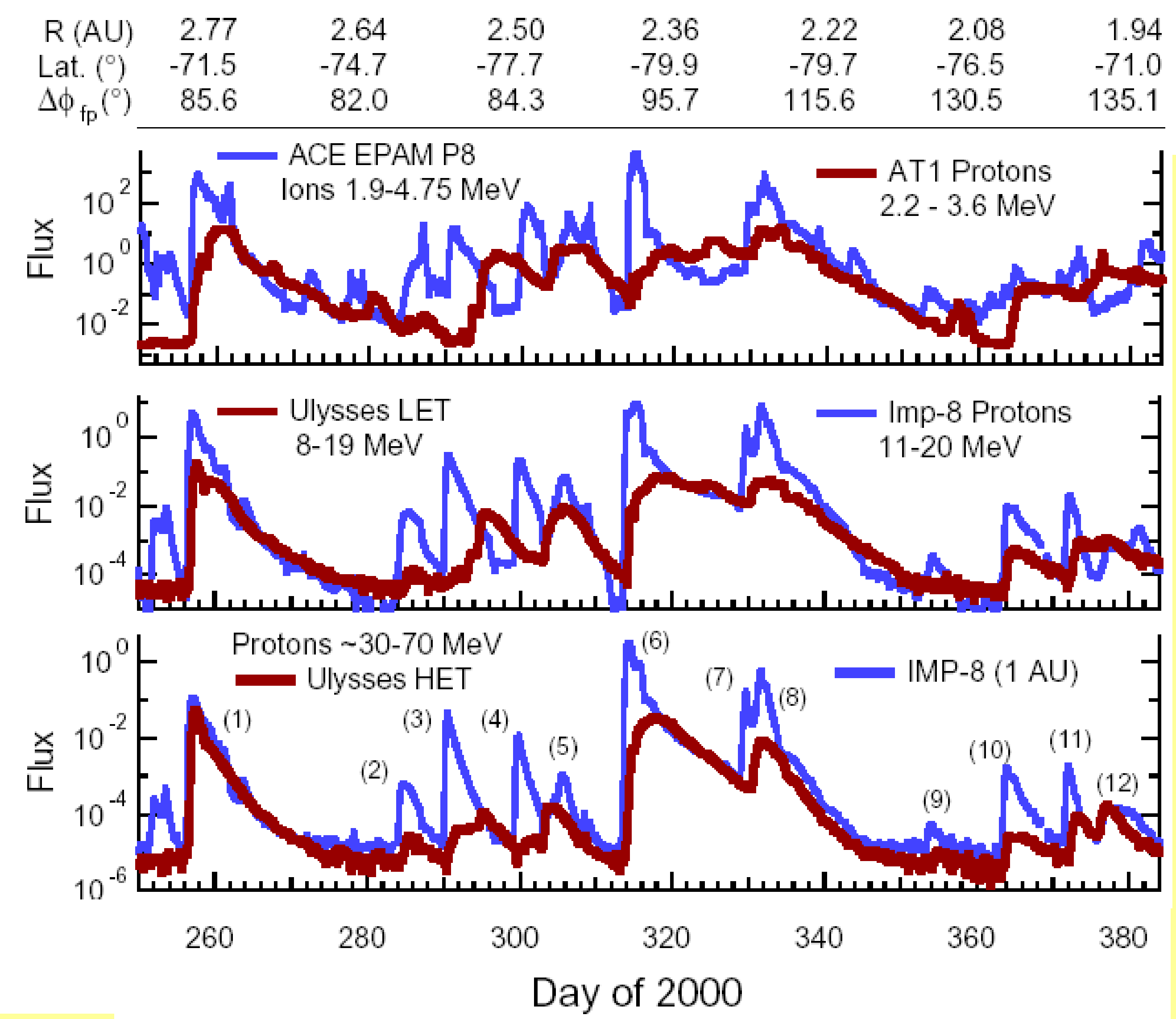
Solar Maximum

Solar Minimum



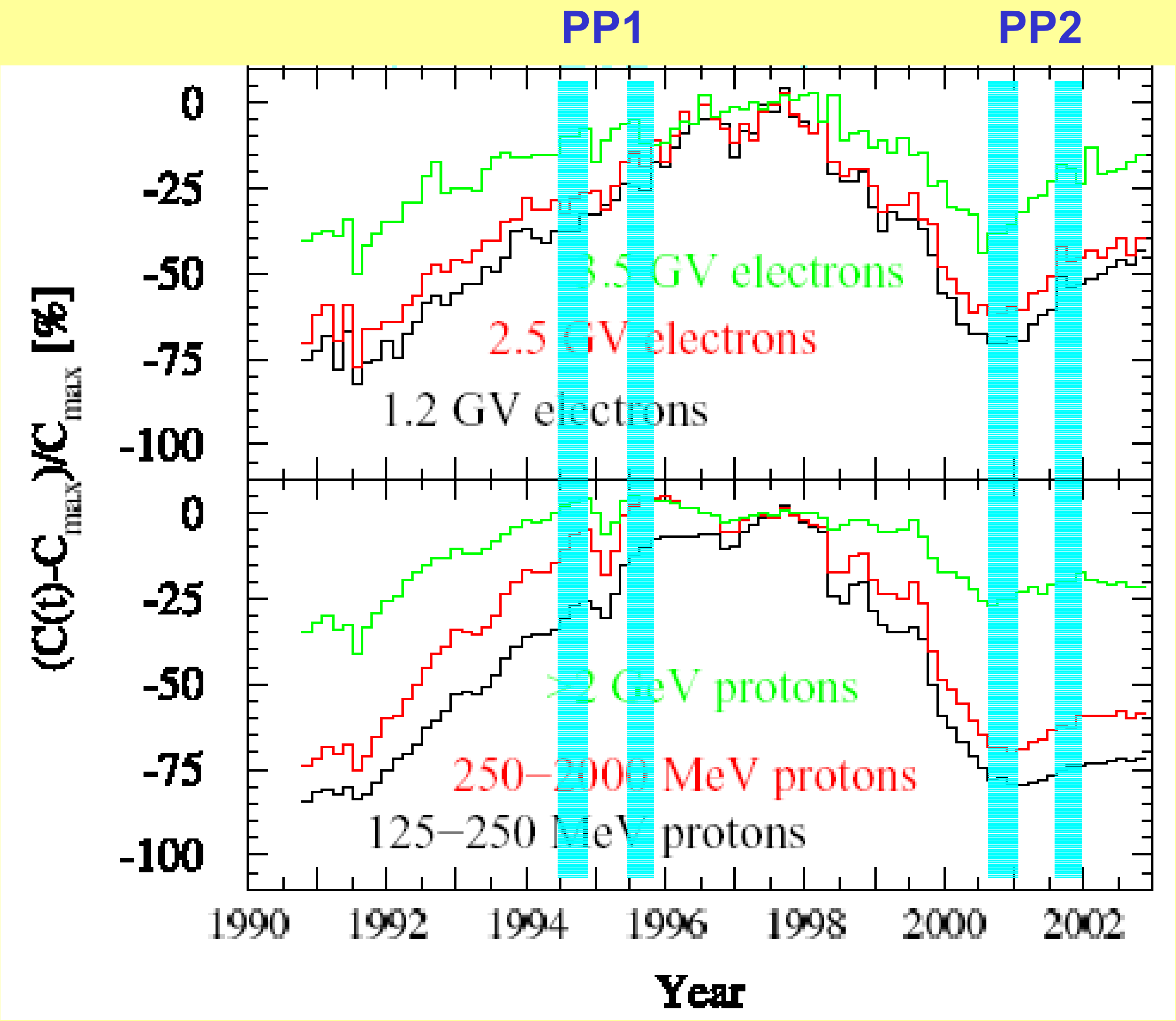
~2 MeV protons

Energetic particles at high latitudes (2)



McKibben et al., 2003

Cosmic rays at high latitudes



Heber et al., 2003

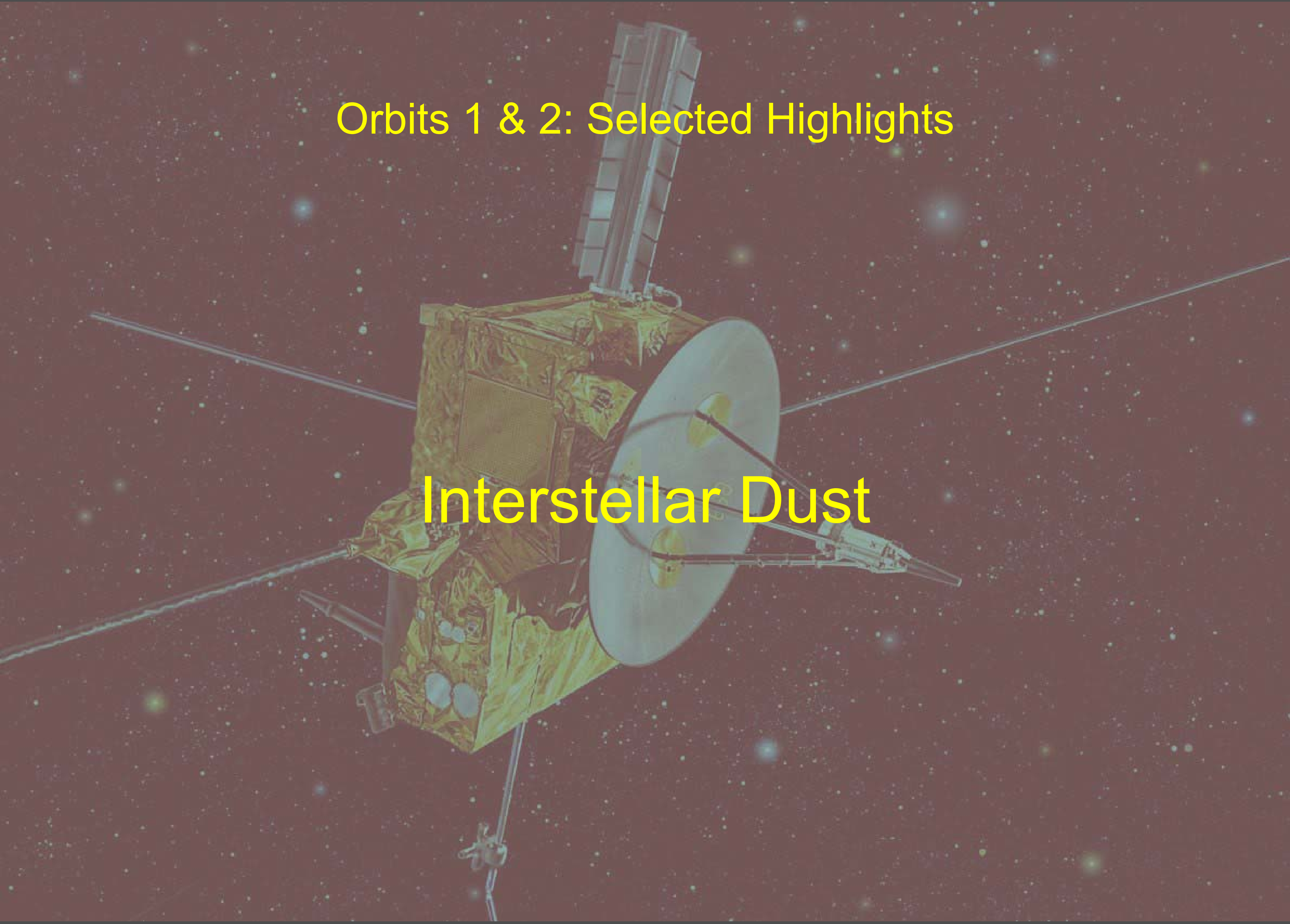
Energetic Particle & Cosmic Ray Summary

- High-latitude particle events:
  - 1 AU events frequently seen at Ulysses regardless of relative positions
  - Events at Ulysses typically have <u>longer rise-times and lower peak intensities</u> than at 1 AU
  - Decay-phase intensities at Ulysses and 1 AU are ~ equal

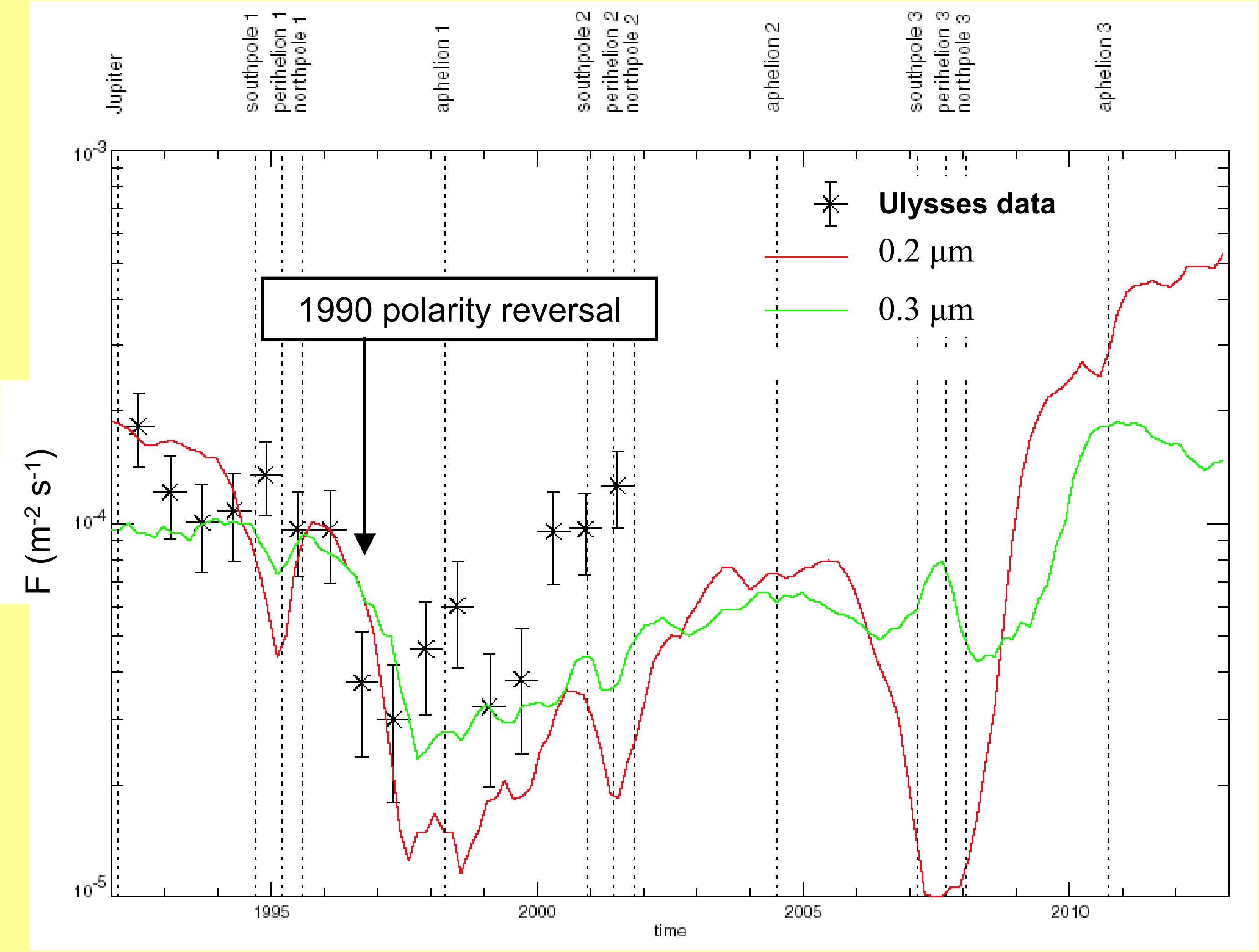
    => disappearance of spatial gradients (latitudinal, longitudinal, radial)
- Cosmic rays:
  - No latitudinal gradients at solar maximum, too small gradients at other times
- These results hold for all sources: cosmic rays, solar energetic particles, Jovian particles, CIR-accelerated particles, etc.

Orbits 1 & 2: Selected Highlights

Interstellar Dust



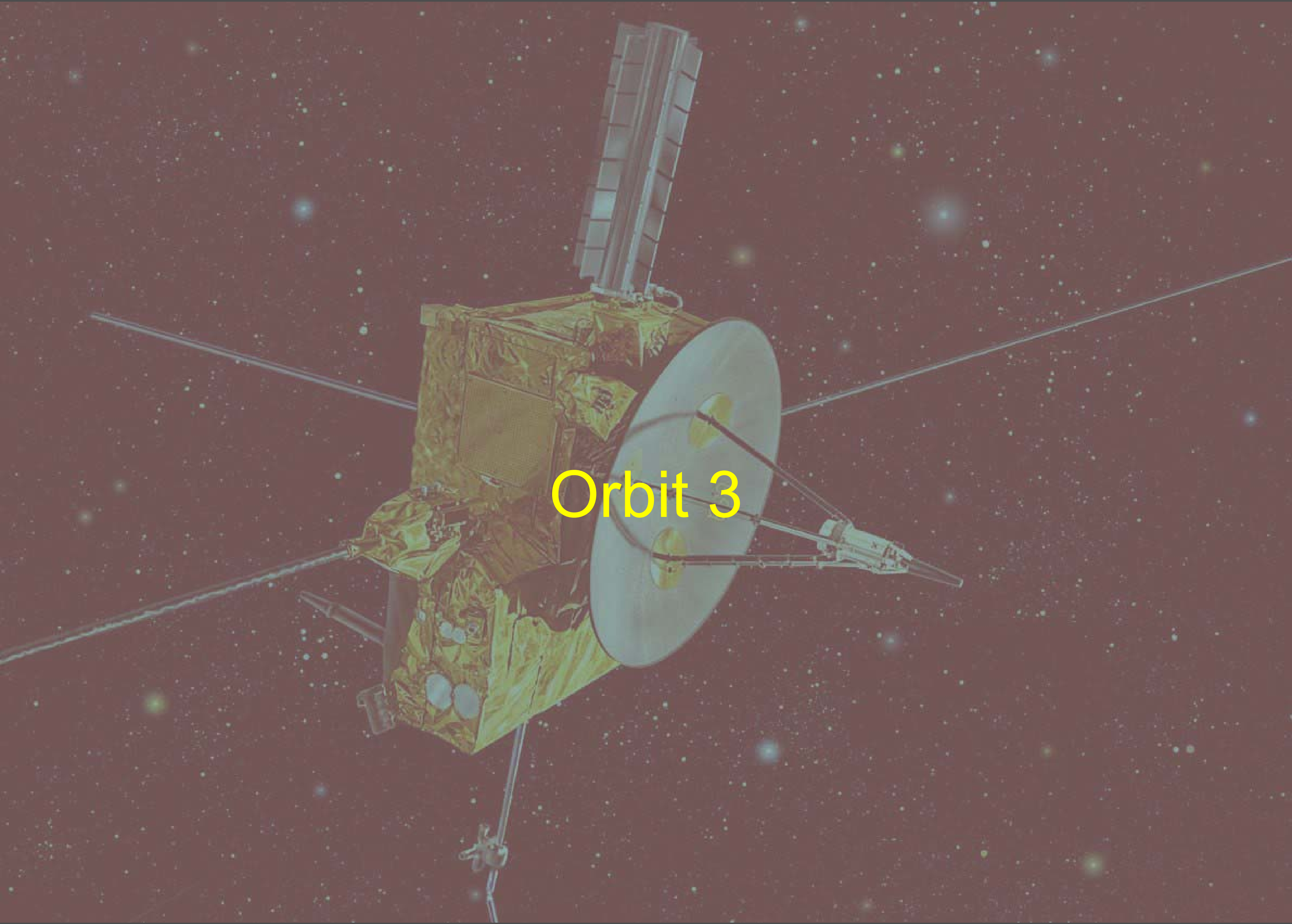
Interstellar dust measurements from Ulysses

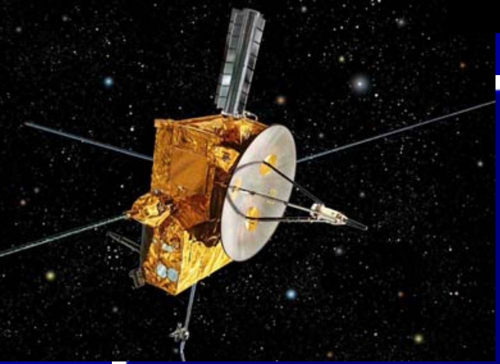


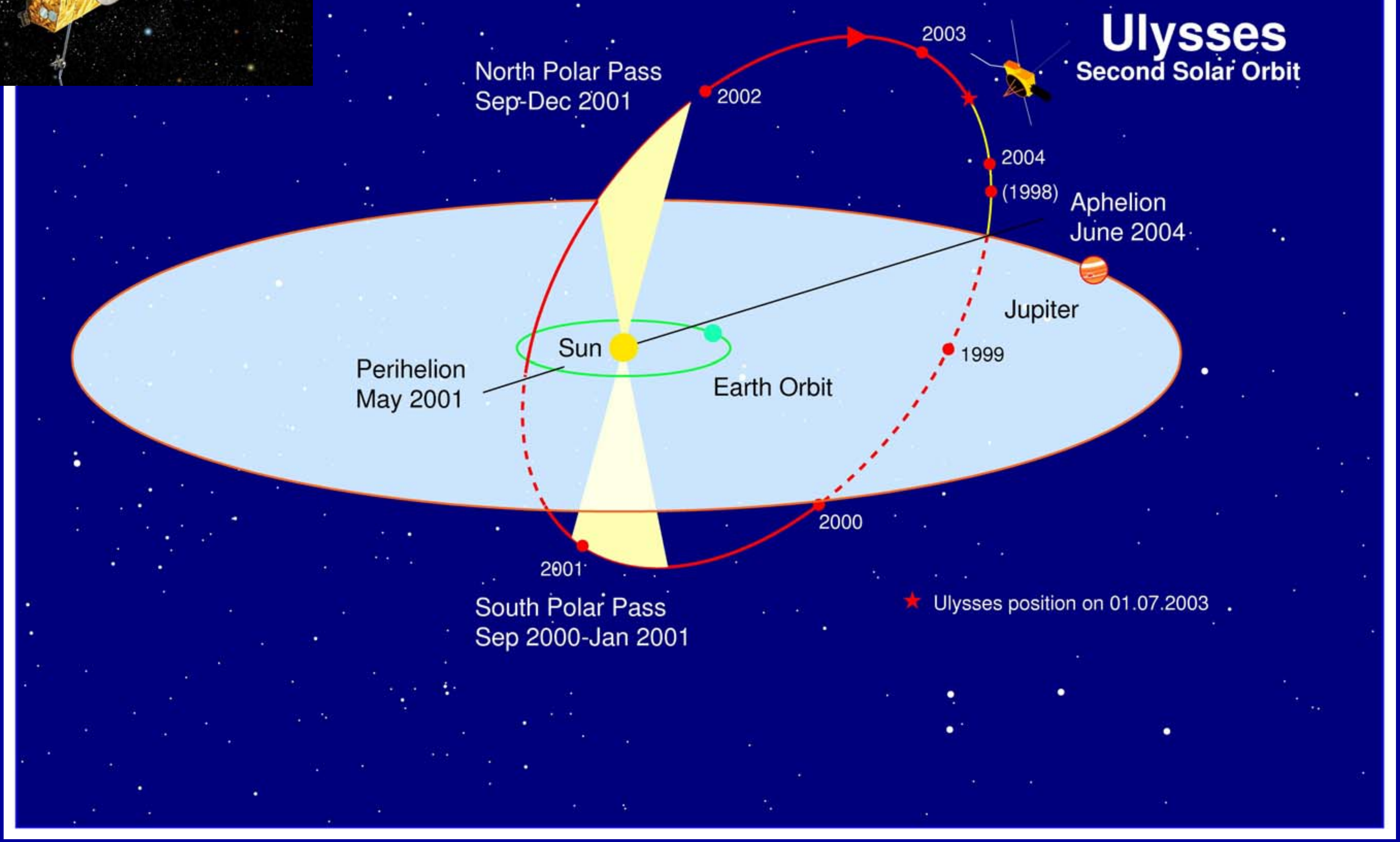
M. Landgraf

Interstellar Dust Summary
(Ulysses made the first direct detection if IS dust)

- Solar cycle effects:
  - IS Dust flux reaching the inner heliosphere is influenced by
    - Solar gravity
    - Solar radiation pressure
    - Electromagnetic forces
  - Changes in dust flux due to electromagnetic forces show delay with respect to changes at the Sun (e.g., polarity reversal)
  - Current models underestimate observed increase seen at Ulysses after ~ 2000
- There are too many large IS dust particles according to IS ‘extinction’ models, and small grains are deficient

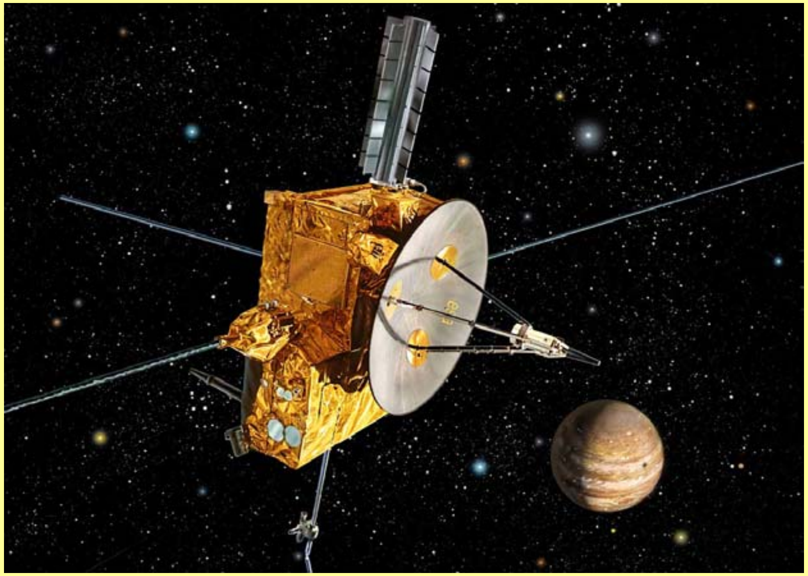

Orbit 3



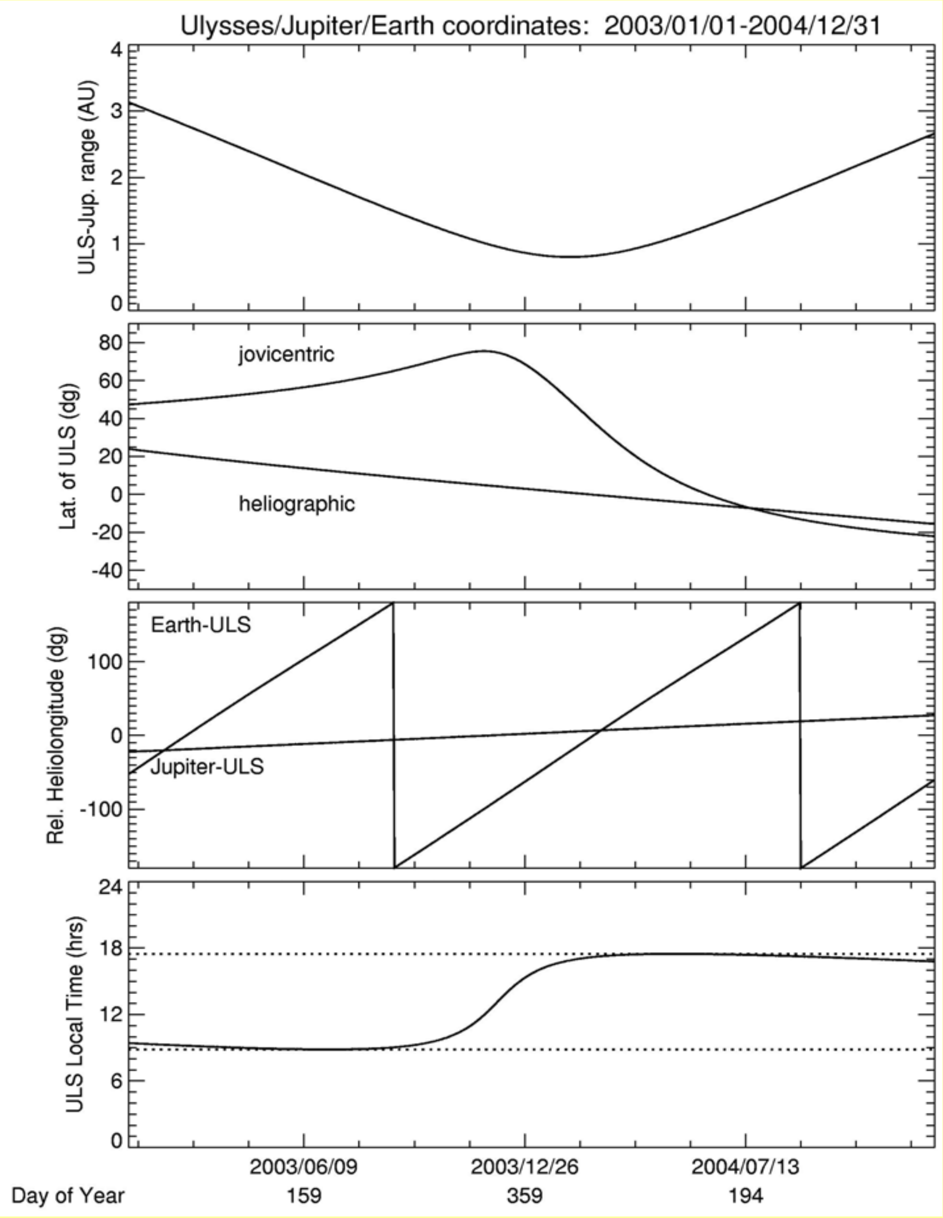


Ulysses
Second Solar Orbit
2003
2002
North Polar Pass
Sep-Dec 2001
2004
(1998)
Aphelion
June 2004
Jupiter
Sun
Earth Orbit
1999
Perihelion
May 2001
2000
2001
South Polar Pass
Sep 2000-Jan 2001
★ Ulysses position on 01.07.2003

2^{nd} Jupiter Encounter



- Closest approach (1684 R_j) on 5 Feb 2004
- Approach from high northern latitude (75º)
- 24-hr/day real-time coverage (23 Jan – 11 Mar 2004): full payload
- Science: radio emissions; neutrals; dust; energetic ions and electrons



Extension through the next fast latitude scan

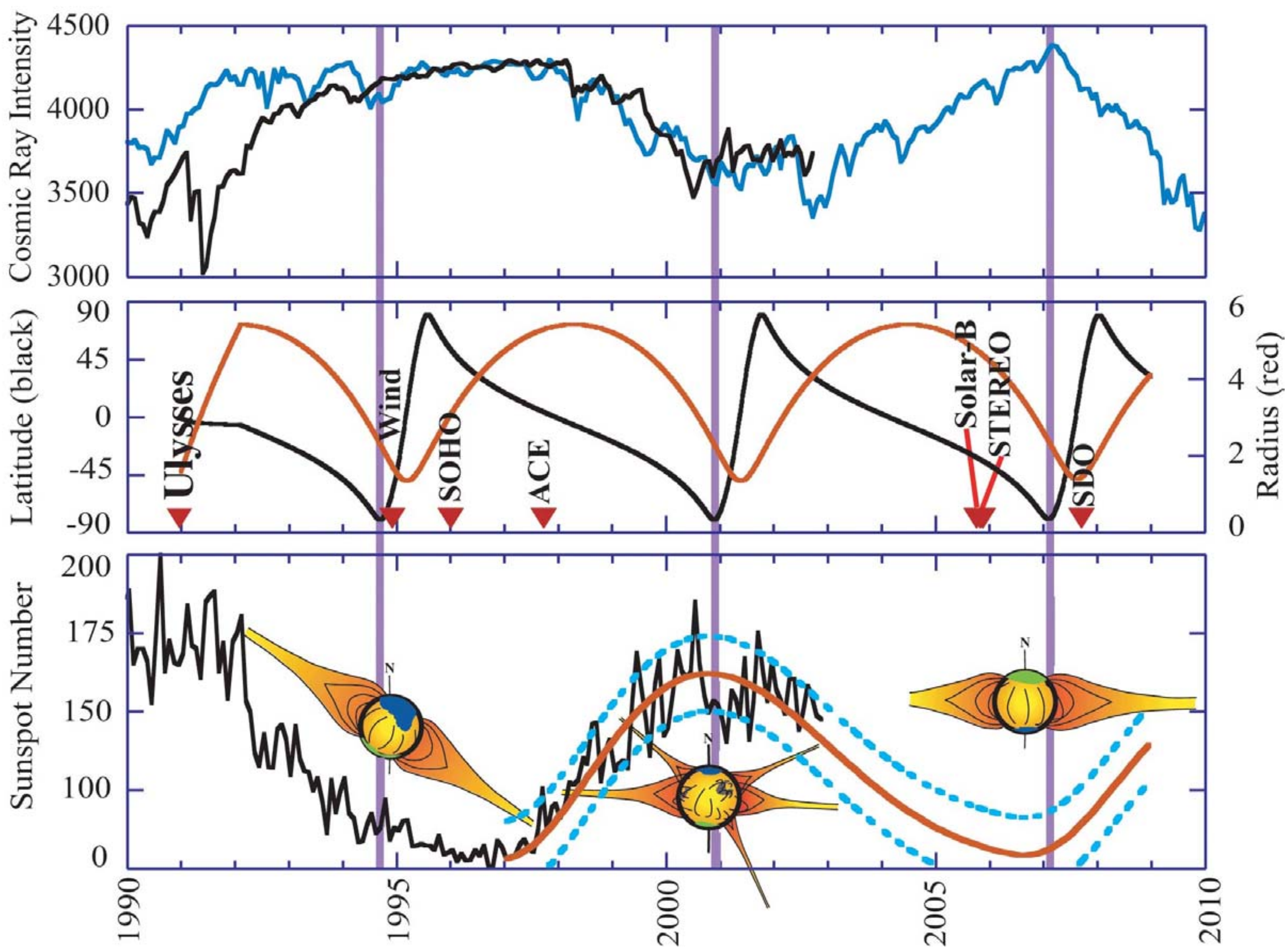
- Now approved (by NASA) extension of scientific operations:
  - 1 Oct 2004 => 31 Mar 2008 (3.5 yrs)
- What is new?:
  - Ulysses is now part of a global network of spacecraft that includes (or will include) SOHO, Wind, ACE, STEREO, Solar-B, and SDO
  - The unique role played by Ulysses is underlined by its inclusion in the International Living With a Star (ILWS) initiative, and its potential contribution to the International Heliophysical Year (IHY) activities (2007-2008)

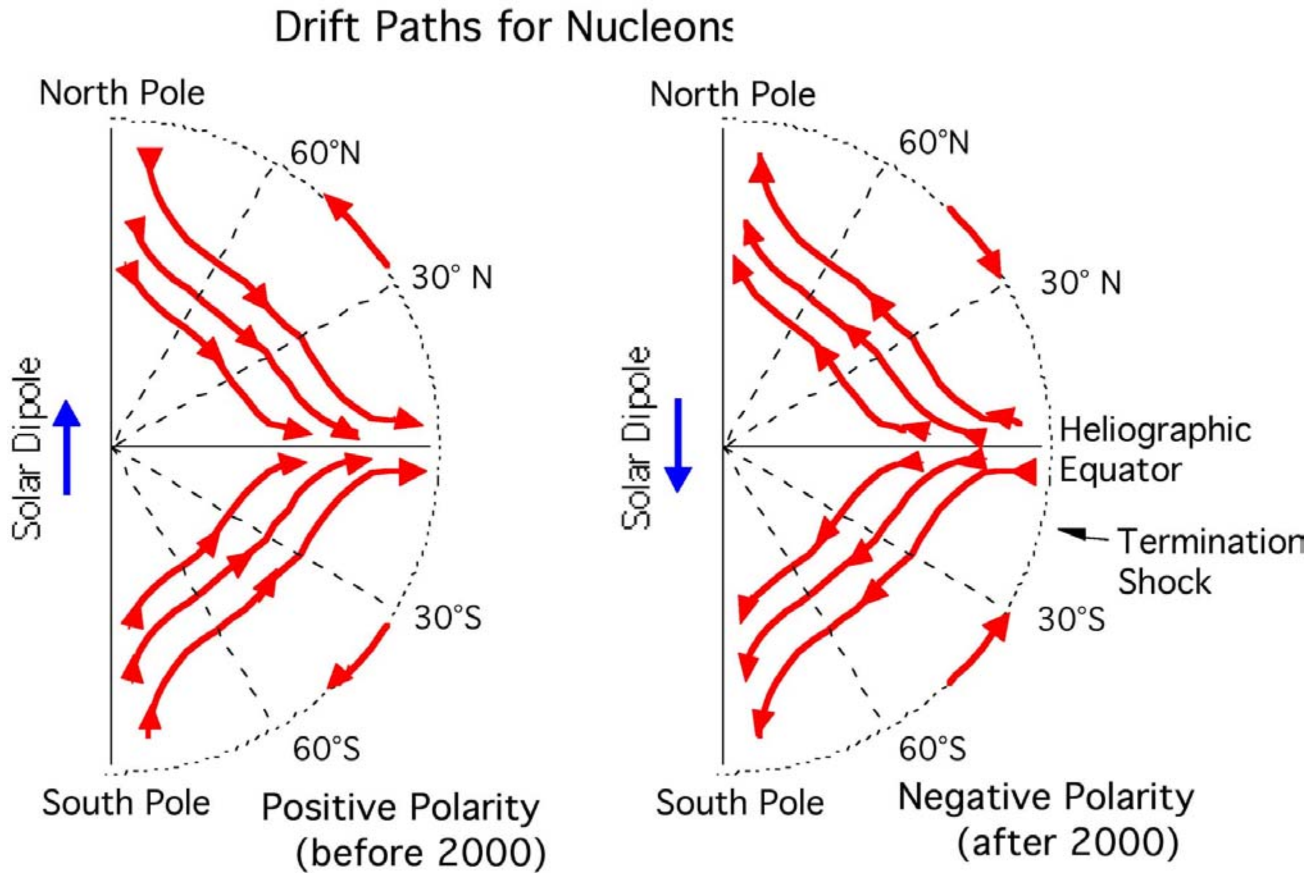
Ulysses 2004-2008

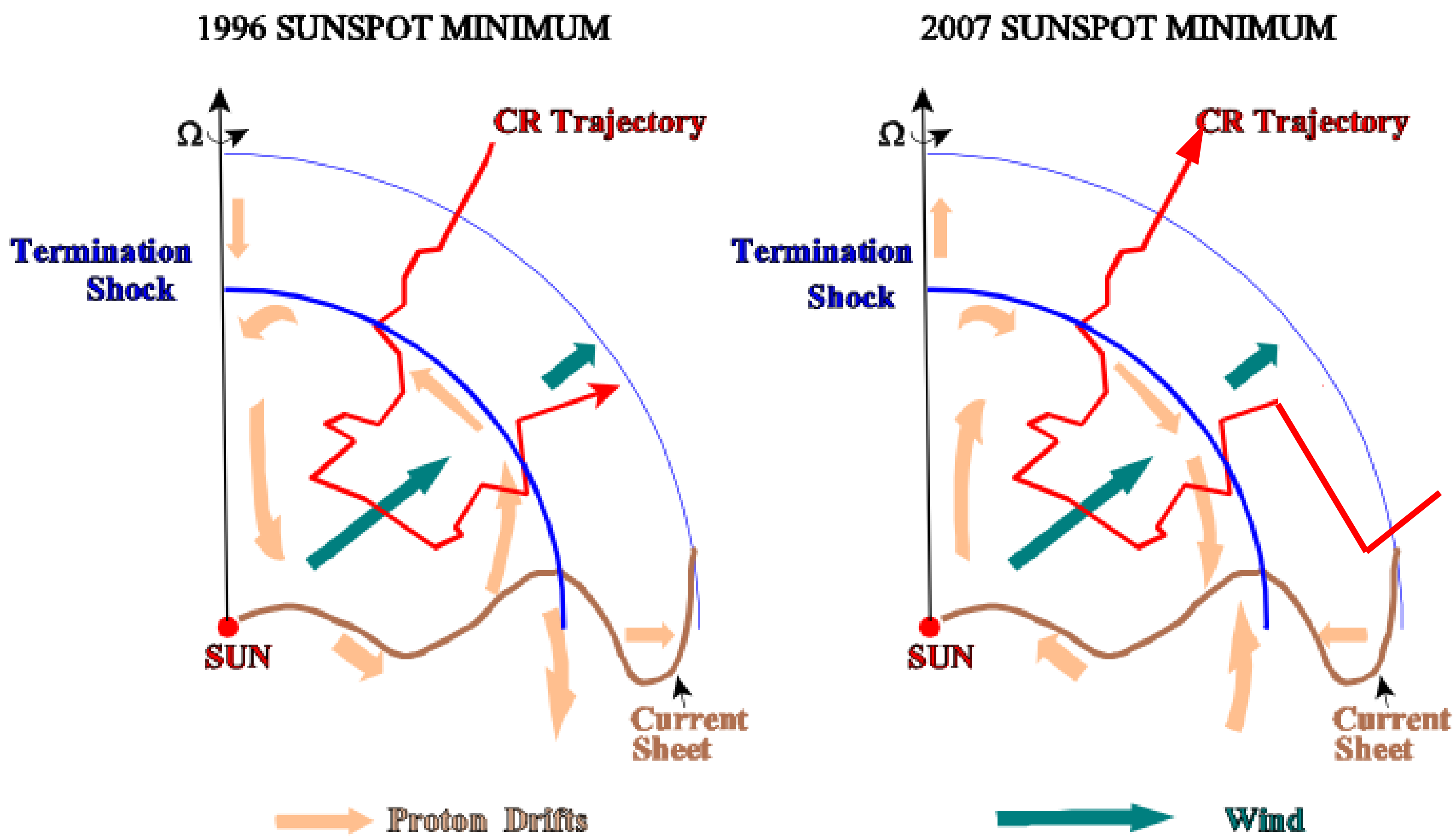
Key Scientific Goals

- Analyze cosmic ray, energetic particle and dust dynamics in the 2nd half of the 22-year Hale solar magnetic cycle, when the reversed field polarity is expected to have a major effect on their latitude dependence
- Determine whether the north-south heliospheric asymmetry discovered during the first orbit is systemic or coincidental
- Answer open questions about the 3-D topology and structure of CMEs and the heliospheric current sheet in conjunction with in-ecliptic spacecraft
- Extend the temporal baseline for measuring the properties of the Local Interstellar Medium (LISM) to investigate spatial / temporal variations
- Contribute to the localization of cosmic gamma-ray bursts when possible

Analyze cosmic ray, energetic particle and dust dynamics in the 2nd half of the 22-year Hale solar magnetic cycle, when the reversed field polarity is expected to have a major effect on their latitude dependence



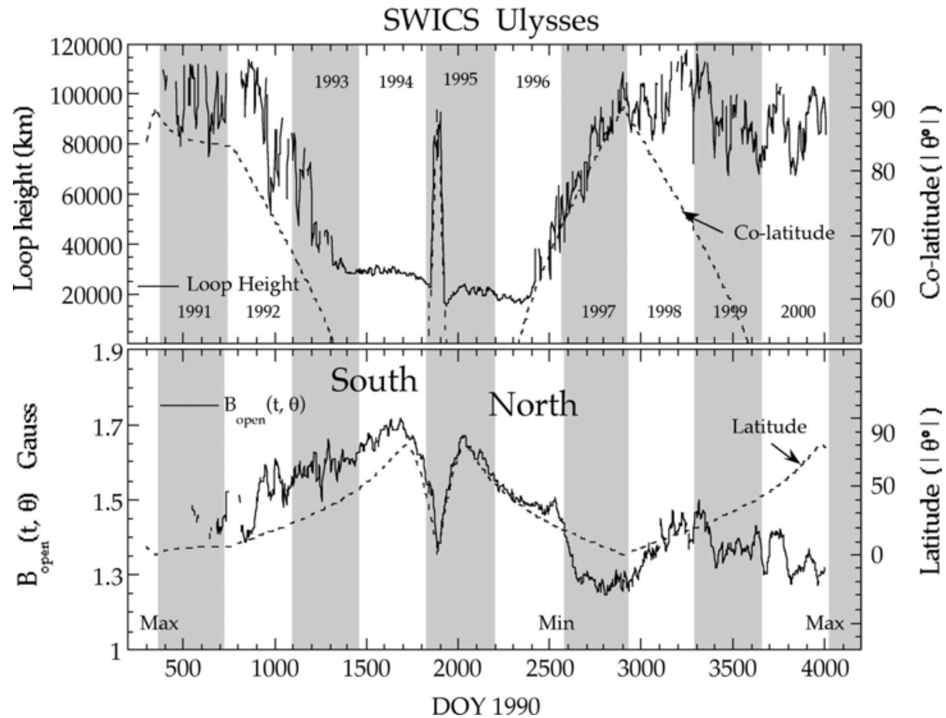

Drift Paths for Nucleons
North Pole
60°N
30° N
Solar Dipole
30°S
60°S
South Pole
Positive Polarity
(before 2000)
North Pole
60°N
30° N
Solar Dipole
Heliographic
Equator
Termination
Shock
30°S
60°S
South Pole
Negative Polarity
(after 2000)



1996 SUNSPOT MINIMUM
2007 SUNSPOT MINIMUM
Ω
CR Trajectory
Termination Shock
SUN
Current Sheet
Ω
CR Trajectory
Termination Shock
SUN
Current Sheet
Proton Drifts
Wind

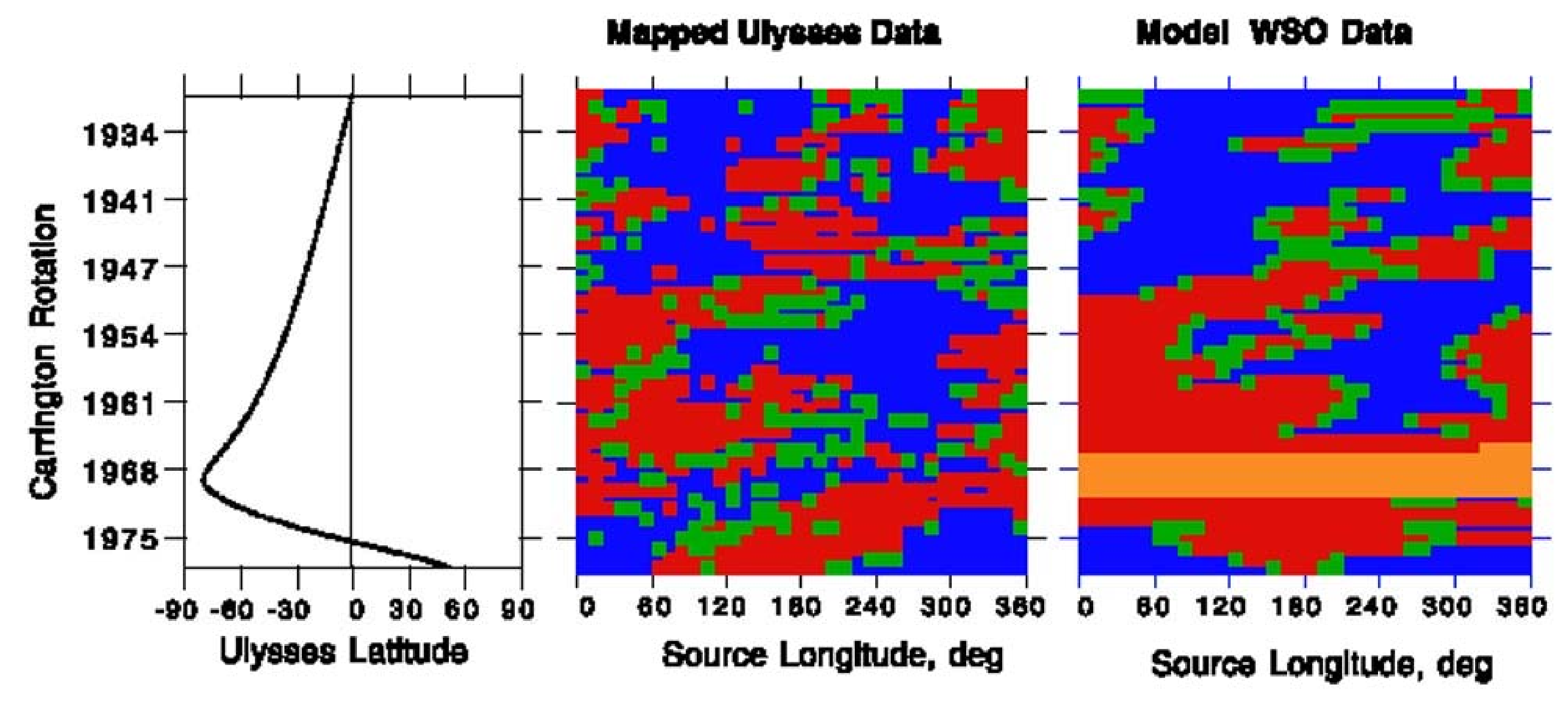
•Determine whether the north-south heliospheric asymmetry discovered during the first orbit is systemic or coincidental

Broken north-south symmetry:
During Orbit 1, Ulysses discovered an unexpected north-south (N-S) heliospheric asymmetry in most data sets. The simplest manifestations are an offset of the heliomagnetic from the heliographic equator, a latitude offset of -10° in the galactic and anomalous cosmic ray fluxes, and hemispheric differences in the solar wind speed and heavy ion fluxes [Smith, et al., 2000; Simpson et al, 1996; Gloeckler et al., 2002]. Negative polarity magnetic fields at southern latitudes filled a smaller volume of the heliosphere than positive northern polarity magnetic fields. In Orbit 3, Ulysses will help understand the persistence of the asymmetry and perhaps an important new aspect of the solar dynamo.



Top: Computed loop height (solid curve) and absolute value of the co-latitude of Ulysses (dashed curve). Bottom: Open magnetic field strength near the Sun (solid curve) and absolute value of the latitude (dashed curve), all vs. DOY 1990 (odd years are indicated by shaded regions) for the ~10-year time period from December 7, 1990 to December 31, 2000. Loop heights clearly show co-latitude dependence. The north-south asymmetry is evident in both loop heights and in open magnetic field strength.

•Answer open questions about the 3-D topology and structure of CMEs and the heliospheric current sheet in conjunction with in-ecliptic spacecraft



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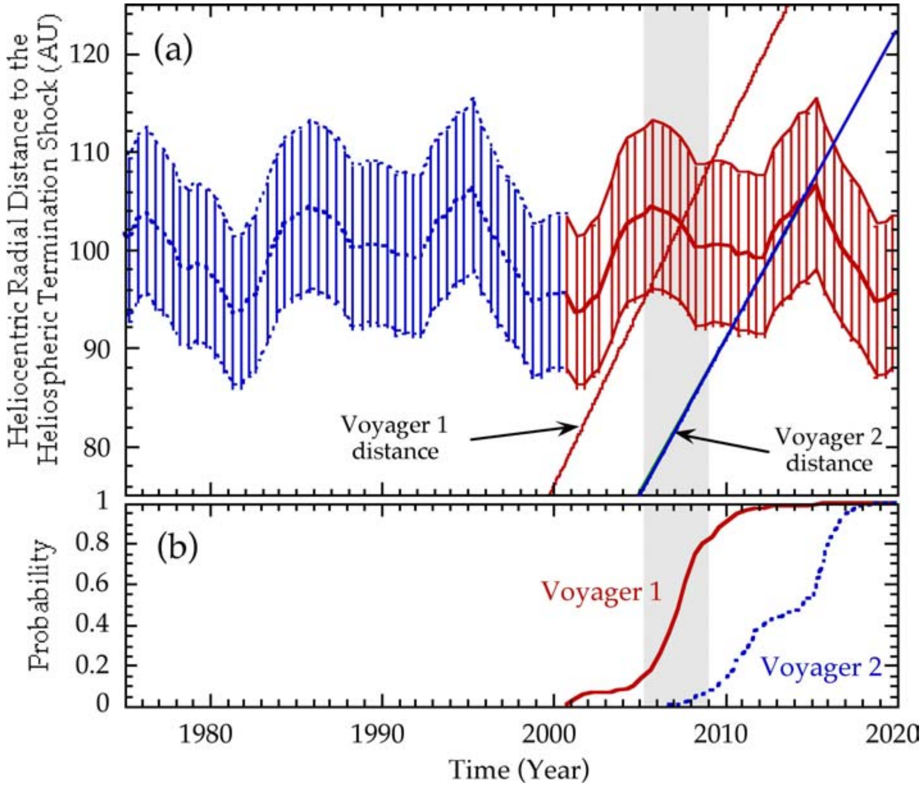
(right) The magnetic polarity expected at the Ulysses' footpoint on the source surface using the WSO potential-field source surface model. Red (blue) denotes outward (inward) field and orange denotes implied outward field.

[Neugebauer et al., 2002]

•Extend the temporal baseline for measuring the properties of the Local Interstellar Medium (LISM) to investigate spatial / temporal variations



Location of the termination shock and probability of shock encounters by Voyagers 1 and 2 as a function of time. Shown in blue is the calculated mean and ±1-σ limits of the termination shock distance using IMP 8 solar wind speed and densities and the modified Baranov-Malama model. Shown in red is the calculated mean and ±1-σ limits of the termination shock distance using a repeat of the previous 20-year sequence [Izmodenov et al., 2002].

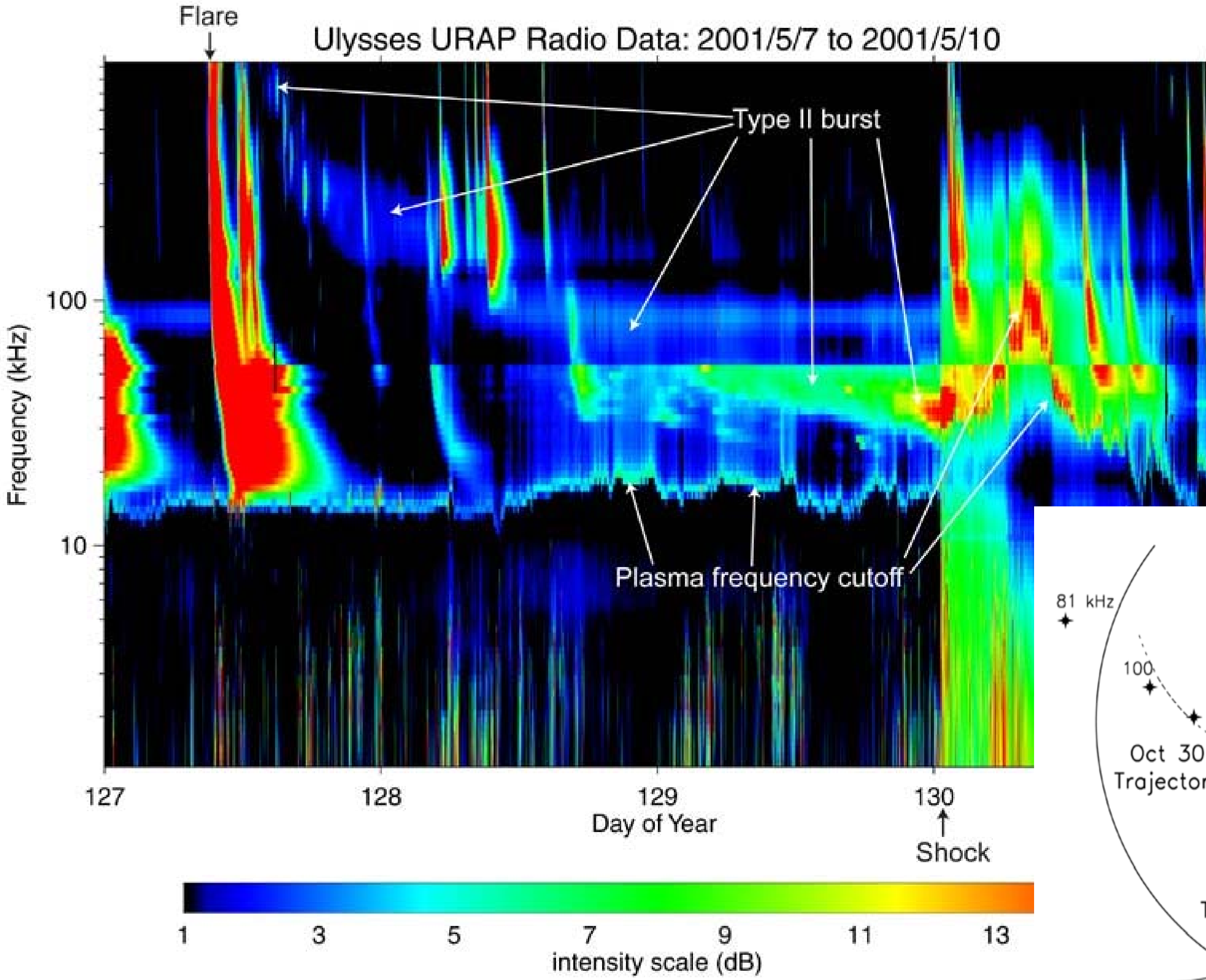
What have I left out?

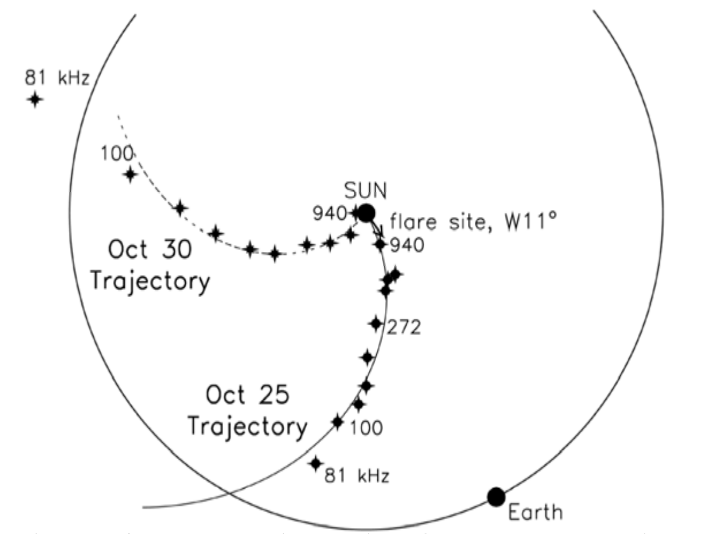
(1) Composition

- The ‘first ionization potential’ (FIP) effect on the composition of solar wind
- $^{3}He/^{4}He$
- Interstellar pickup ions
- Anomalous cosmic rays
- ‘Inner source’ anomalous cosmic rays

Use the identical SWICS instrument on ACE for 1 AU, in-ecliptic baseline measurements of composition.

(2) Type II and III radio burst out-of-ecliptic perspective in collaboration with STEREO





Ulysses/URAP trajectories for type III exciter electrons from two 1994 solar flares. Ulysses was south of the ecliptic, permitting determination of the ecliptic trajectories [Reiner et al., 1995].

Ulysses 2002-2008
Scientific Payload

- Core payload units
  - Solar wind ions (SWOOPS-I)
  - Solar wind ion composition (SWICS)
  - Magnetic fields (FGM/VHM)
  - Energetic particles (HI-SCALE)
  - Cosmic rays and solar energetic particles (COSPIN)

- Discretionary payload units:
  - Solar wind electrons (SWOOPS-E)
  - Radio and plasma waves (URAP1 and 2)
  - Cosmic dust (DUST)
  - Low-energy particles and neutral gas (EPAC/GAS)
  - Gamma-ray bursts (GRB)

Ulysses 2004-2008
Technical feasibility

- Spacecraft and scientific payload are in excellent health
- On-board resources:
  - Radioisotope Thermoelectric Generator (RTG) power:
    - decreasing at a rate of ~4 Watts/year (currently 212 W)
    - operation of core set of scientific instruments (Oct 2004-May 2007)
    - ALL scientific instruments on during 3rd Fast Latitude Scan (Jun 2007 – Mar 2008)
  - hydrazine
    - 7.7 kg available for post-2004 operations
    - usage Oct 2004 – Mar 2008: 2.5 kg
- Nutation is fully in control