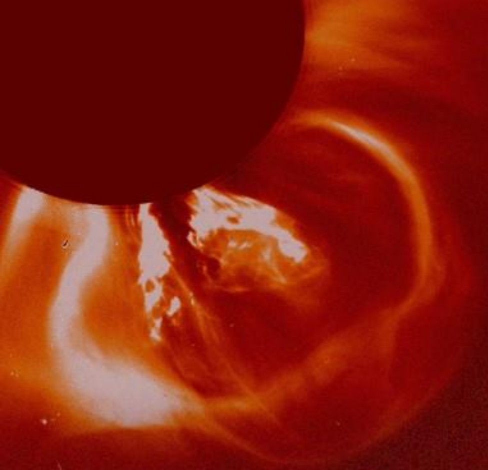

ELECTRON DENSITY DISTRIBUTIONS IN 1D, 2D, AND 3D FROM INVERSION OF CORONAL WHITE-LIGHT IMAGES

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The importance of the electron density

The distribution of the coronal electron density (Ne) and its temporal evolution is important for understanding many fundamental coronal processes.

- *Accurate specification of the background state of the corona for studies of shock acceleration of energetic particles and of propagation of coronal mass ejections (CMEs).*
- The propagation, acceleration and mass loading of CMEs are strongly affected by their significant interactions with streamer belt structures and the amount of plasma swept up.
- Estimation of the Alfvèn Mach number and compression rate of CME-driven shocks.
- *Localization of type II and type IV radio bursts.*
- In the absence of direct measurements, density structures trace the configuration of the magnetic field lines since the plasma is frozen in the field.
- *The magnetic field strength may be estimated from the propagation of fast magnetosonic waves.*
- Validation of MHD models of the corona

  -> R<1.25 Rsun: DEMT of soft X-ray and EUV images provides density + temperature

  -> R>1.25 Rsun: Inversion of white-light images provides density

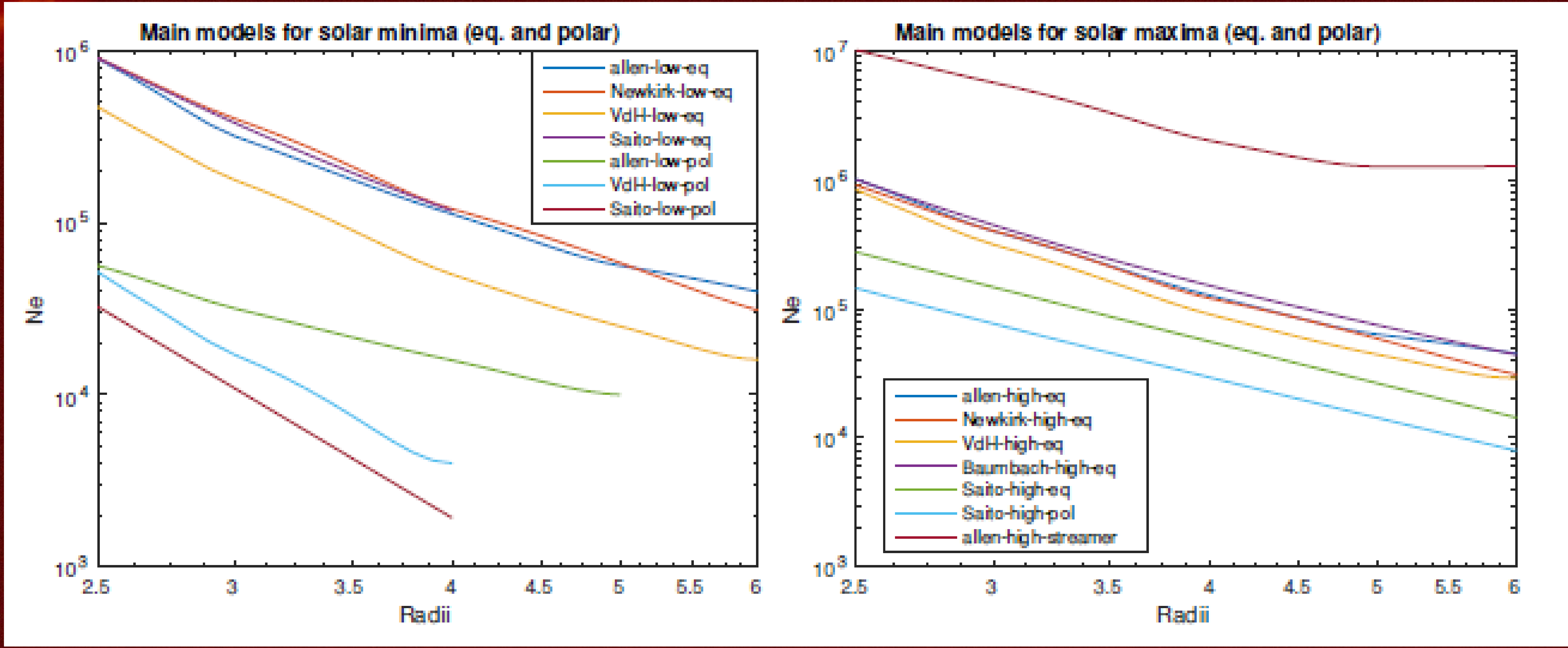
1D Inversion

- Classical inversion first addressed by Minnaert (1930) and developed by Van de Hulst (1950) in a formalism called spherically symmetric inversion (SSI).
- Ne is assumed to be a function of the radial distance Ne(ρ) since the latitudinal and azimuthal gradients in electron density are weaker than the radial gradient (local spherical symmetry approximation).
- The polarized brightness pB is best fitted to a polynomial

$$pB(\rho) = \sum_k a_k \rho^{-k}.$$

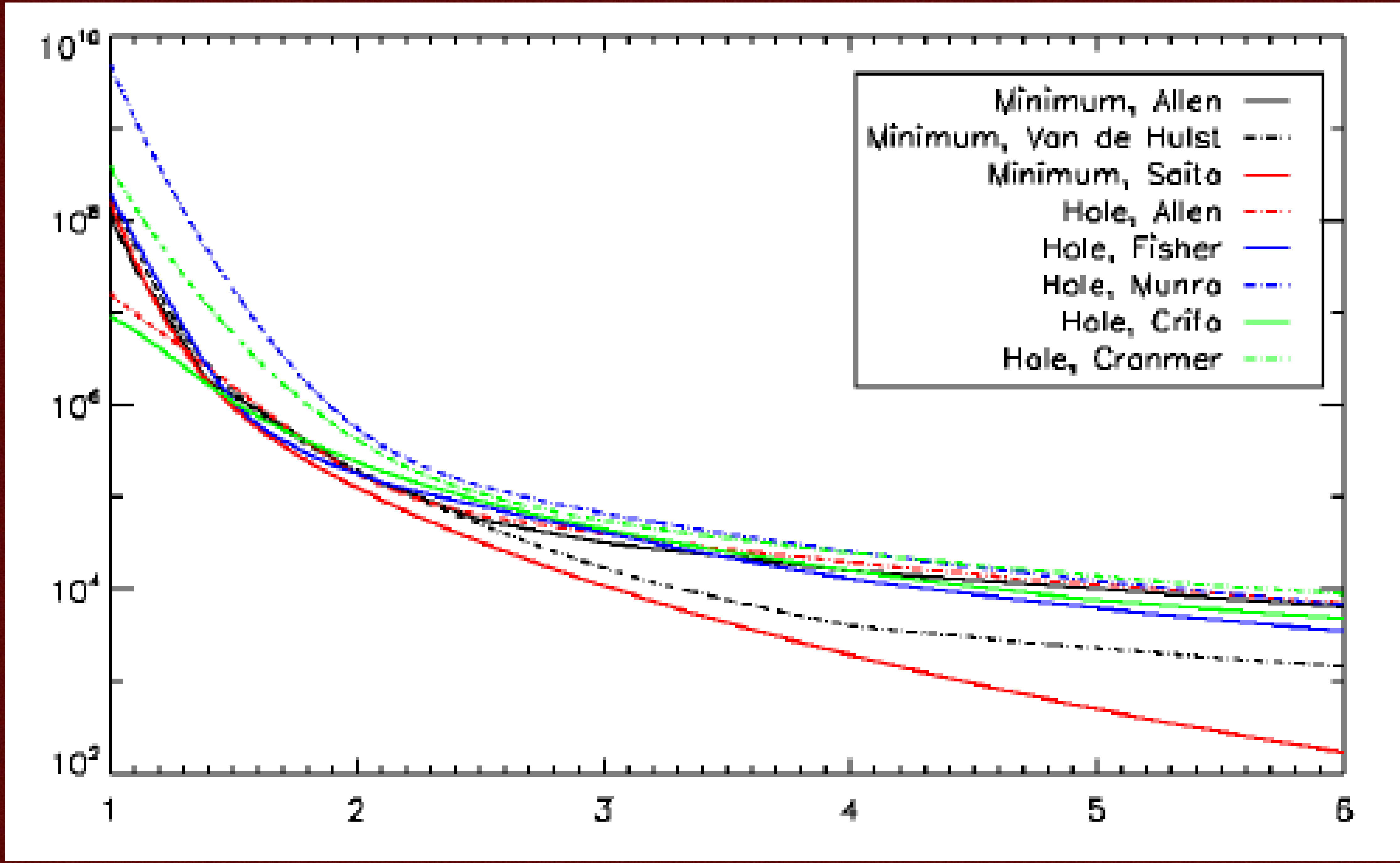
- Then the brightness integral can be inverted and Ne(ρ) takes the form of a new polynomial whose coefficients are expressed in terms of the a_k
- It has been applied to establish the standard density models of the coronal background at equator and pole in the solar minimum and maximum (Van de Hulst and Allen)
- It has then been extended to near-symmetric coronal structures such as streamers and coronal holes for which radial profiles of Ne(ρ) were obtained (e.g., Saito et al. 1977, Munro & Jackson 1977, Gibson & Bagenal, 1995; Guhathakurta & Fisher, 1995….)
- More general solutions have been proposed by expressing the electron density as a sum of Legendre polynomials (Altschuler & Perry 1972; Gabryl et al. 1999) but have not been pursued.

Ne Standard profiles

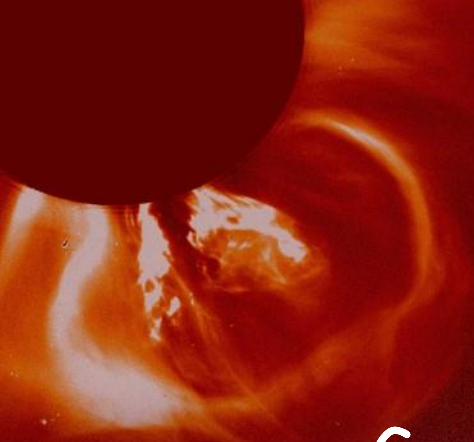


From Van de Hulst, Allen, Saito, and Newkirk

Ne minimum and coronal hole profiles



From Van de Hulst, Allen, Saito, Fisher, Munro, Crifo, and Cranmer



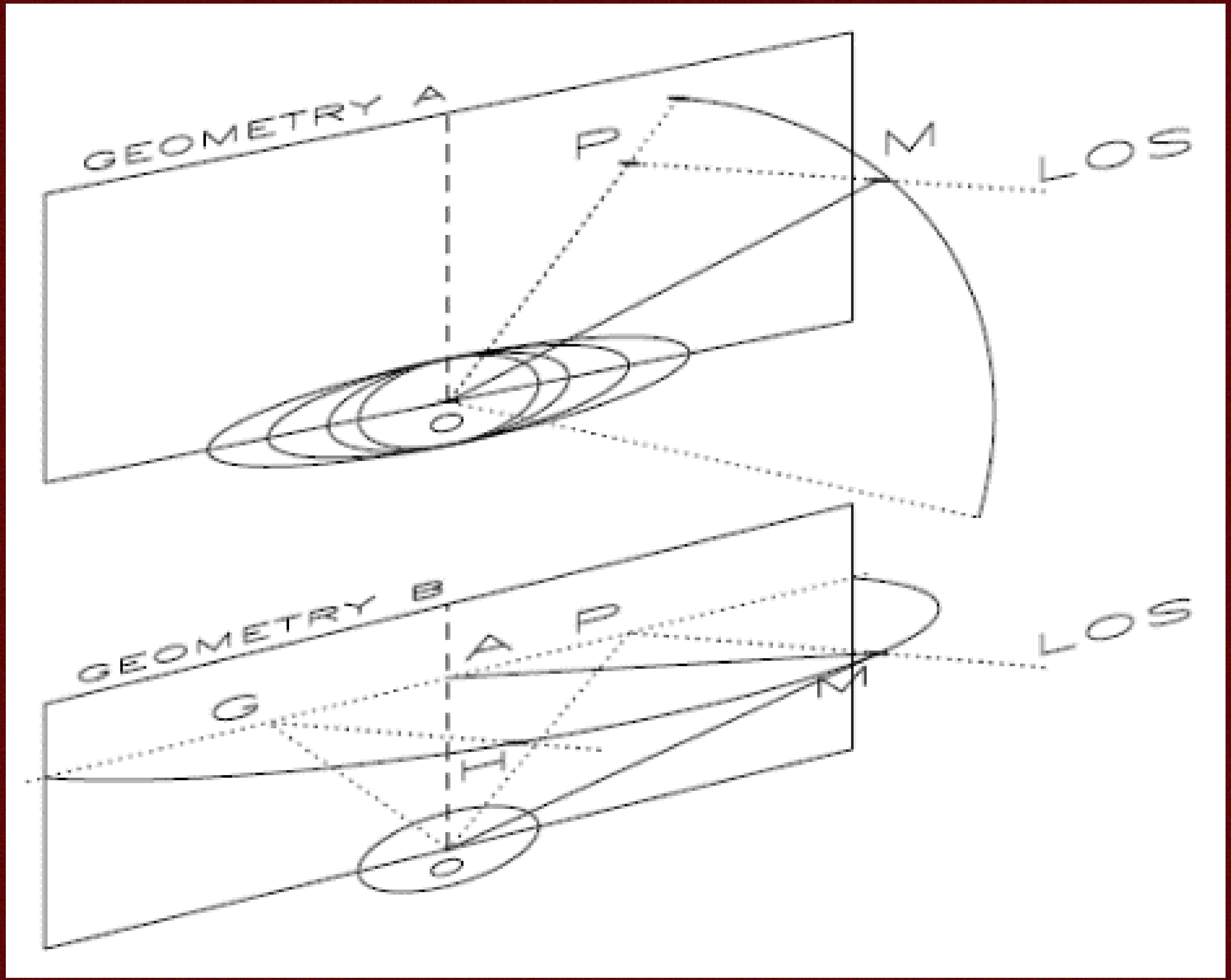
2D Inversion

- Generalization of the inversion SSI method of Van de Hulst (1950) independently by Hayes et al. (2001) and Quémerais & Lamy (2002) for deriving Ne map from the LASCO-C2 pB images. The formalism is called spherically symmetric polynomial approximation (SSPA).
- Ne is assumed to be a function of the radial distance Ne(r) and each radial profile is described by a polynomial. (local spherical symmetry approximation).
- The coefficients b_k are determined by forcing the recalculated brightness profile to match the observed one and the procedure is repeated for different position angles to generate a 2D map of the electron density.

$$N(r) = \sum_k b_k r^{-k}$$

- The method only requires local spherical symmetry (that is in each half plane defined by the k_{th} radial direction and the line of sight).
- It has also been generalized to the case of axial-symmetry (c.f. axi-symmetric model of Saito et al. 1970) best suited to a corona of the minimum type.
- Wang et al. (2014) have shown that the SSI and SSPA methods are formally equivalent.

Geometry for the 2D inversion method



Spherical symmetry

Axial symmetry

Quémerais & Lamy, A&A 2002

Maps of Ne from 2D inversion of LASCO-C2 images

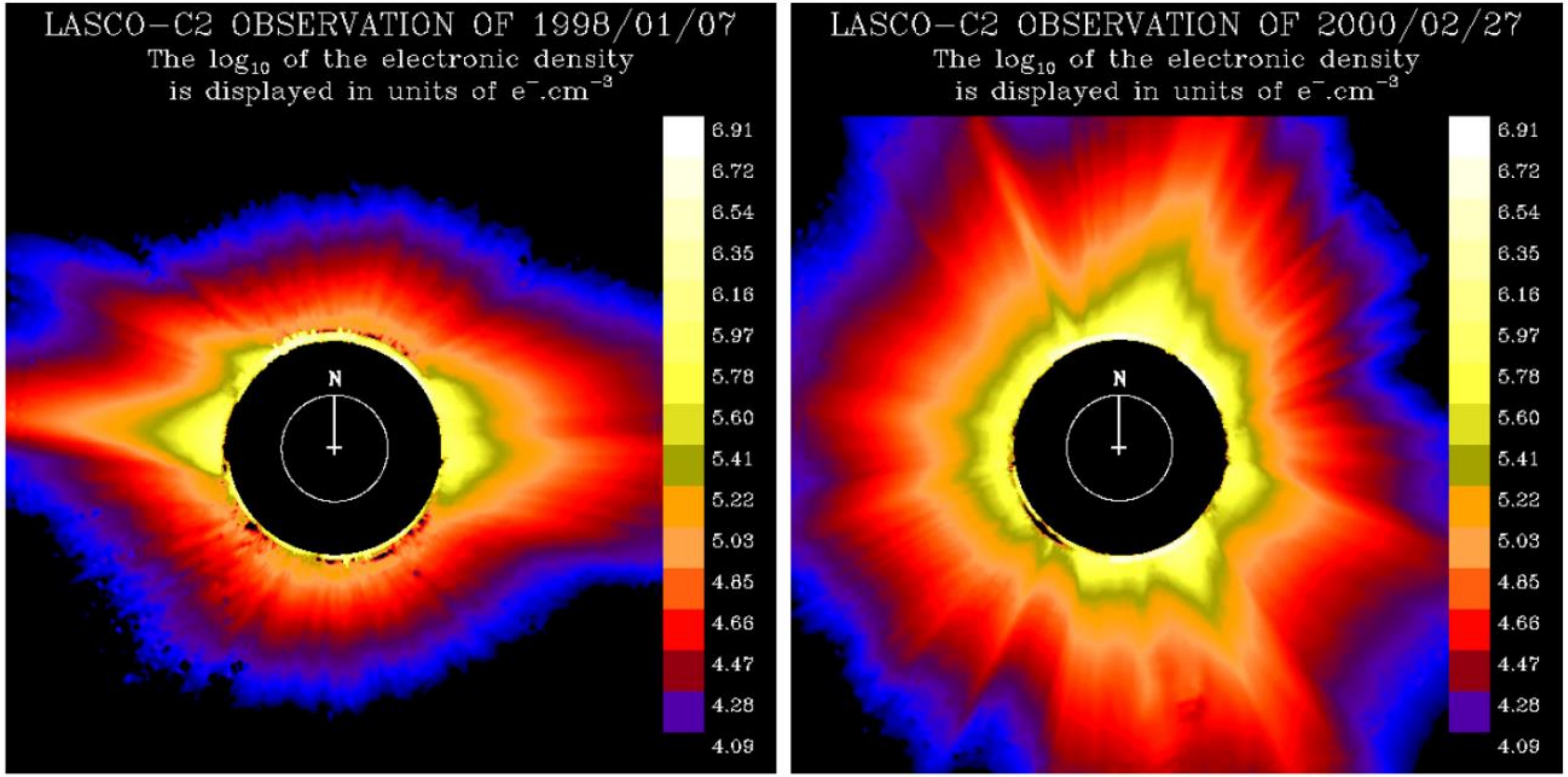
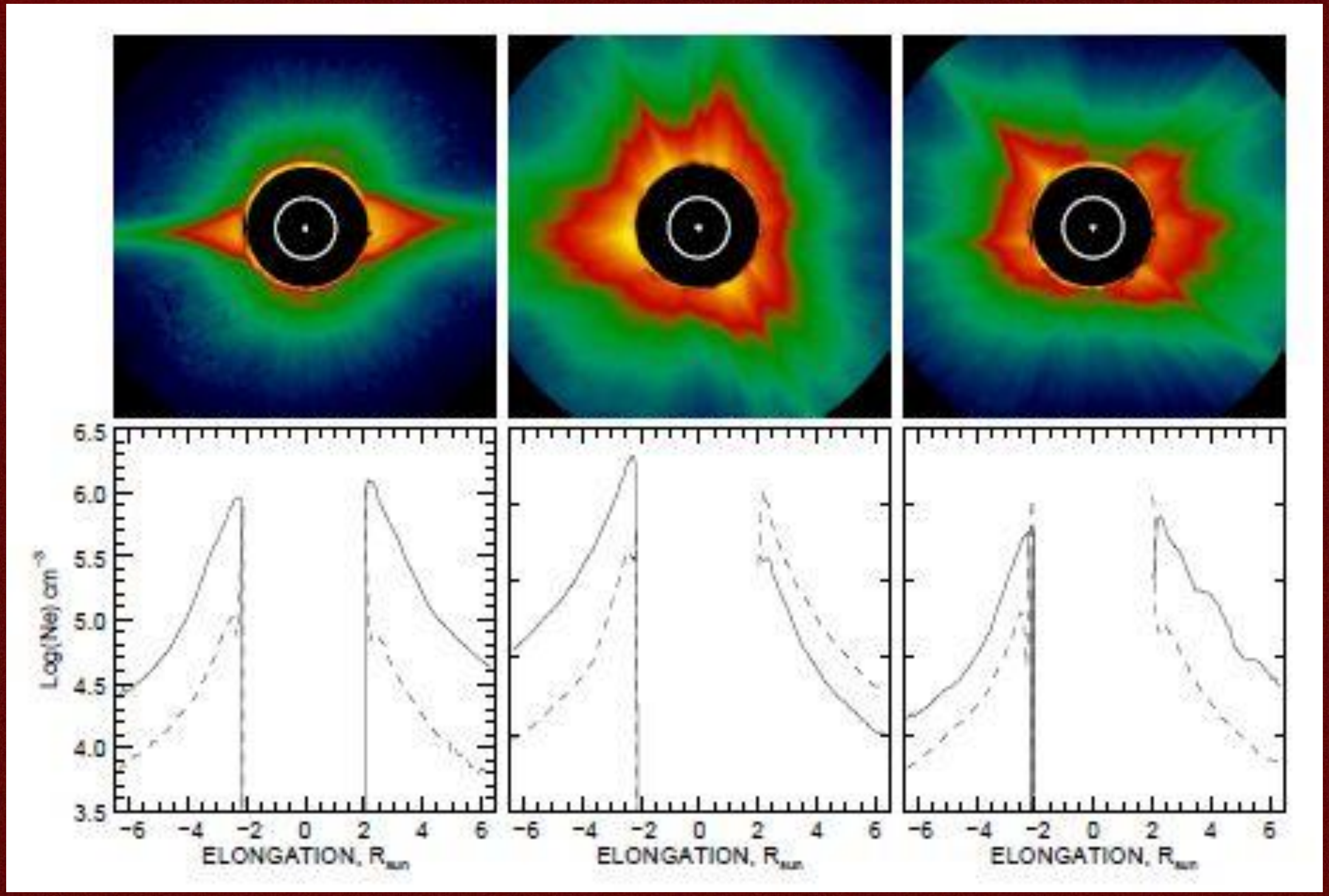


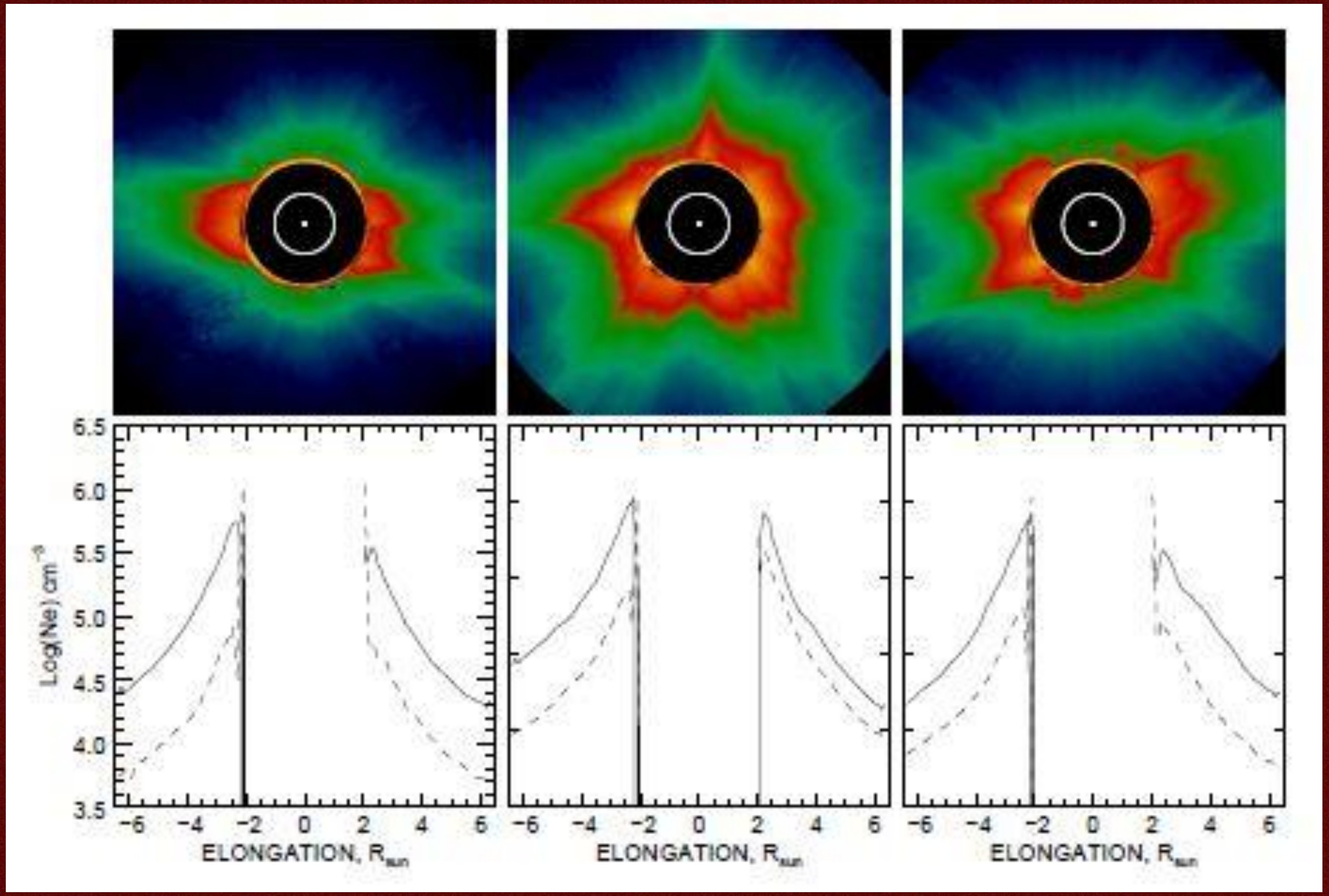
Figure 16. Two examples of maps of the coronal electron density obtained by 2D inversion during two phases of solar activity. Left panel: low activity on 7 January 1998 (CR1931). Right panel: high activity on 27 February 2000 (CR1960).

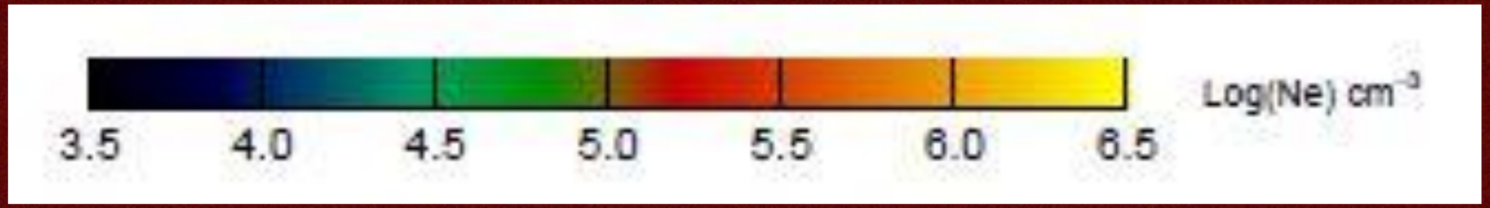
LASCO-C2 Ne images and profiles at 3 phases of SC 23 & 24

SC 23



SC 24





3D Inversion based on SSPA

- Generalization of the spherically symmetric polynomial approximation (SSPA).
- Proposed by Wang et al. (2014) as a “poor man” alternative to tomography.
- Their basic idea was to run successive SSPA inversions, each one providing a 3D reconstruction of the coronal density in a sector centered on the plane of the sky with an angular extent of ≈ 50° where the spherical symmetry is assumed to hold.
- They obtained a rough agreement with a tomographic reconstruction in the case of low solar activity.
- In a follow-up article, Wang et al. (2017) applied this method to 100 Carrington Rotations (CR 2054-2153 from March 2007 to August 2014, i.e., from the minimum to the maximum of Solar Cycle 24) of white-light pB images obtained with the COR1 coronagraphs of the STEREO mission.

3D Inversion based on static SRT
(Solar Rotational Tomography)

- SRT requires continuous observations over half a solar (14 days) to achieve a complete view of the solar corona in the general case of a single vantage point.
- In a first simpler approach, the corona is assumed to be static during this time interval.
- Probably valid during minima of solar activity but highly questionable during maxima.
- Initially developed by Altschuler and Perry (1972) and applied to Skylab data by Altschuler (1979).
- Many efforts by different groups using long time series of observations from the SOHO and STEREO missions and also from the Mauna Loa Solar Observatory K-coronameters, see Aschwanden (2011) for a summary until 2011.
- Noteworthy works include: Zidowitz et al. (1996, 1997, 1999), Butala et al. (2005), Frazin et al. (2002, 2005, 2007, 2010), Kramar (2009, 2014, 2016), and Morgan et al. (2009, 2010).
- Tomagraphic reconstructions using EUVI emissions have also been performed.

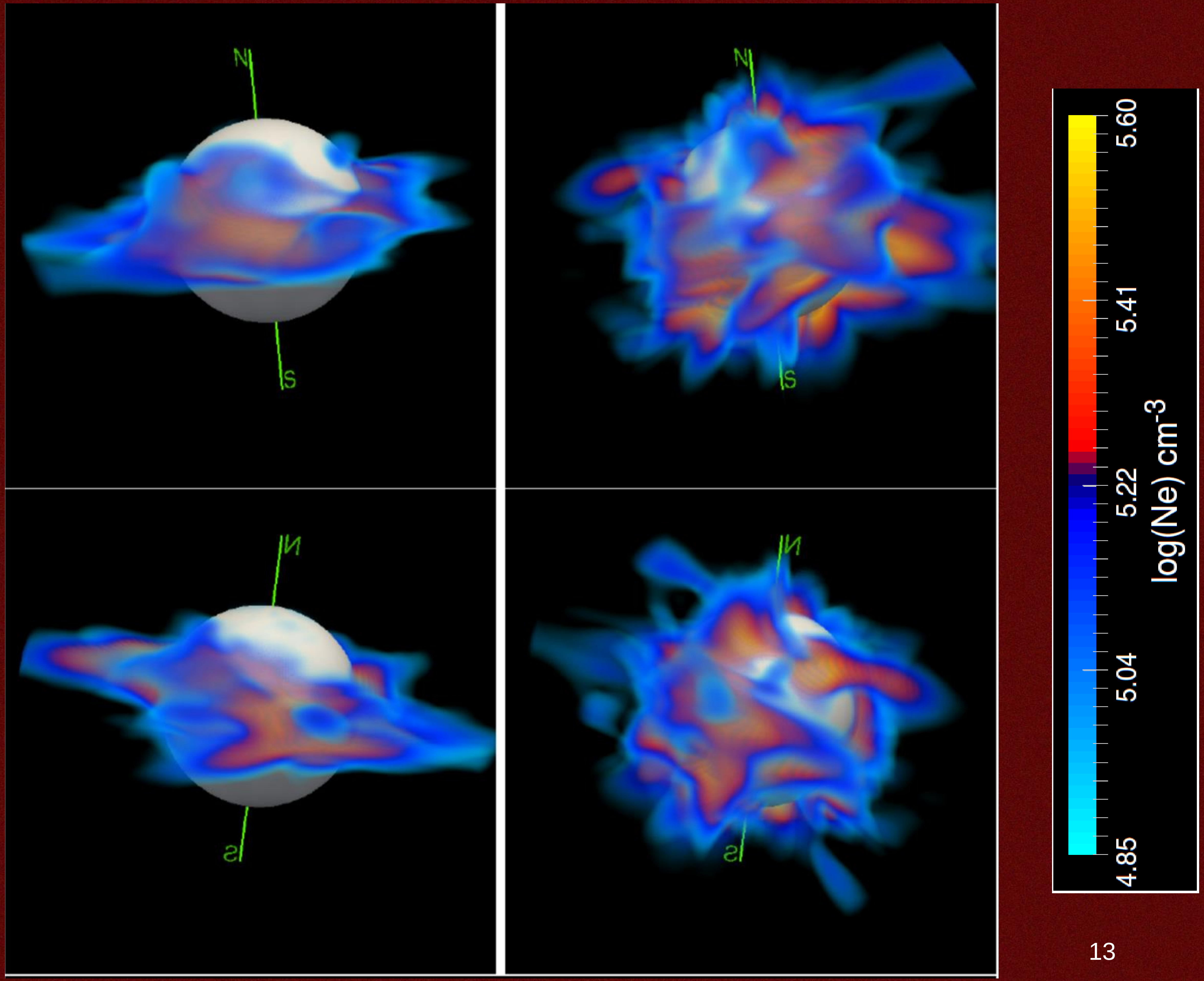
3D Inversion based on time-dependent SRT

- First attempt to develop a full time-dependent tomographic reconstruction performed by Butala et al. (2010) who implemented a procedure based on Kalman filters. It left the time-dependent tomography problem under-determined and the solution very reliant on the regularization choices.
- Vibert et al. (2016) achieved a time-dependent tomographic reconstruction by implementing a simpler spatio-temporal regularization. The respective weights of the spatial and temporal regularizations were determined by reconstructing a time-varying model of the corona.
- The procedure was successfully applied to a set of 53 LASCO-C2 pB images from 15 to 29 March 2009.
- Its application to the presently available 23 years [1996-2018] of LASCO-C2 pB images encompassing two complete solar cycles, SC 23 and 24, is complete.
- The resulting Ne "cubes", one every 4 days, will be shortly available on a dedicated website part of the LASCO-C2 Legacy Archive.

Two examples of 3D inversions

Left: CR 1931
Minimum corona

Right: CR 2146
Maximum corona



The white sphere has a radius of 2.5 Rsun, the inner limit of the FoV of LASCO-C2

Comparison of 2D & 3D reconstructions

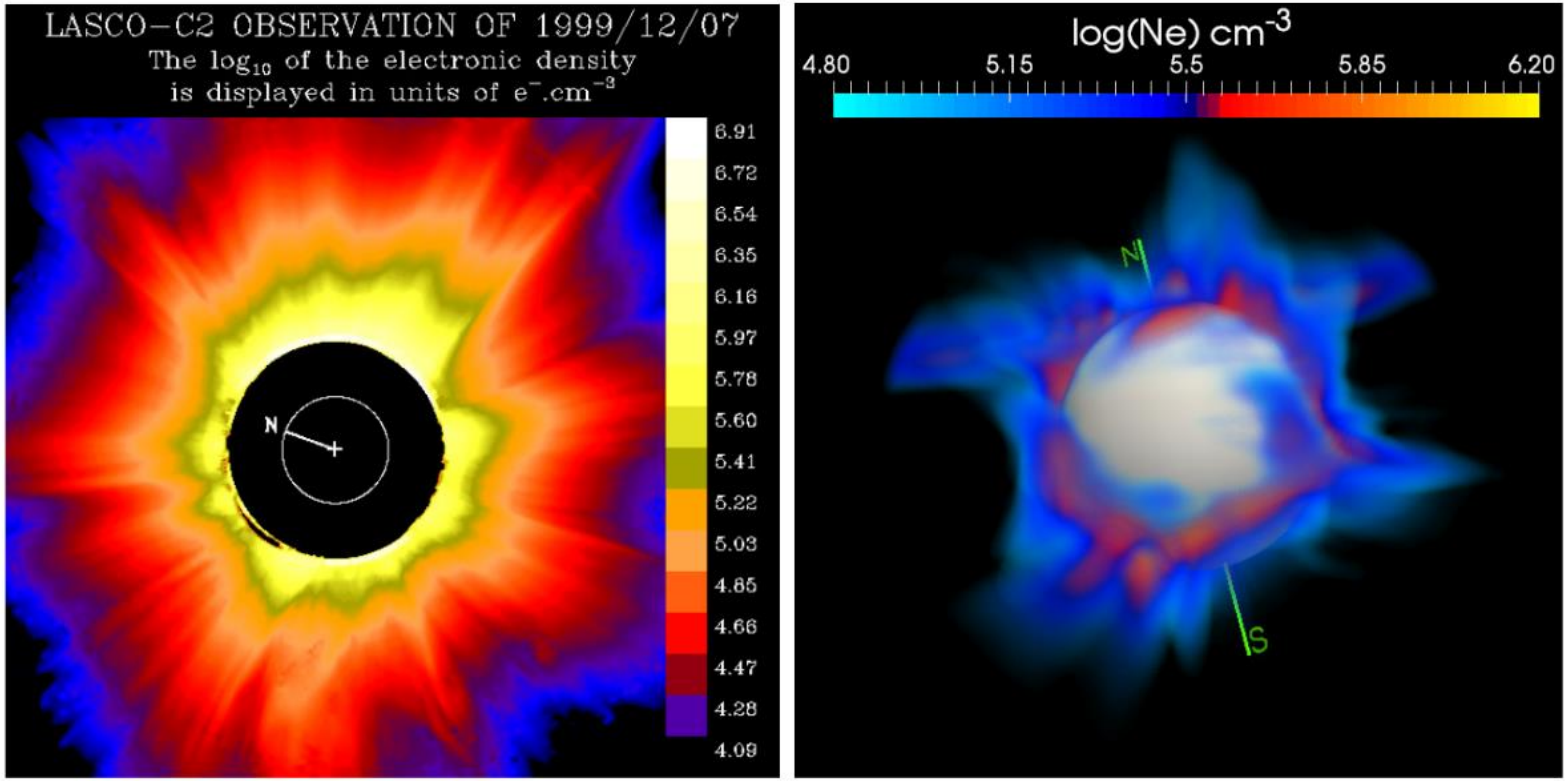
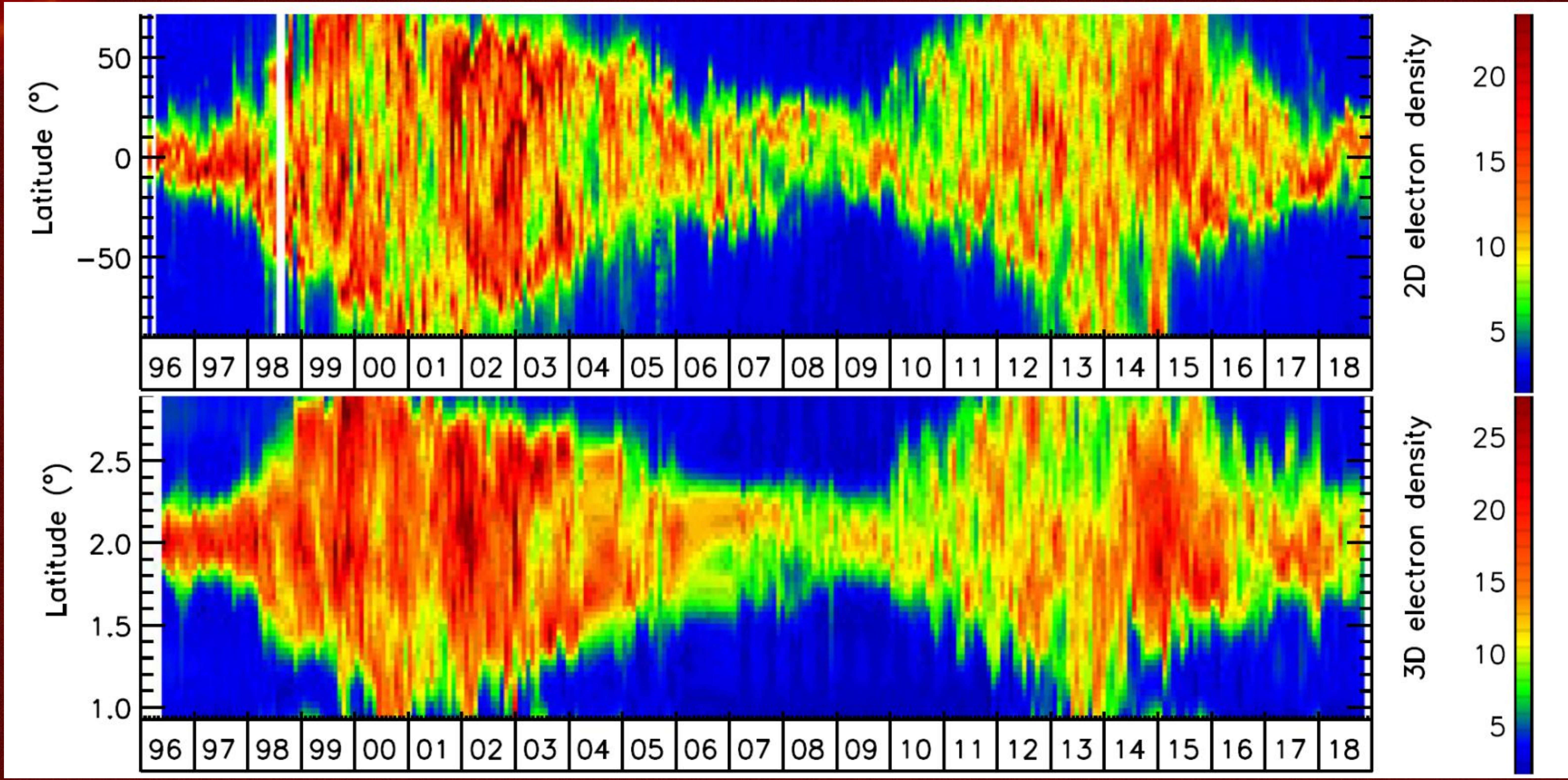
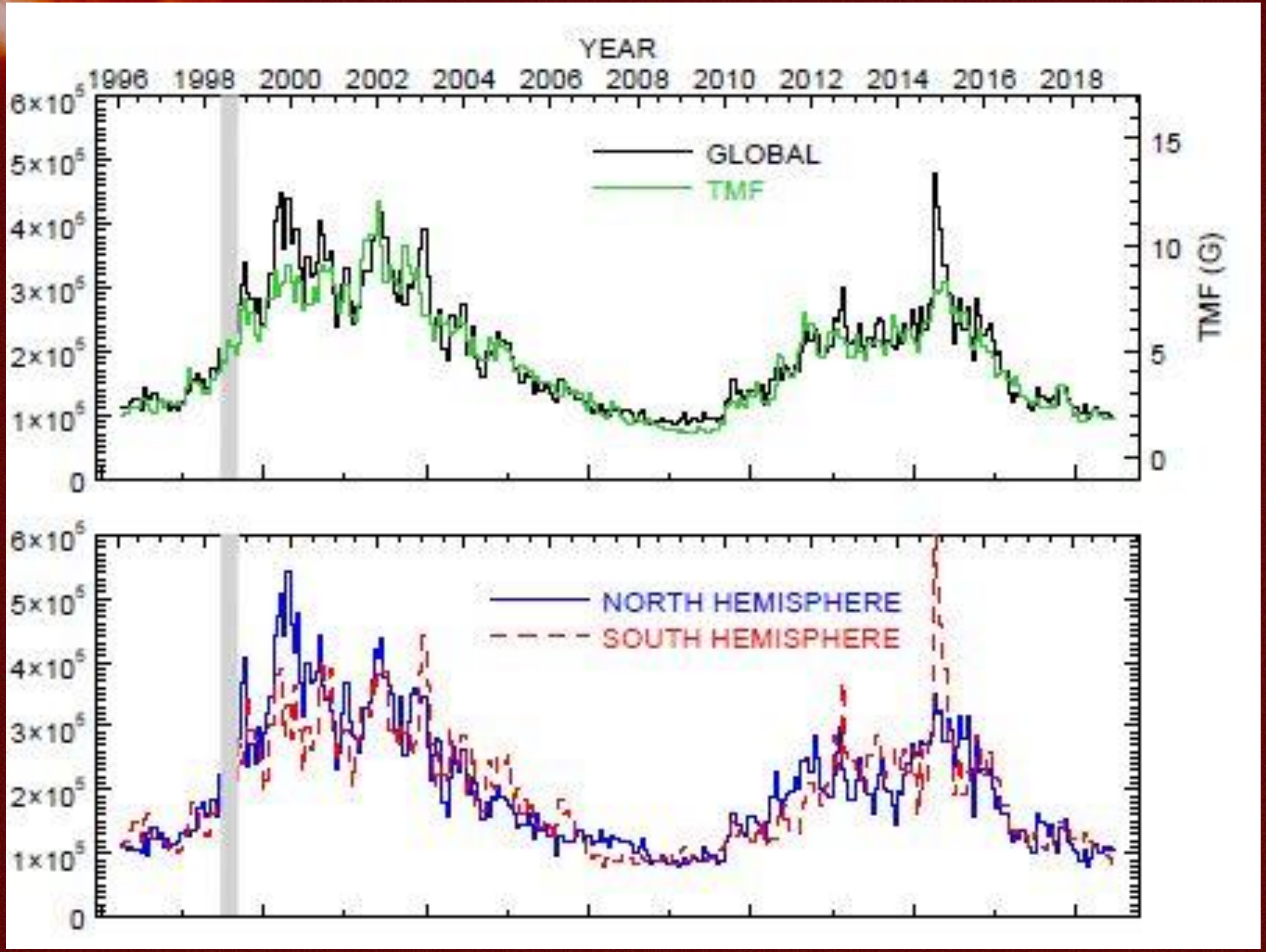


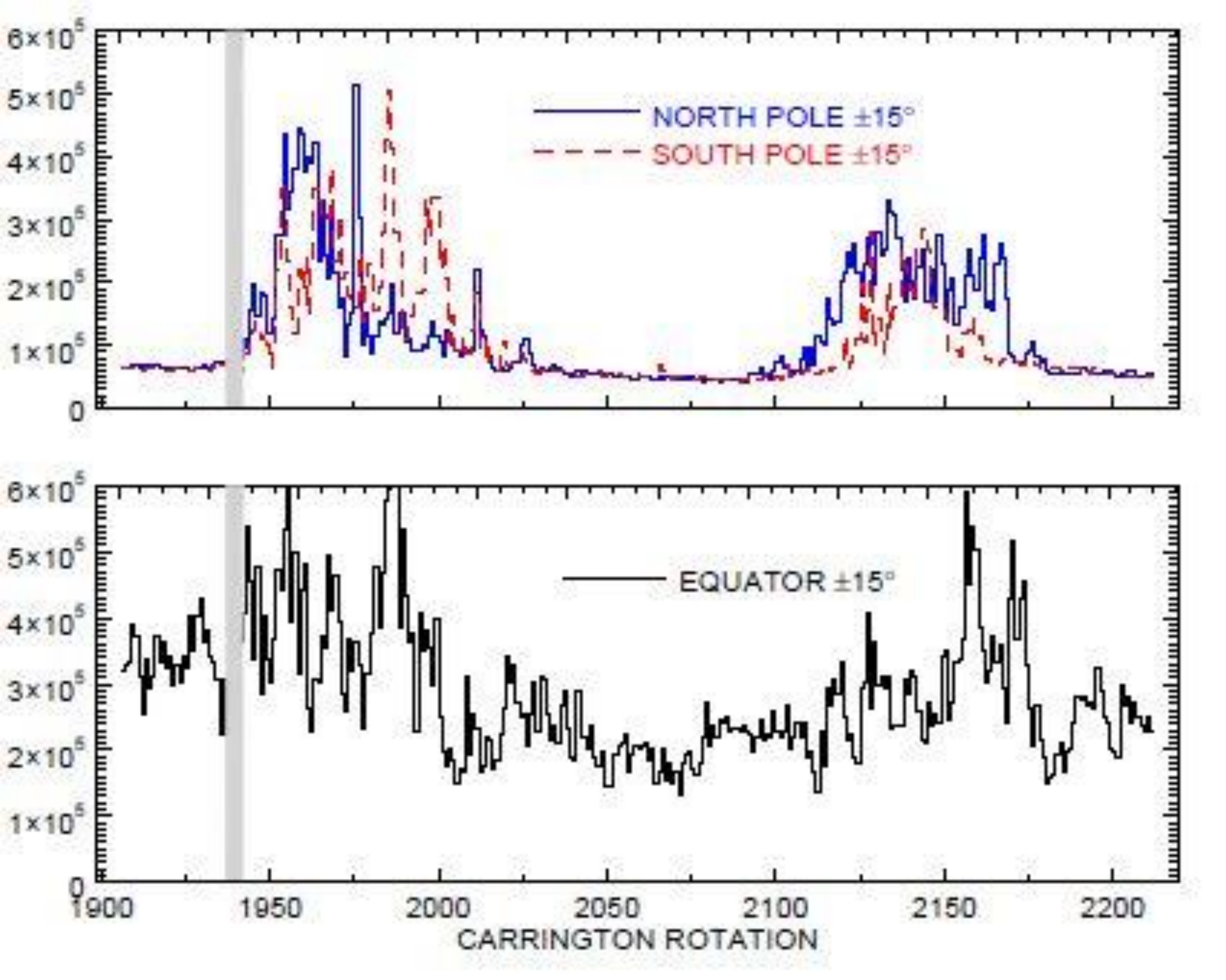
Figure 8. Comparison of 2D and 3D displays of the coronal electron density during CR1957. The extent of the large equatorial coronal hole is best perceived on the 3D display when selecting the optimal vantage point. The color bar is scaled to the logarithm of the electron density in units of cm^{-3}.

Multi-annual synoptic maps of Ne from 2D & 3D inversions



Monthly averaged profiles of the electron density at 2.7 Rs





TMF = Total Magnetic field (courtesy Y.-M. Wang)

Application to SOLO/METIS

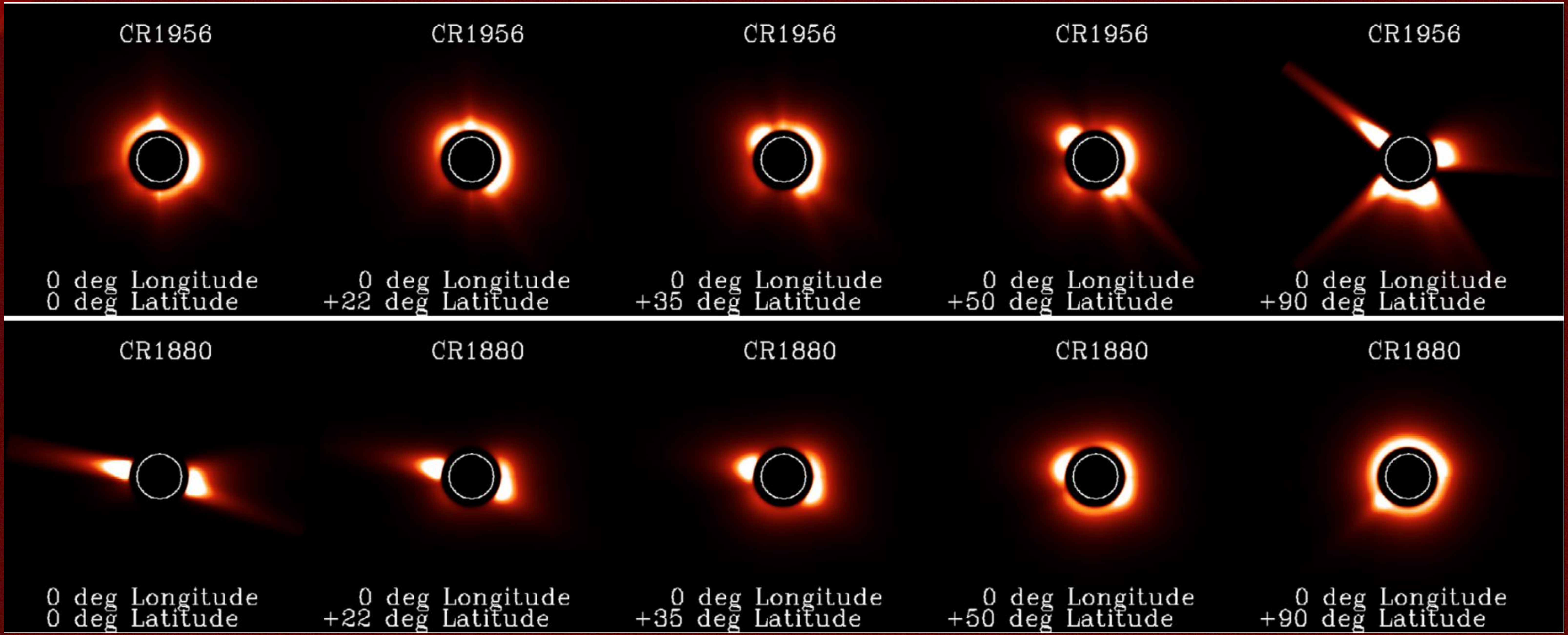
- 2D inversion and reconstruction of Ne using SSPA is possible at any time using preferably pB images. When corotation will take place, we will see the true temporal evolution of Ne (unspoiled by solar rotation as it is the case for observations at 1 AU).
- 3D inversion and reconstruction of Ne using time-dependent SRT should be possible during some phases.
  - It is required that the observations cover half a Carrington rotation (CR)
  - A minimum sampling by 14 images roughly equally spaced is adequate based on LASCO-C2 experience
  - pB images are favoured

- Bear in mind the appearance of the corona as a function of solar activity and orbit inclination (Saez et al. 2007). In a nutshell, a maximum corona when seen at high inclinations looks pretty much like a minimum corona.

Maximum and minimum K-coronae seen from different helio latitudes

Max SC 23
Early 2000

Min SC 23
Mid 1996

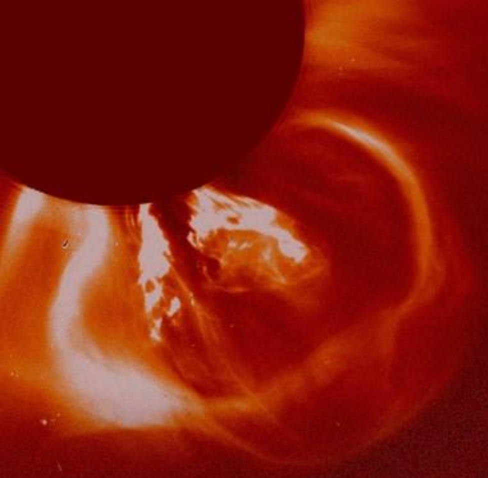


Images calculated using a 3D plasma sheet centered on PFSS neutral lines

Application to SPP/WISPR

the heliospheric imager aboard the Parker Solar Probe

- Tomographic reconstruction is not possible during the first orbits
- For Orbit 12, tomographic reconstruction is possible in the heliocentric height range 5 – 15 Rsun, over a region spanning up to 160° in Carrington longitude, with data gathered over a $\approx$ 3.4 day-long period.
- For Orbit 24, tomographic reconstruction is possible in the heliocentric height range 3 – 10 Rsun, over a region spanning up to 170° in Carrington longitude, with data gathered over a $\approx$2.8 day-long period.
- In all cases, the spatial coverage is provided by the very fast motion of PSP, not by the solar rotation.
- See complete study in Vasquez et al. Sol. Phys. 2019



Good luck to METIS
and
Thank you for your attention