Radial and Latitudinal Gradients of Anomalous Cosmic Ray Oxygen in the Inner Heliosphere

A. C. Cummings, *Caltech*

STEREO SWG

Pasadena, CA

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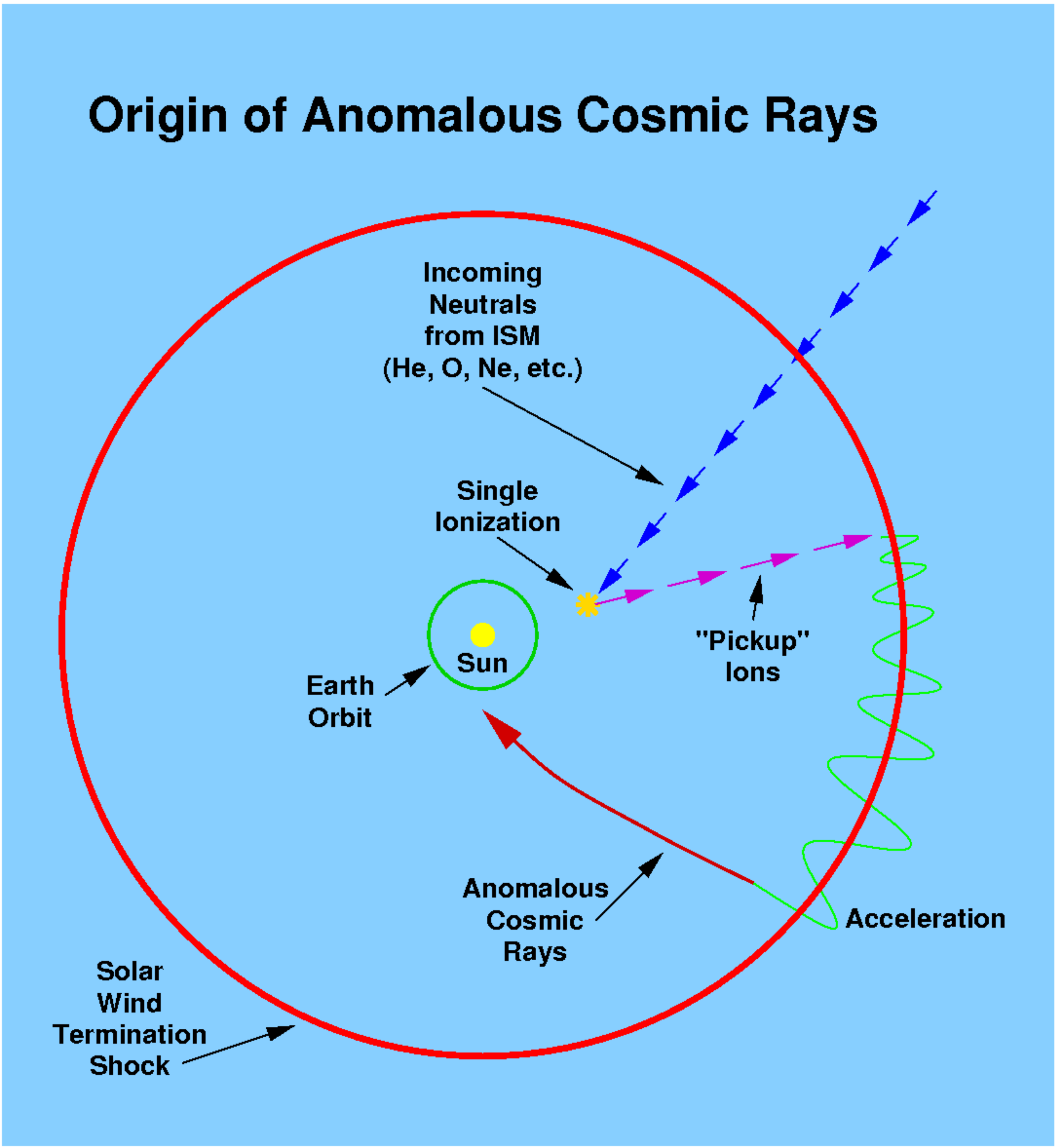


This has been the paradigm since ~1974 up until Voyager 1 crossed the termination shock.

Some of this is probably still relevant.

Drift Patterns for qA>0

plane, and evolves in the outer heliosphere as a latitudinal wave of the type depicted in Figure 2. The latitudinal extent of this wave as specified by the parameter α is greater at solar maximum than at solar minimum. It is the purpose of the rest of this paper to investigate the effects of this inferred magnetic field structure on cosmic-ray propagation.

III. THE COMPUTATIONAL MODEL

The basic transport equation for cosmic rays in the heliosphere is the Fokker-Planck equation, which has been discussed by a number of authors over the past 15 years (e.g., Parker 1965; Gleeson and Axford 1967; Jokipii and Parker 1970). For computational purposes it is most convenient to work in terms of the phase space density $f(r, P) = j/P^2$, where j is the intensity, for which the steady-state transport equation becomes

$$\frac{\partial f}{\partial t} = 0 = \frac{\partial}{\partial X_i}\left(K_{ij}\frac{\partial f}{\partial X_j}\right) - (V_{w,i} + \langle V_d \rangle_i) \times \frac{\partial f}{\partial X_i} + \frac{\nabla \cdot V_w}{3} P \frac{\partial f}{\partial P} . \quad (2)$$

Here V_w is the solar wind velocity, $\langle V_d \rangle$ is the gradient and curvature drift velocity averaged over the nearly isotropic pitch angle distribution, P is the particle momentum, r is position, and K_{ij} is the (symmetric) diffusion coefficient.

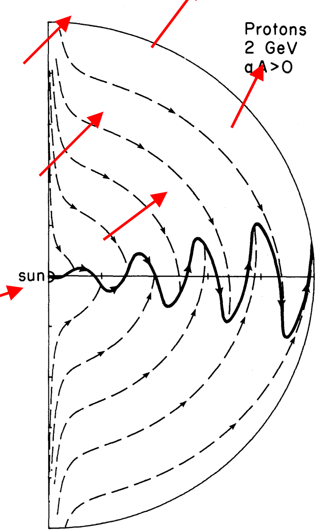


FIG. 4.—Meridional projection of the drift trajectories (including convection with the solar wind) for 2 GeV protons with $qA > 0$. The parameters of the current sheet are as in Fig. 2. The tick marks are at 5 AU intervals. The arrows will change direction for $qA < 0$.

The drift velocity $\langle V_d \rangle$ is determined by the structure of the interplanetary magnetic field,

$$\langle V_d \rangle = \frac{Pcw}{3q} \nabla X \left(\frac{B}{B^2}\right) \quad (3)$$

(e.g., Isenberg and Jokipii 1979). This expression is readily evaluated for the magnetic-field model discussed above in § II.

The formal expression for the magnetic vector using the approximate form of equation (1), which is adequate if $\alpha \lesssim 30°$, is

$$B = \frac{A}{r^2}(\hat{e}_{r^2} - \Gamma \hat{e}_\phi) \times \left\{1 - 2S\left[\theta - \left(\frac{\pi}{2} + \alpha \sin\left(\phi - \frac{r\Omega_0}{V_w}\right)\right)\right]\right\}, \quad (4)$$

where $S(X)$ is the Heaviside step function and $\Gamma = r\Omega_0 \sin\theta / V_w$. This corresponds to a simple Parker spiral magnetic field directed in opposite directions above and below the current sheet. As discussed above, the current sheet corresponds to a plane at $r \approx 0$ which is at an angle α relative to the equatorial plane of the Sun.

The drift velocity for the assumed magnetic field configuration is readily computed by substituting B from equation (4) into equation (3). One obtains

Drifts carry positive particles from high latitudes to low latitudes during A>0 portion of solar cycle.

$$\langle V_d \rangle = \langle V_d \rangle_M \left\{1 - 2S\left[\theta - \left(\frac{\pi}{2} + \alpha \sin\left(\phi - \frac{r\Omega_0}{V_w}\right)\right)\right]\right\} + \frac{2Pcwr}{3qA(1+\Gamma^2)^{1/2}} \hat{e}_\parallel \times \delta\left[\theta - \left(\frac{\pi}{2} + \alpha \sin\left(\phi - \frac{r\Omega_0}{V_w}\right)\right)\right] |\cos\eta| , \quad (5a)$$

Arrows reversed in A<0.

where

$$\langle V_d \rangle_M = \frac{2Pcwr}{3qA(1+\Gamma^2)^2} \times \left[\frac{\Gamma}{\tan\theta}\hat{e}_r + (2+\Gamma^2)\Gamma\hat{e}_\theta + \frac{\Gamma^2}{\tan\theta}\hat{e}_\phi\right] , \quad (5b)$$

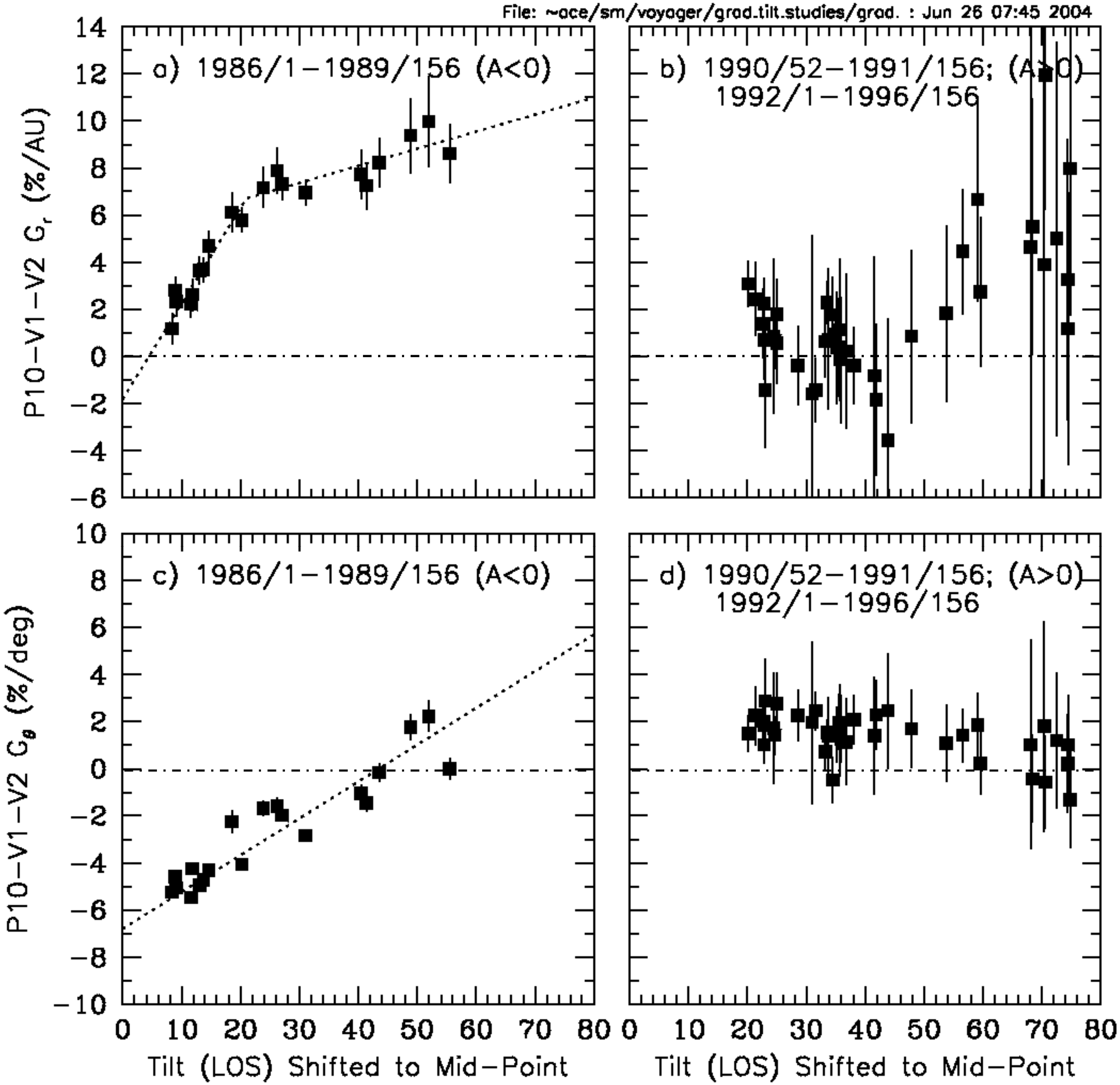
Expect radial gradient to depend on tilt angle during current A<0 period. Not so sensitive during A>0.

is the now familiar drift velocity in an Archimedean spiral field, and η is the angle between the normal to the current sheet and e_θ. The singular term containing the δ-function represents the rapid migration of particles along the current sheet, normal to the magnetic field. Hence, the unit vector $e_\parallel$ is a vector locally parallel to the current sheet, and normal to the local magnetic field. The drift trajectories are indicated schematically in Figure 4 for positive particles in a configuration where $A > 0$. Changing the sign of the charge or the sign of A will reverse the direction of the arrows, but leave the drifts otherwise unchanged.

Adapted from Jokipii & Thomas, 1981

Previous papers in this series (e.g., Jokipii and Kopriva 1979; Isenberg and Jokipii 1981) have considered the solution of equations (2) and (5) for the case $\alpha = 0$ (no tilt). In this case, all parameters are independent of azimuth ϕ, and one may suppress the azimuth. The resulting model depends on only two spatial dimensions.

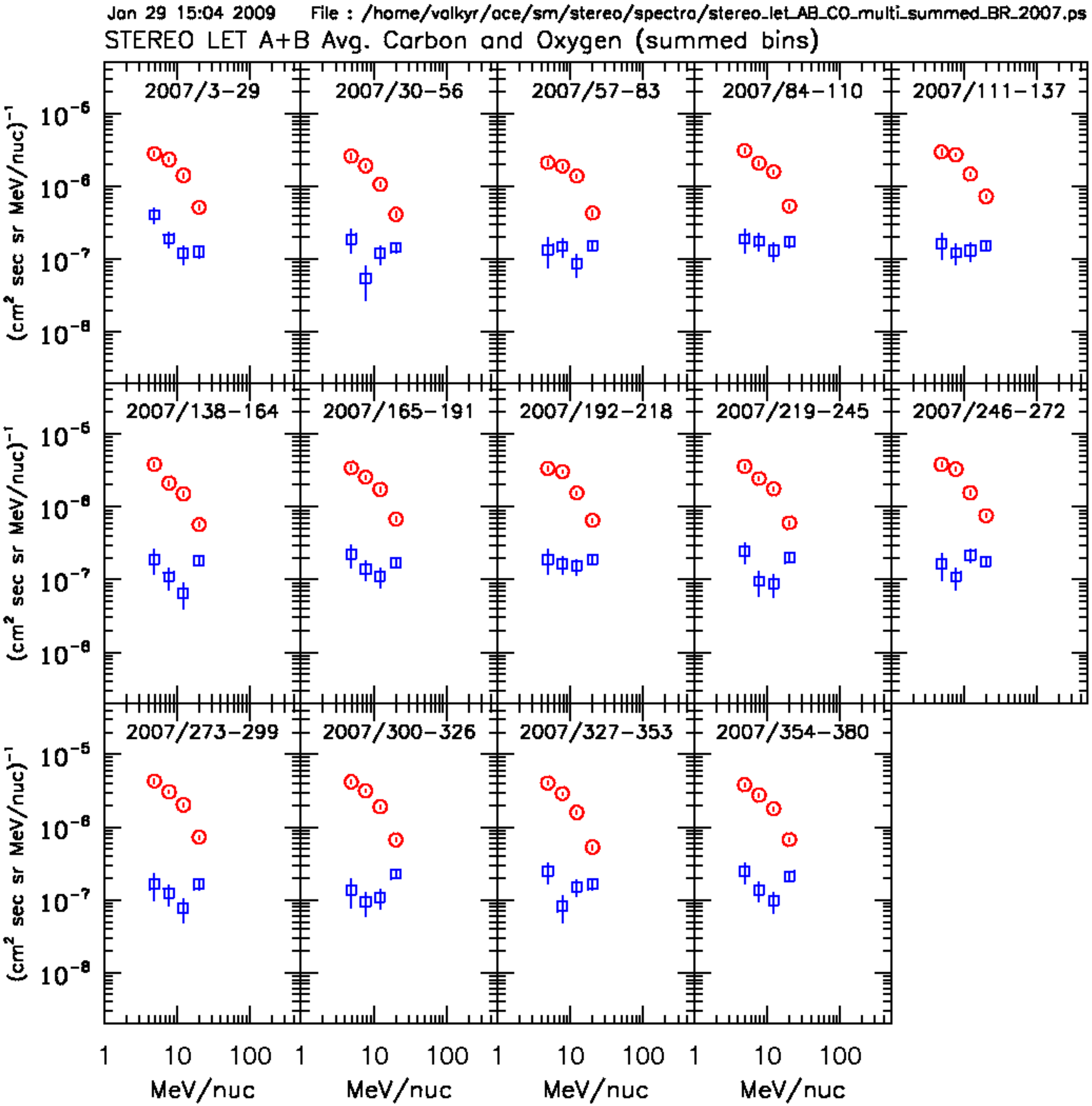
Gradients of 7.1-17.1 MeV/nuc ACR O in Outer Heliosphere vs Tilt



Current period of study is 2007-2008, A<0, and will use Ulysses & STEREO data to explore gradients inside 5 AU.

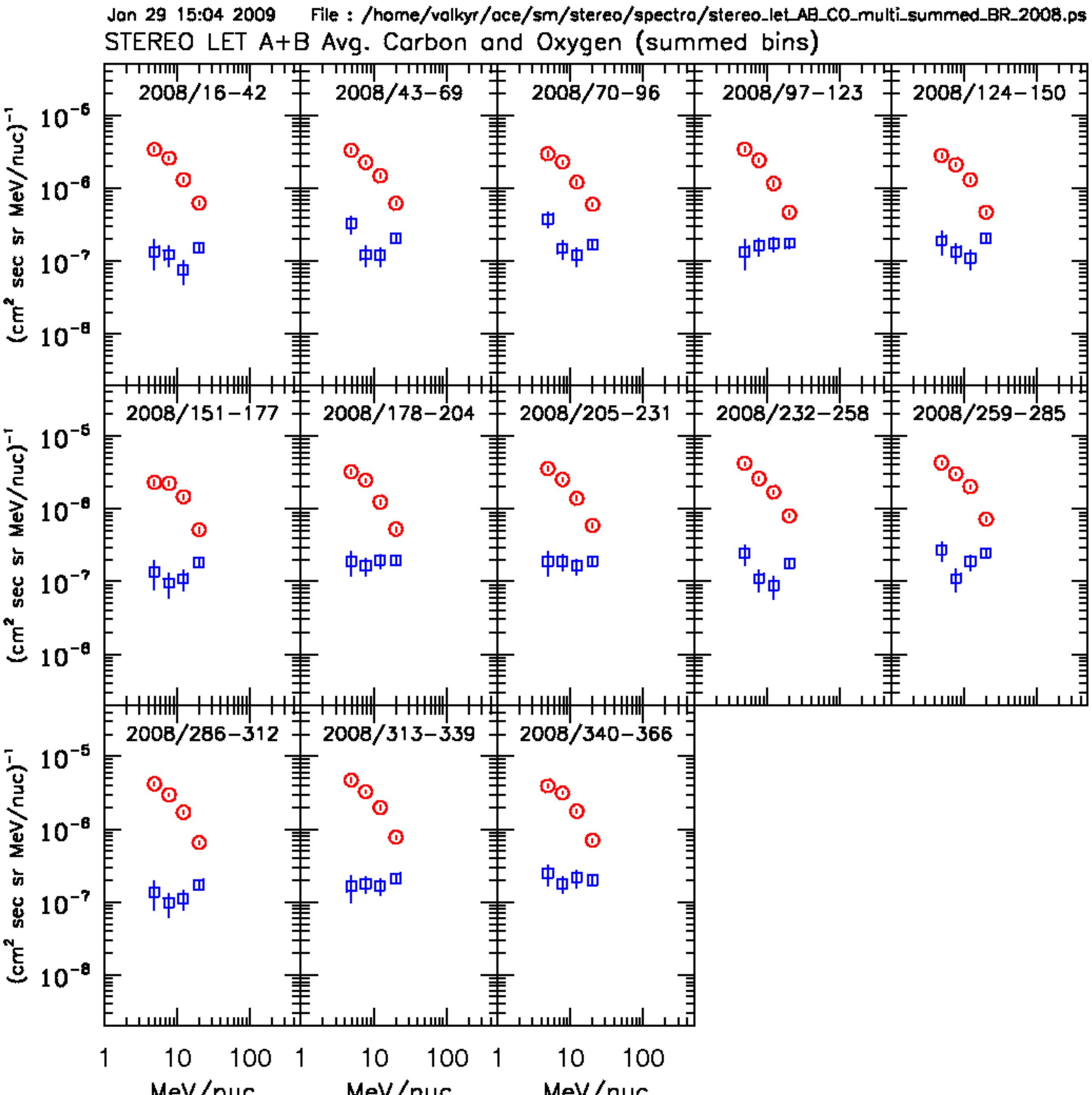
Previous History in Inner Heliosphere

- **Pioneer 10 & 11 launched in early 70's during A>0 solar minimum**
  - **P10, P11, & IMP 1972-1978: 25±5%/AU for 1-5 AU (Webber et al. 1979) for ~9-24 MeV/nuc O**
  - **Could not infer latitudinal gradient**
- **Previous Ulysses studies (all during A>0)**
  - **Ulysses + SOHO/ERNE 1997 at 10 MeV/nuc: 18±2.4 %/AU and 0.6±0.1 %/deg**
  - **Other Ulysses studies found positive lat grads from ~1-5 %/deg., similar to what was found in outer heliosphere**
- **Gradient studies have never been done observationally for A<0 period inside 5 AU**
    - **Cummings et al. tilt models inferred ~30-50 %/AU radial gradients inside 5 AU**



Evolution of STEREO C&O energy spectra, 27d intervals

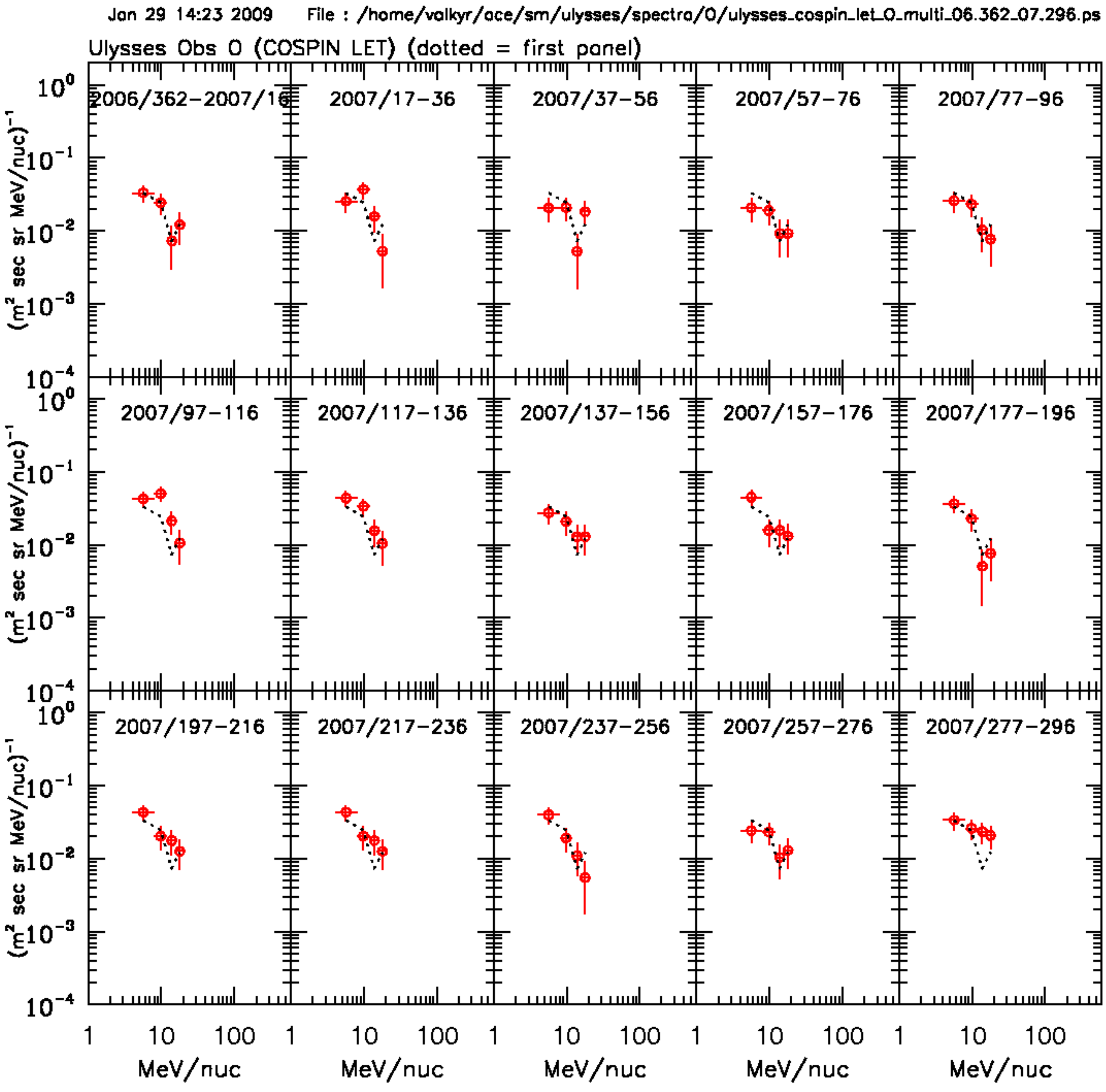
2007



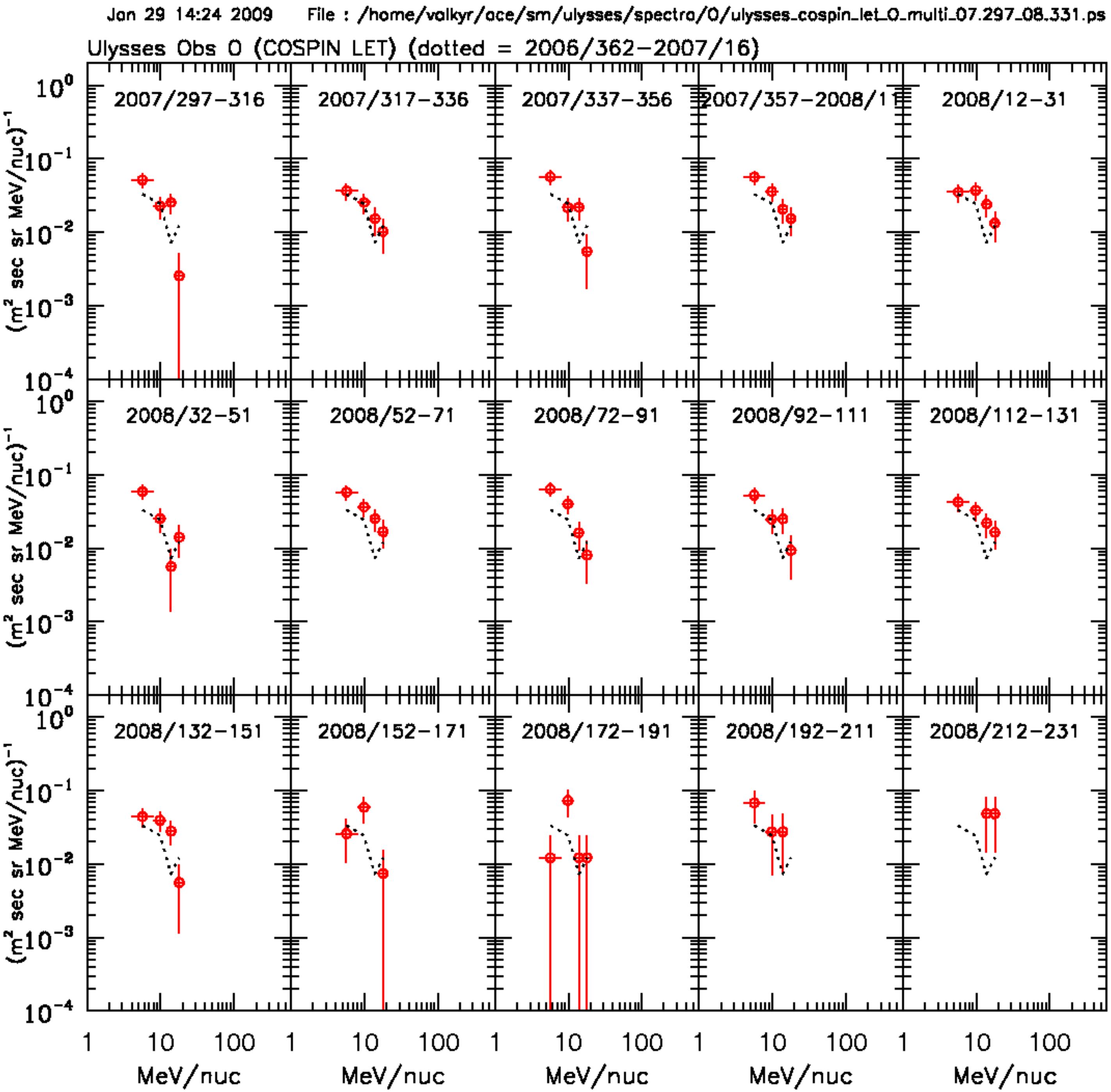
Evolution of STEREO C&O energy spectra, 27d intervals

2008

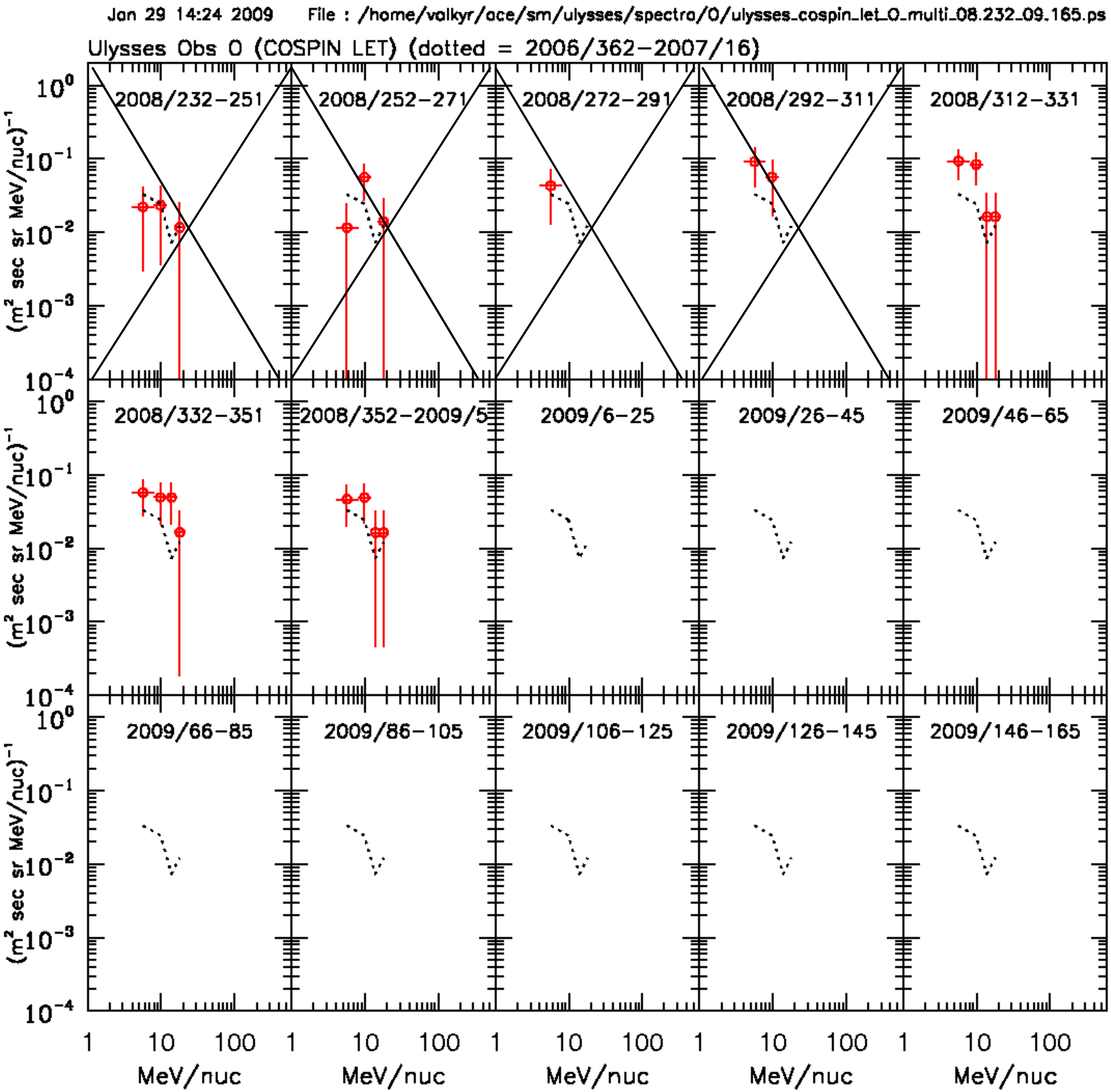
2007 & 2008 very quiet; no need to worry about SEP contamination of ACRs



Evolution of Ulysses O energy spectra, 20d intervals



Evolution of Ulysses O energy spectra, 20d intervals



Evolution of Ulysses O energy spectra, 20d intervals

Period of instrument issues; ignore these periods for now.

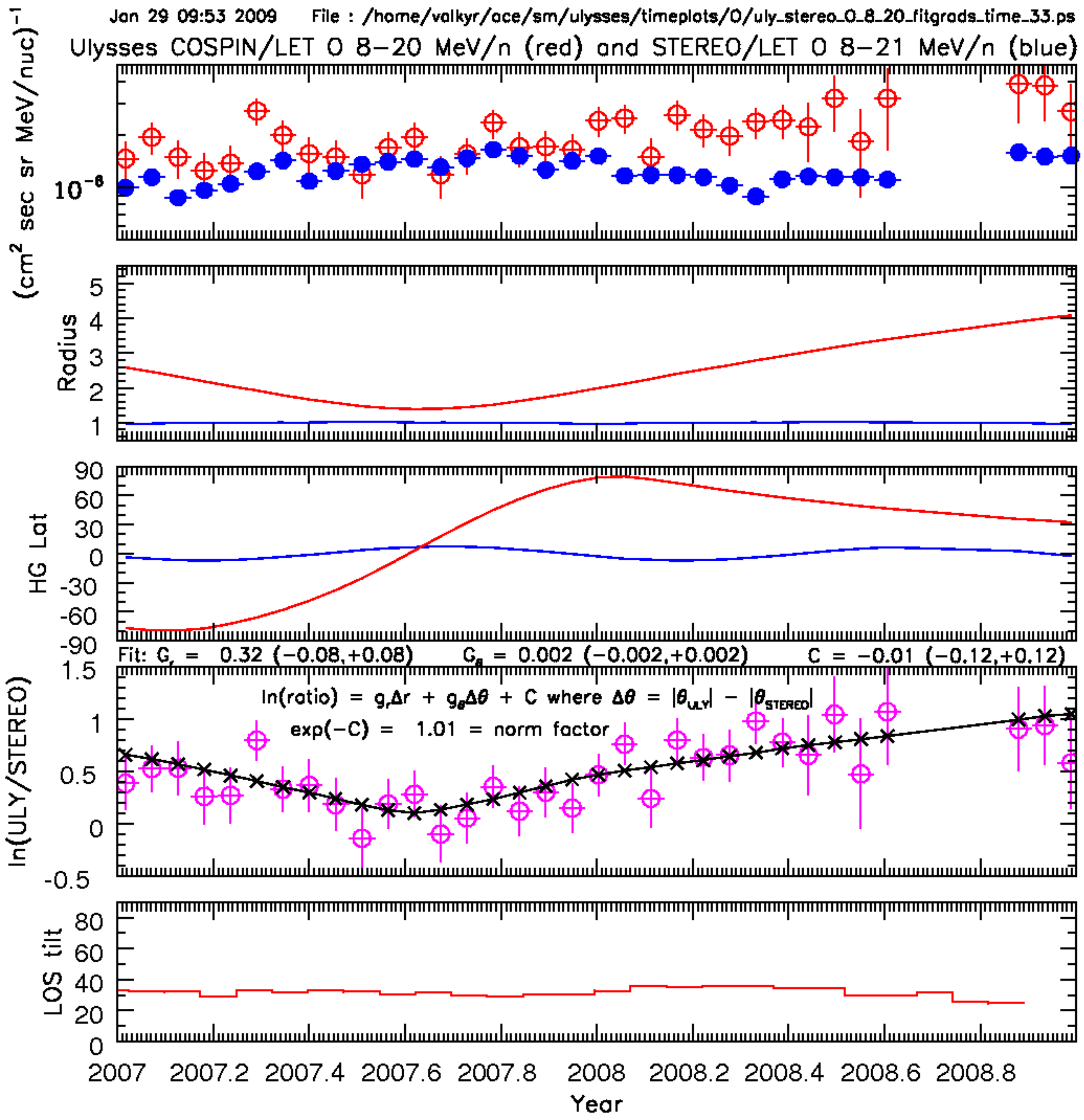
Determining radial and latitudinal gradients from Ulysses and STEREO Oxygen data

$$ln(f_U/f_S) = g_r \Delta r + g_\theta \Delta\theta + C$$

Where

$$\Delta\theta = |\theta_{Uly}| - |\theta_{1AU}|$$

- C accounts for possible normalization factor between 8-21 MeV/nuc STEREO/LET O and 8-20 MeV/nuc Ulysses COSPIN/LET O
- Assume gradients constant



Gradients of ~8-20 MeV/nuc O

C = -0.01 -> norm factor = 1.01

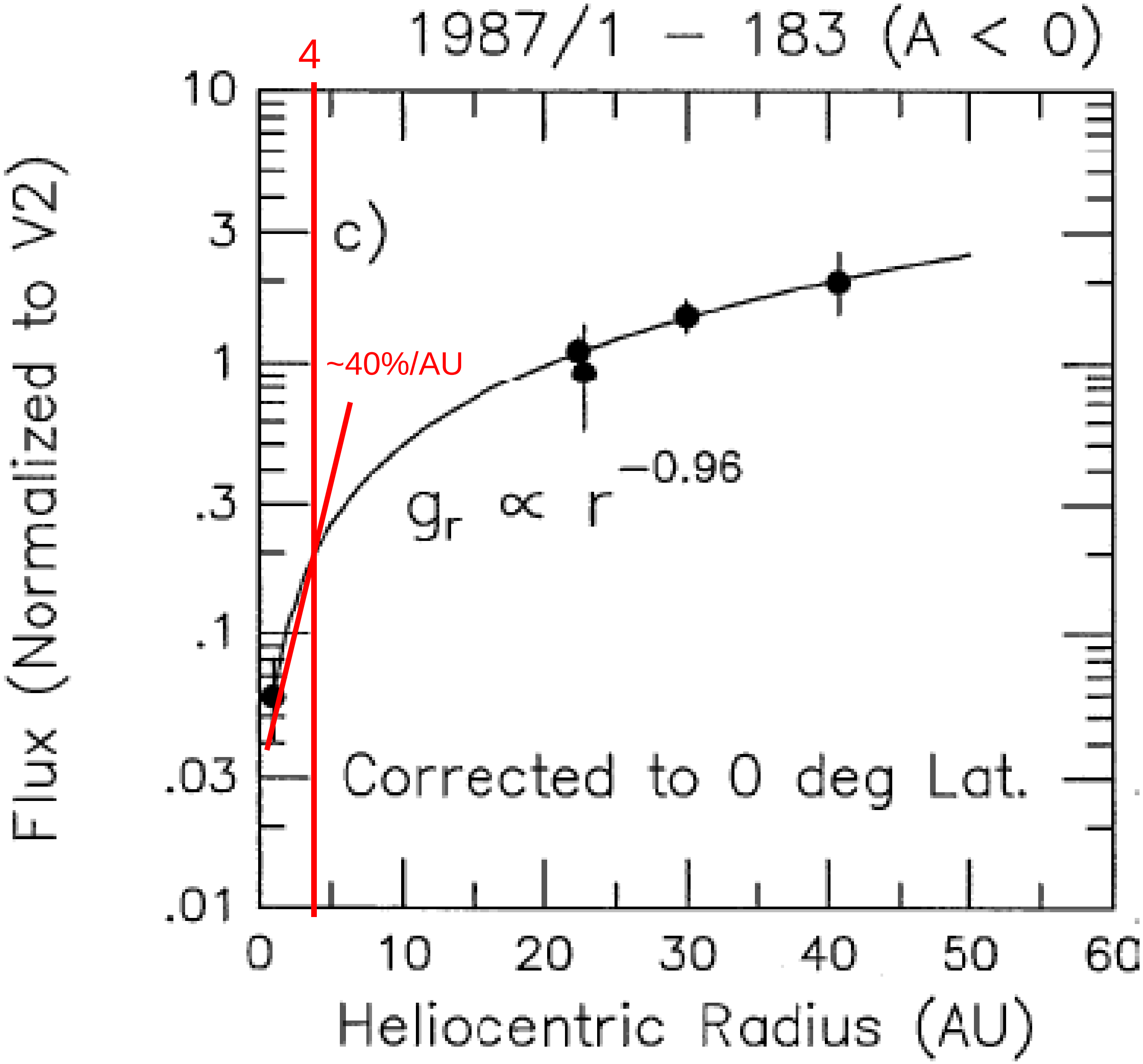
Rad grad = 32 ± 8 %/AU

Lat grad = 0.2 ± 0.2 %/º

Chisq = 20.4 for 30 degrees of freedom

Mean free path = 0.13 AU, based on G = CV/K

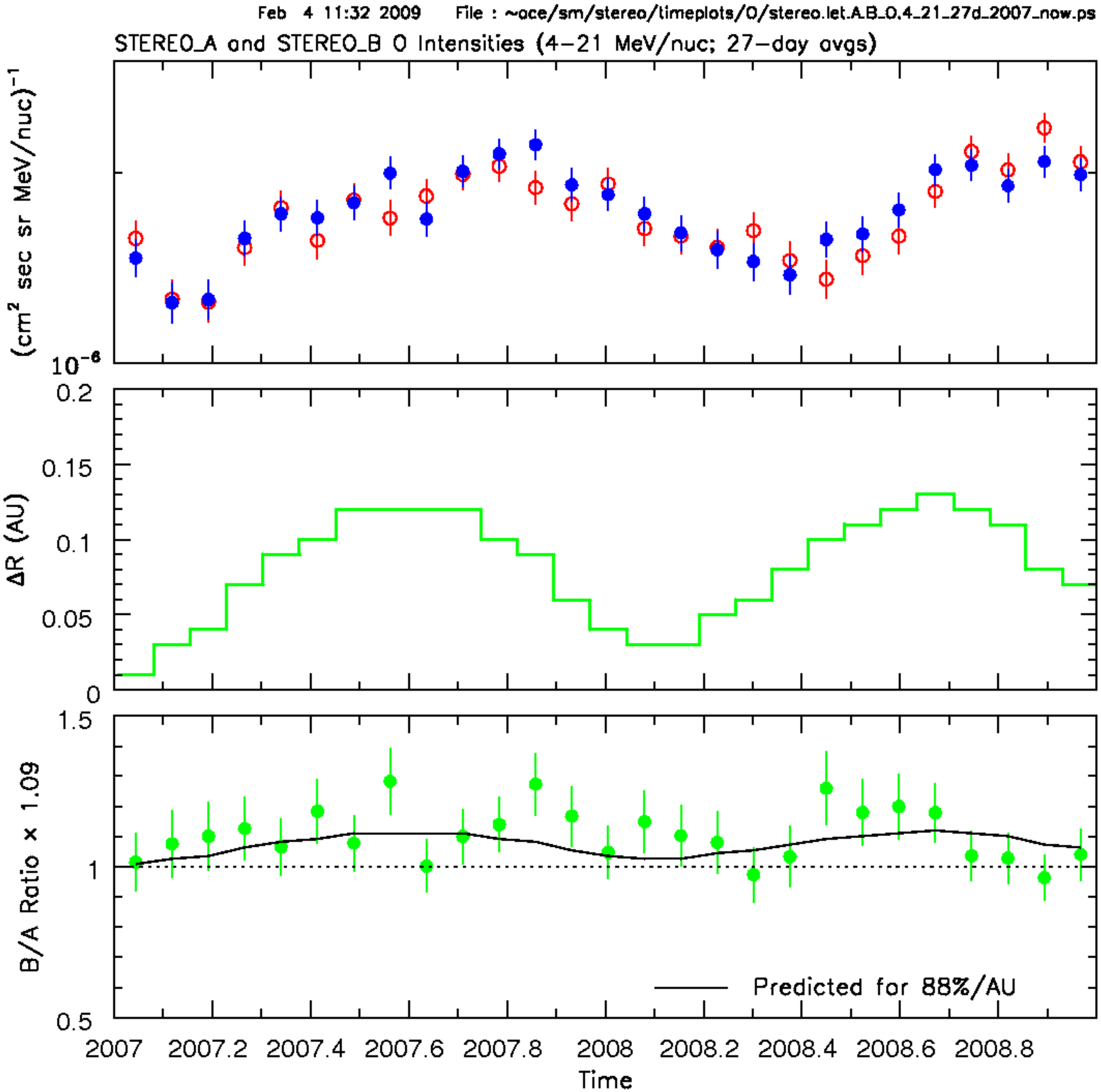
Radial Gradient of 7-25 MeV/nuc ACR O during A<0



Indirect inference from 5-S/C study suggests G_r~40%/AU from 1-4 AU, similar to this result.

But at 1 AU, the gradient From the curve is 88%/AU.

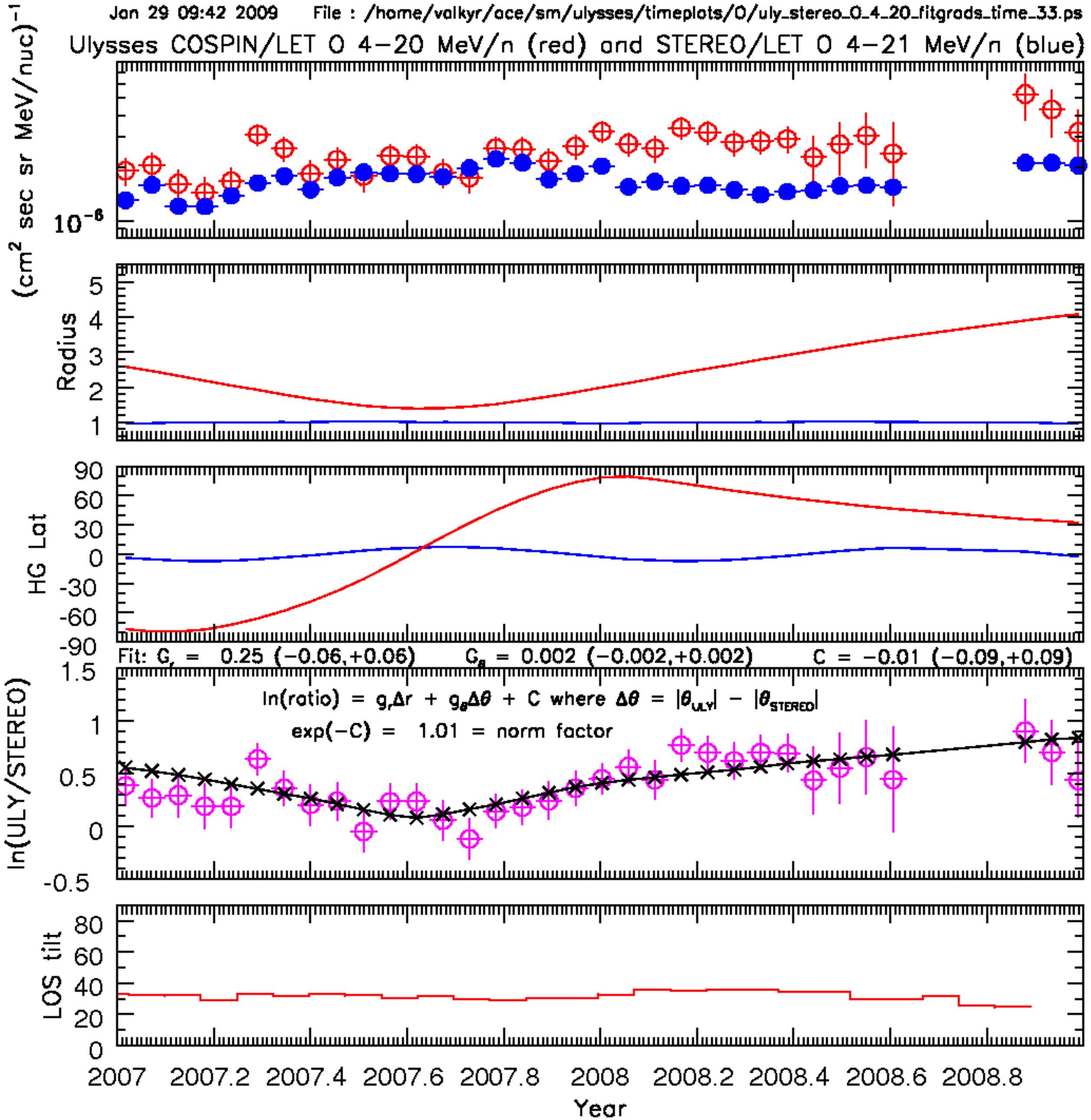
From Cummings et al., 1995


Feb 4 11:32 2009 File : ~ace/sm/stereo/timeplots/O/stereo.let.A.B_O.4_21_27d_2007_now.ps
STEREO_A and STEREO_B O Intensities (4–21 MeV/nuc; 27–day avgs)
(cm² sec sr MeV/nuc)⁻¹
10⁻⁶
ΔR (AU)
0.2
0.15
0.1
0.05
0
B/A Ratio × 1.09
1.5
1
0.5
Predicted for 88%/AU
2007
2007.2
2007.4
2007.6
2007.8
2008
2008.2
2008.4
2008.6
2008.8
Time

Summary

- **ACR O (8-20 MeV/nuc) gradients in inner heliosphere for A<0:**
  - **Radial gradient from ~1-4 AU: 32 ± 8 %/AU**
    - **Consistent with inferences from multi-S/C studies**
  - **Latitudinal gradient: 0.2 ± 0.2 %/AU**
    - **Previous A>0 studies were in range 1-5%/deg, reasonably consistent with outer heliosphere studies**
    - **Previous A<0 result in outer heliosphere for 30 deg tilt -2%/deg, inconsistent with new result for inner heliosphere**
  - **Expected negative latitudinal gradients might show up if tilt drops significantly below 30 deg.**
- **Will also be able to explore gradients down to 4 MeV/nuc with STEREO and Ulysses data and maybe just STEREO A & B near 1 AU**

The End



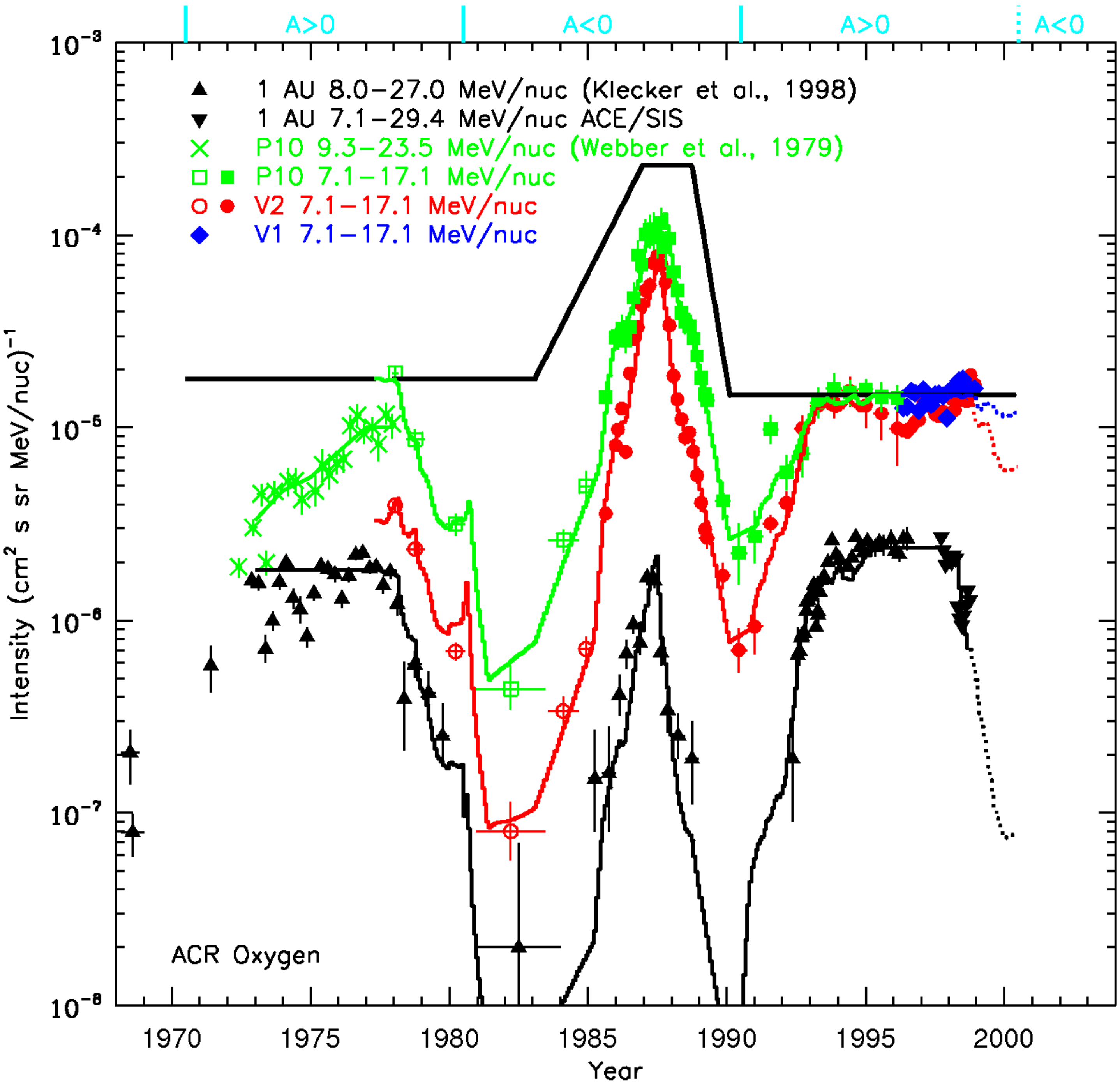
Gradients of ~4-20 MeV/nuc O

C = -0.01 -> norm factor = 1.01

Rad grad = 25 ± 6 %/AU

Lat grad = 0.2 ± 0.2 %/º

Chisq = 23.2 for 30 degrees of freedom



From ICRC 1999: Tilt Model

To fit observations in A<0 period had to use fixed radial gradient of 48%/AU from 1 to 4.5 AU – very similar to this result.

Stone & Cummings. ICRC 1999

ACR O and Tilt vs time