Active Region Upflow Plasma:
Does it Reach the near-Earth Environment?

J. L. Culhane[1], D.H. Brooks[2], L. van Driel-Gesztelyi[1,3,4], P. Démoulin[3], D. Baker[1], M. L. DeRosa[5], C. H. Mandrini[6,7], L. Zhao[8], T.H. Zurbuchen[8]

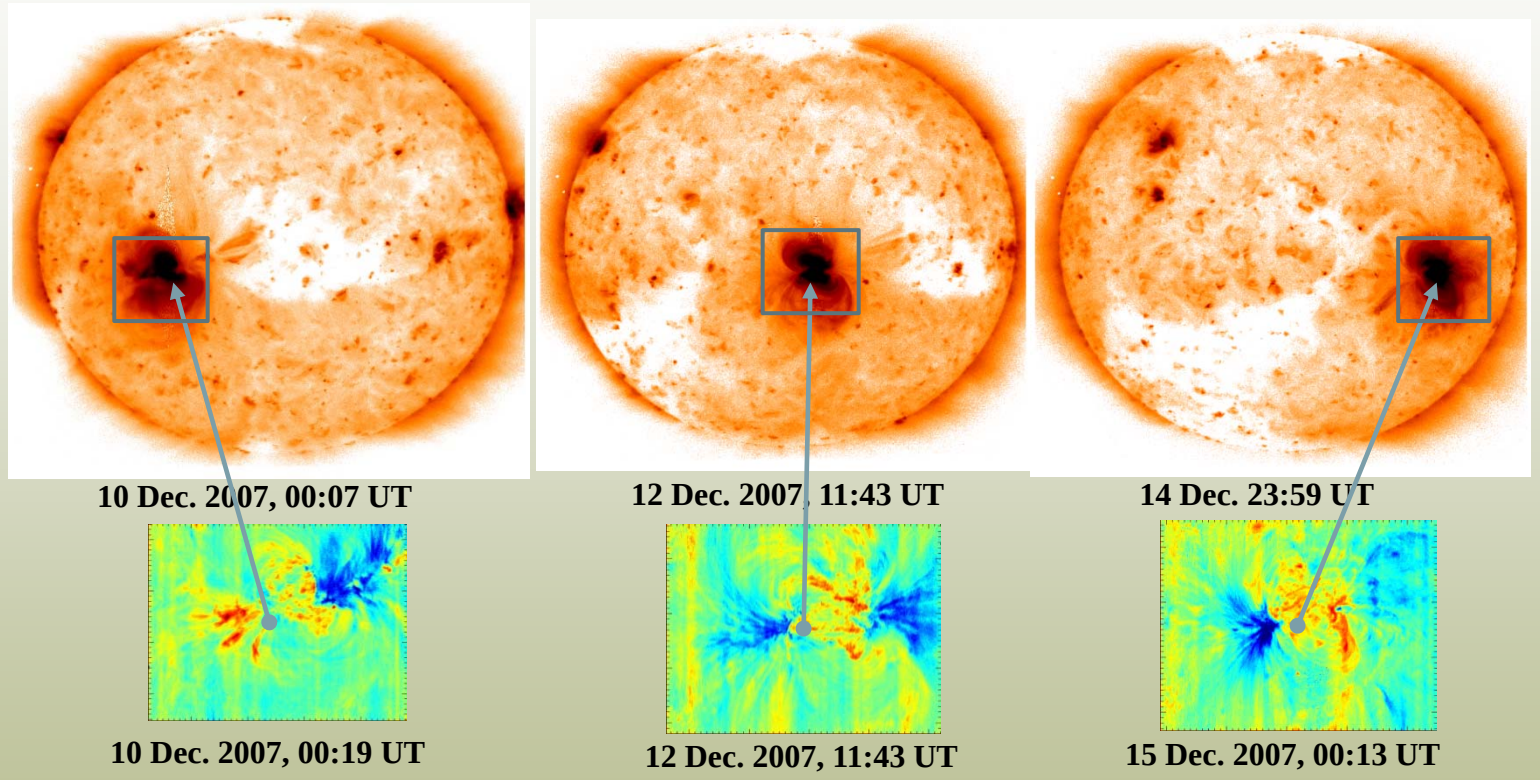
[1]University College London, Mullard Space Science Laboratory, Dorking, UK
[2] Naval Research Laboratory, Washington DC, USA
[3]Observatoire de Paris, LESIA, Meudon, France
[4]Konkoly Observatory, Hungarian Academy of Sciences, Budapest, Hungary
[5]Lockheed Martin Solar and Astrophysics Lab oratory, Palo Alto, CA, USA
[6]Instituto de Astronomia y Fisica del Espacio (IAFE), CONICET-UBA, Buenos Aires, Argentina
[7]Facultad de Ciencias Exactas y Naturales (FCEN), UBA, Buenos Aires, Argentina
[8]Dept. of Atmospheric, Oceanic and Earth Sciences, Univ. of Michigan, Ann Arbor, MI, USA,

Summary

- Upflows from AR 10978, passed disc centre 10 – 15 Dec. 2007, studied by Hinode/EIS
  - plasma parameters (T_e, n_e, v, FIP-bias) measured as f(t)
- Upflow inclinations to the line-of-sight (LoS) estimated by Démoulin et al (2013) from the systematic changes in the upflow regions with distance from disc centre
  - linear force-free field (LFFF) extrapolation for local AR field gave consistent upflow results
- NSO/GONG PFSS model shows that the inward Heliospheric Current Sheet (HCS) projection bisects AR 10978 and essentially coincides with its magnetic inversion line
- Global PFSS model shows AR 10978 completely covered by helmet streamer closed field
  - not clear how any upflowing plasma could reach heliosphere and contribute to slow solar wind
- ACE in-situ plasma data back-mapped to 2.5 $R_\odot$ show that increases in O^{+7}/O^{+6} , C^{+6}/C^{+5} and Fe/O (FIP bias proxy) are present from just past the HCS crossing to the West of the AR
  - this looks very like AR-originating material
- Poster (Baker, Mandrini et al.) presented at this meeting suggests a mechanism for upflow material from AR 10978 to reach the heliosphere and be detected by ACE

AR 10978 and Associated Upflows

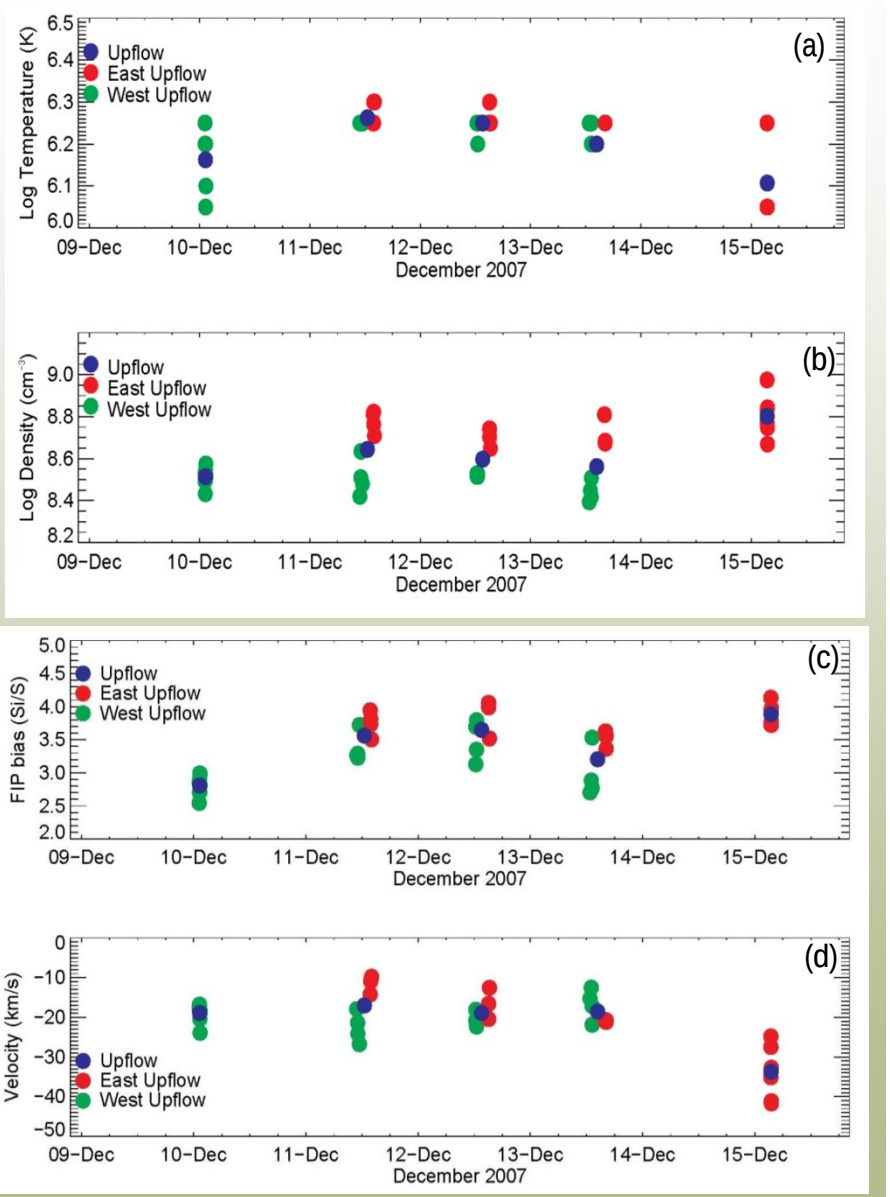
- From 10 – 15 Dec. 2007, AR 10978 passed Central Meridian (CM)
  - AR 10978 and the two principal associated upflow regions at its boundaries are shown below



- Upflows persistent during the 5 day interval though with greater fluctuation for the Western upflow due to emerging flux
  - XRT images are with Ti/Poly filters; EIS velocity maps from Fe XII/195.12 Å line profiles
  - apparent upflow velocity reversal from West to East due to flows' changing inclination to line-of-sight

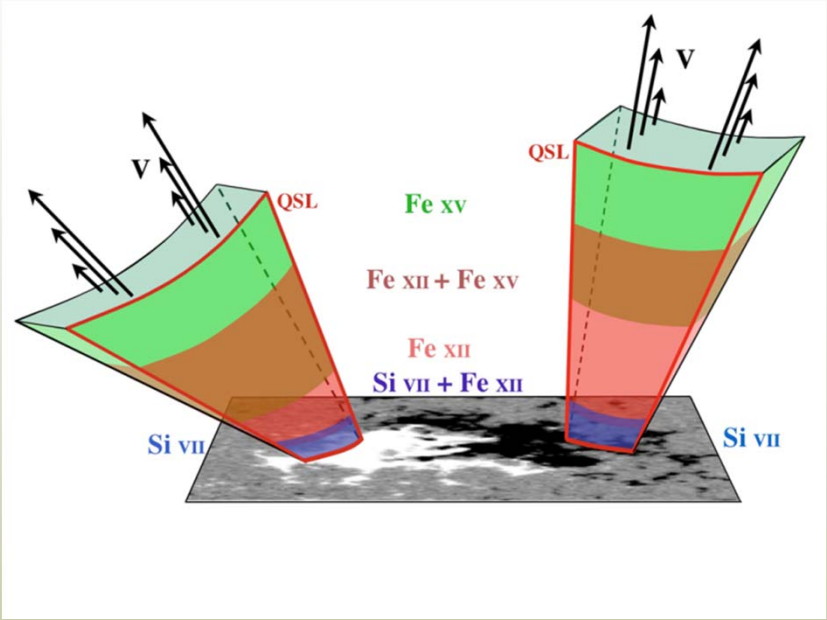
Upflowing Plasma Properties

- Plasma parameters measured for East and West upflows and also average values included
  - temp. (T_e), density (n_e), FIP-bias (f_{FIP}), velocity (v)
- n_e is estimated from Fe XIII line intensity ratio ($I_{202.0\,Å}/I_{203.8\,Å}$), v from line profiles
- T_e and FIP-bias are obtained from a Differential Emission Measure (DEM) analysis based on a set of 9 emission line (Fe VIII – XVI) intensities
  - method as in Brooks & Warren, Ap.J. 2011
- FIP-bias values $3.0 \leq f_{FIP} \leq 4.0$ are characteristic of slow solar wind
- East upflow has higher FIP-bias than that from the West where ongoing flux emergence brings lower FIP-bias plasma into the coronal upflow



Upflows and Local Magnetic Field

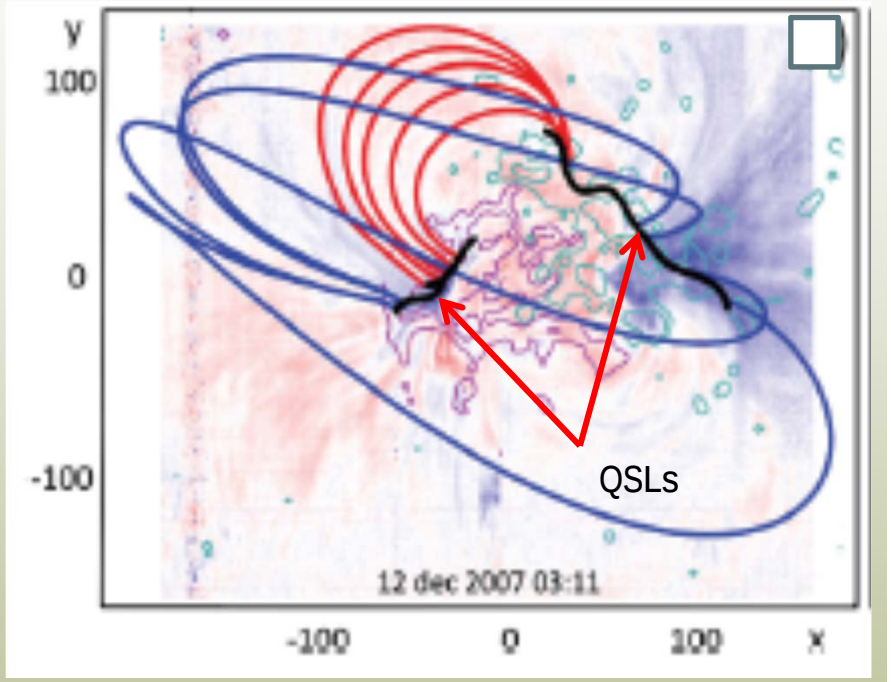
- Study of upflow evolution with solar rotation (Demoulin et al., 2013) shows flow inclinations to LoS as $\delta_{East} \sim -50^0$ and $\delta_{West} \sim +20^0$



- Upflows observed in Si VII, Fe XII and Fe XV emission lines as spatially coherent thin fan-like structures
- Velocities and temporal evolution comparable for all three lines
- Flows show short-term variability but with a strong stationary component indicating a long-lived (days/weeks) driving mechanism

Linear Force Free Field (LFFF) Extrapolation for AR 10978

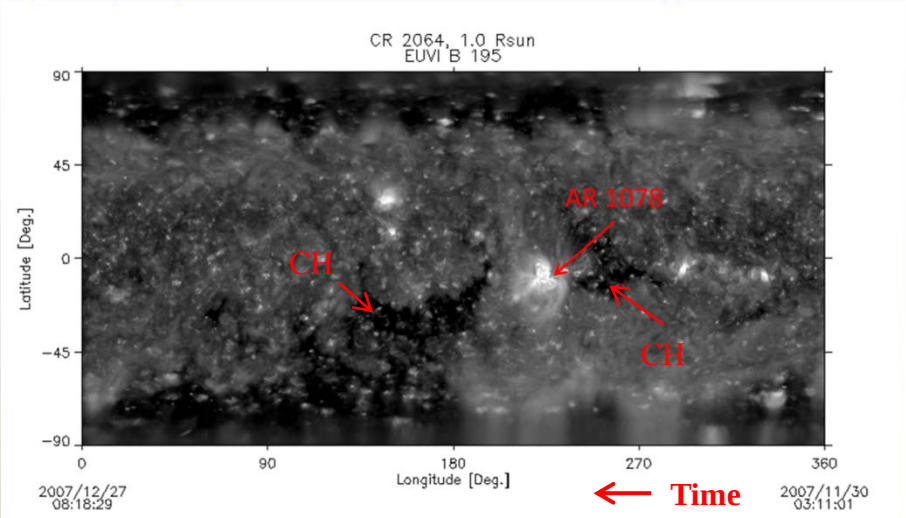
- Topological analysis in the linear force-free field extrapolation (Demoulin et al., 2013) allows identification of Quasi-Separatrix Layers (QSLs: black lines))
  - red field lines start from East of the eastern QSL
  - Blue " " " " West " " western "



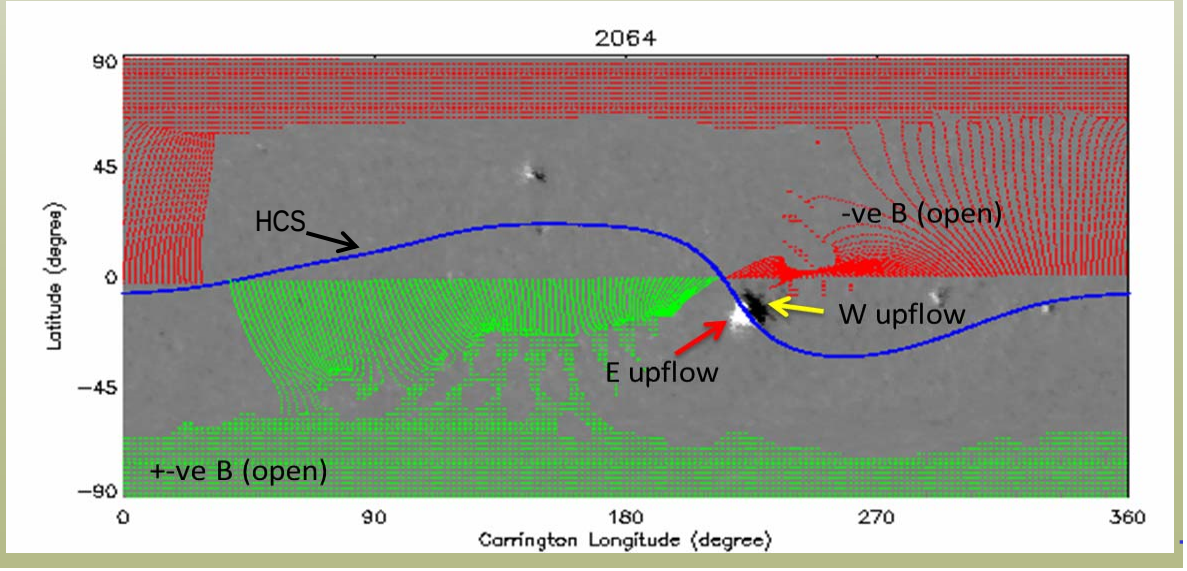
- Upflows originate from these QSL sites
- Upflows from reconnection at QSLs between dense AR loops and long low-density loops
- Reconnection at QSLs results from AR growth and dispersion
- LFFF magnetic field configurations are valid **close to the AR**
  - computed field lines at AR borders have similar inclinations to those shown by direct modelling of the EIS upflows
  - they **do not imply** that the upflowing plasma leaves the Sun

AR 10978 related to Global Magnetic Field Configuration

- Carrington (CR 2064) display of a Stereo-B EUVI image shows AR and two nearby opposite polarity CHs

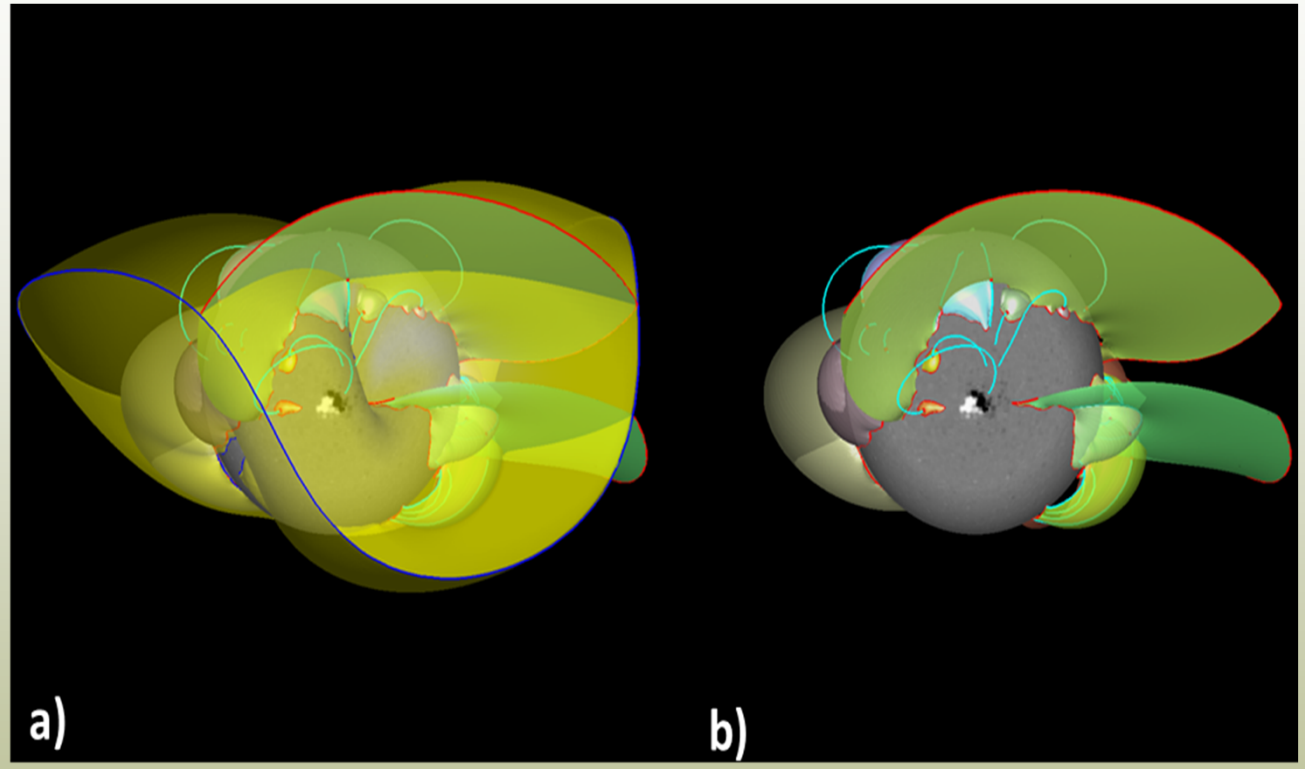


- NSO/GONG PFSS model: open field reaches the source surface at 2.5 $R_\odot$
  - inward projection of HCS bisects AR and separates East and West upflow regions
  - red/green areas show –ve/+ve polarity of open B-field regions
  - grey area shows mainly closed B-field regions and LoS magnetogram features for AR 10978



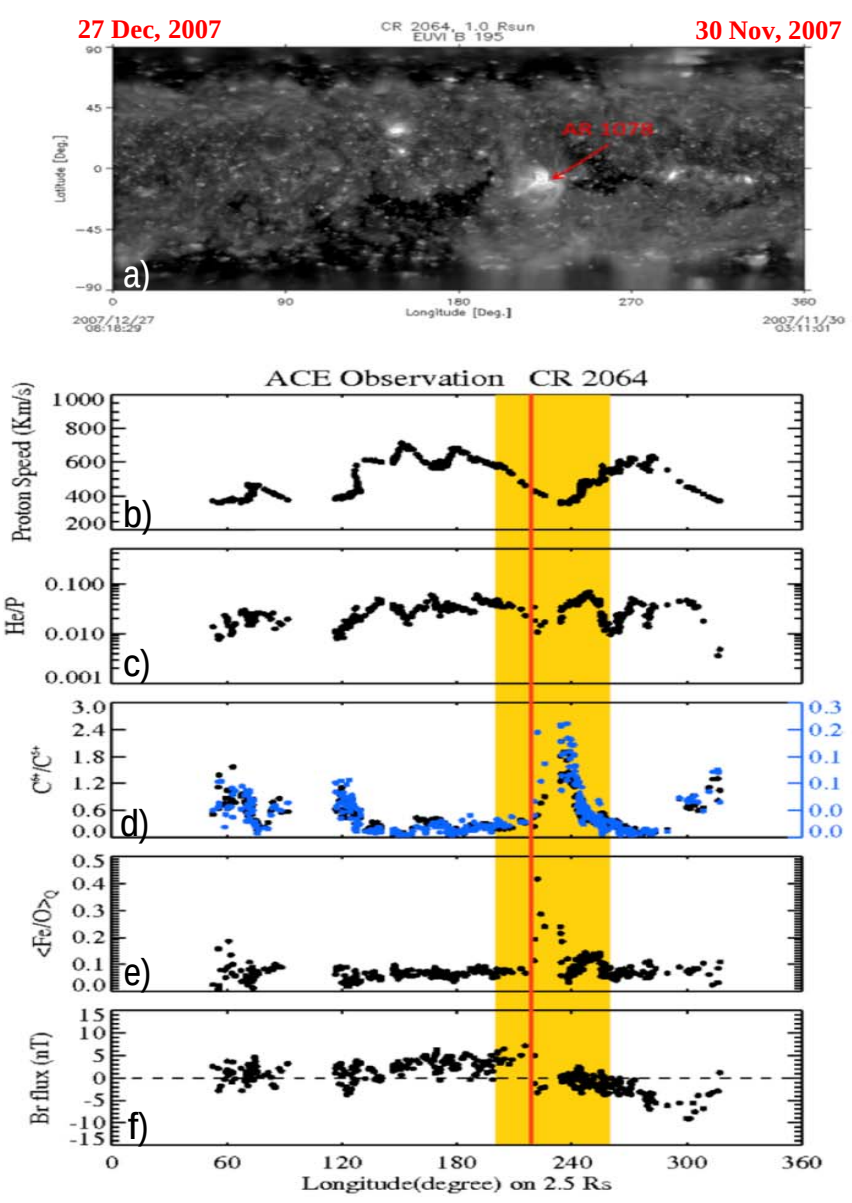
Global Solar Magnetic Field Configuration

- PFSS model for 12-Dec-07 shows large-scale topological structures and AR 10978
  - helmet streamer separatrix surface in semi-transparent yellow (a)
  - AR shown without helmet surface (b)
  - AR in closed–field region **fully covered** by streamer
  - streamer is bordered by the two adjacent CHs E and W of the AR
  - continuous blue line (a) shows the HCS



- Right-hand panel (b) has the helmet surface removed for greater clarity
  - LoS magnetic field structures of AR 10978 are shown
  - spine field lines (light-blue) do not enter the open field domain but remain closed below the streamer
  - thus long low density loops carrying the upflowing plasma are fully contained below the streamer
  - not obvious how plasma with AR composition could gain access to the Heliosphere

ACE in-situ Observations Related to AR 10978 Passage

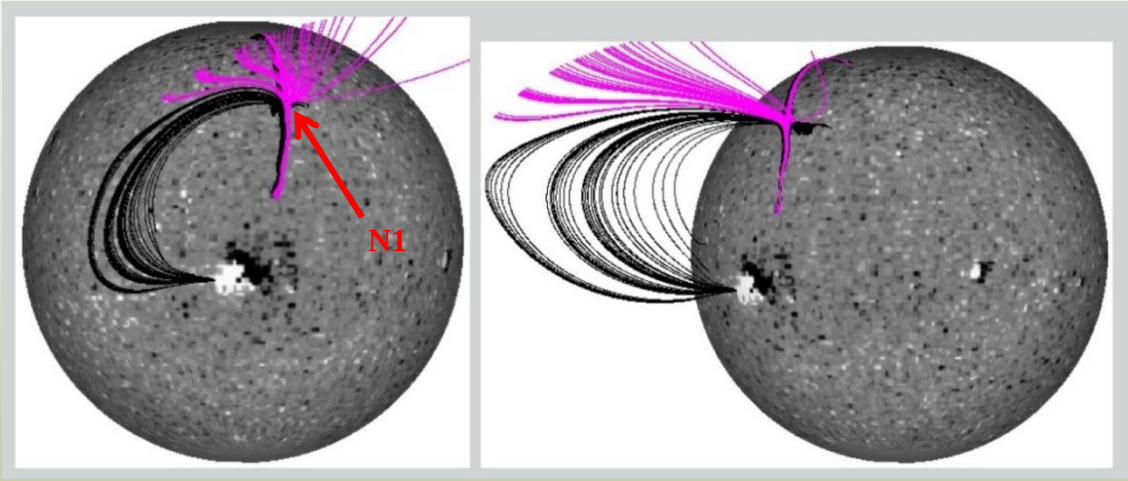


- ACE data shown relative to a) ST-B EUVI 195 Å synoptic map for CR 2064
- Data include:
  - b) v_p c) He/p, d) O^{+7}/O^{+6} and C^{+6}/C^{+5}, e) Fe/O, f) B_{radial}
  - red line indicates change in B_{radial} polarity seen at ACE which shows HCS crossing
- Increases in O^{+7}/O^{+6} , C^{+6}/C^{+5} and Fe/O (FIP bias) are present from just past the HCS crossing to the West of the AR
  - active region material in a slow solar wind flow
  - reduction in He/p indicates streamer tip contribution
- Fast solar wind parameters are evident before and after the HCS transition (shown in yellow)
- Fast wind flow originates from the two adjacent CHs that are E and W of AR 10978

Possible Mechanism for Plasma Escape from AR 10978

- Mandrini et al., (2013: to be submitted) describe a detailed analysis of the AR 10978 magnetic topology which locates four high altitude magnetic null points near the AR
  - one of these (**N1**) has associated open field lines
  - see poster by Baker, Mandrini et al presented at this meeting

- AR loops reconnect with large scale network fields (black) at the Eastern QSL
  - this high to low density reconnection drives the observed upflows



- The large scale loops reconnect with the open fields (pink) at N1 that are associated with the northern CH

- Open field lines bend towards the ecliptic and so can deliver the upflowing plasma from *East* of the AR to the Sun – ACE line *before* the HCS passage i.e. from the *West*

Conclusions

- Detailed measurement of upflow plasma properties for AR 10978 in December, 2007 showed typical active region values which are also found in the slow solar wind
  - flow geometry (Demoulin et al.) agreed with description based on LFF magnetic field extrapolation
  - upflows found to originate in QSLs that were identified in the LFF analysis

- PFSS models show that the HCS bisects the AR approximately above its inversion line but also demonstrate that the AR is completely covered by a helmet streamer
  - no direct open field connections from the AR to the Heliosphere

- ACE in-situ plasma data were displayed relative to a Carrington synoptic map (CR 2064) for the interval 30-NOV-2007 to 27-DEC-07 which includes the disc transit of AR 10978

- By relating these data to the polarity change in B_r it is apparent that the speed and composition assume slow wind characteristics just to the West of the AR
  - supported by backmapping of the ACE data wrt the HCS crossing and B_r polarity change
  - given streamer coverage of the AR on both sides of the HCS, not clear how AR plasma escapes

- Mandrini et al. – see poster by Baker et al., show how upflow material from *East* of the AR can reach ACE from *West* of the AR following at least two magnetic field reconnections