Helioseismology and dynamo science

Takashi Sekii
and
SOLAR-C HSD sub-WG
NAOJ

SOLAR-C Plan A

- The main scientific target is

Observational studies of the solar dynamo processes

By helioseismology and other measurements

The HSD sub-WG

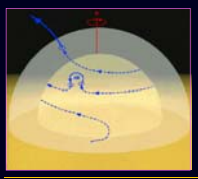
- Helioseismology and the Solar Dynamo (HSD) sub-WG
  - Appourchaux (co-chair), Birch, Braun, Brun, *Charbonneau*, Gizon, Hara, Kosovichev, *Leibacher*, Miesch, Rempel, *Schuessler*, Sekii (co-chair), *Toomre*, Yokoyama, Zhao

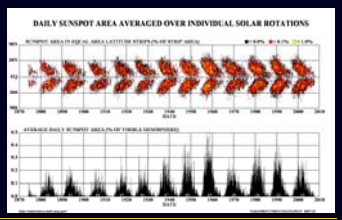
The HSD sub-WG

- Mission
  - What are the outstanding issues in our understanding of the solar dynamo mechanism? (Brun)
  - How do we address them by Plan-A helioseismology (ad other) observations? (Kosovichev)
  - How does Plan A compare with other 'similar' missions (Appourchaux, Kosovichev)

The solar dynamo

- The 11-yr solar activity cycle is thought to be driven by a dynamo mechanism
  - i.e. interaction between magnetic field and plasma flow





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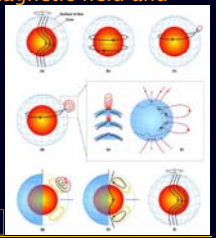


Dikpati & Gilman (2006)

The solar dynamo

- We have had some success
  - A flux-transport dynamo model by Dikpati and Gilman (2006)
  - Successfully 'predicted' cycles 16-23 using data from preceding cycles

Dikpati & Gilman (2006)

The solar dynamo

- But the full understanding is still far away
  - Kinematic theories (such as Dikpati & Gilman 2006) *assumes* the flow structure
  - Aside from some physical questions…
    - the extremely low activity at the beginning of the current cycle was predicted by nobody
- Both theoretical and observational approaches are required to advance our knowledge
  - How do we observe the solar interior?

Helioseismology

- Probing the solar interior using waves
- Equilibrium thermal structure
  - Can be modelled
- Solar internal flow
  - Can be modelled too?
    - Reynolds number > 10^{10}
    - Kolmogorov's law: dof per dimension~$10^{10\times3/4}$
      - For the 3-d case dof > 10^{22}…TOUGH!
  - Helioseismology is more important for measuring flows

Helioseismology

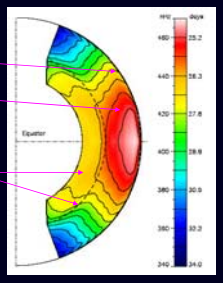
- Solar differential rotation

Surface shear layer

Non-columnar rotation

'Tachocline'

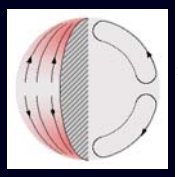
Rigid rotation?

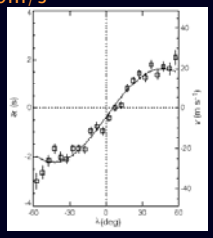


Thompson et al (1996)

Helioseismology

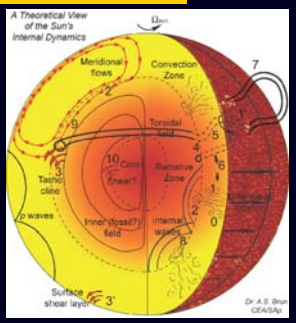
- Meridional flow
  - Poleward, up to 20m/s





Giles et al (1997)

What are the issues?



What are the issues?

- Location of dynamo
  - Wavespeed anomalies due to magnetic field, or flows induced by the magnetic field
  - Tachocline?
    - Difficult to detect as a wavespeed anomaly (high β)
    - ~10^2 m/s flow? Maybe possible to detect
      - Sekii@SDM1: "in the realm of possibility, depending on exactly magnetic field strength and width"

What are the issues?

- Magnetic field transport
  - Magnetic buoyancy, meridional flow and turbulent transport
  - Meridional flow in high-latitude region
  - Meridional counter flow?
    - Probably ~10^0 m/s flow. Extremely difficult
  - Turbulent transport
    - Can we measure diffusivity?
  - Rising flux tubes?

What should be observed?

- Global flows
  - Differential rotation/torsional oscillation at high latitudes
  - Polar vortex?
  - Tachocline
- Poloidal field regeneration ('α effect')
  - Helical flow?
  - Magnetic helicity

What should be observed?

- High-latitude magnetic fields
  - There are many aspects:
    - Energy & flux budget of dynamo
    - Multi-polar structure of the mean poloidal field
    - Efficiency of Babcock-Leighton
    - Magnetic helicity
    - Magnetic effect on rotation inversions?
  - But to summarize
    - To see interplay of flows and magnetic fields THERE

What should be observed?

- The main goals:
  - Helioseismic measurement of various flows in
    - the high-latitude region
    - the tachocline region
  - The polar magnetic field

How do we observe?

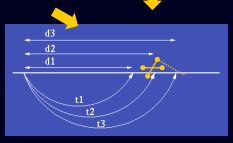
- Global helioseismology?
  - Rotation at high-latitude inaccessible to global helioseismology because of the structure of global eigenfunctions
  - Meridional flow also inaccessible to global helioseismology (in the linear regime)
  - Tachocline structure: yes unless a feature is too localized. Would it be localized?

How do we observe?

- Local helioseismology?
  - Can observe high-latitude flows i.e. no limitation due to eigenfunctions but…
  - Can observe localized tachocline feature if we can catch 45-degree skip rays, but…
  - it is difficult from within the ecliptic plane because of…
    - foreshortening
    - projection

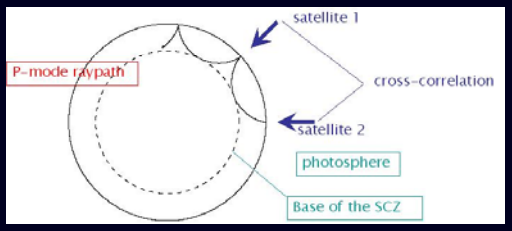
How do we observe?

- Difficult because…
  - Foreshortening: loss of spatial resolution
    - Travel time poorly defined for a pixel pair
  - Projection: Doppler velocity S/N degradation
    - Convective noise predominantly horizontal
- We can alleviate these problems by
  - Observing from above



How do we observe?

- Local helioseismology from high latitudes is the only way



How high should we go?

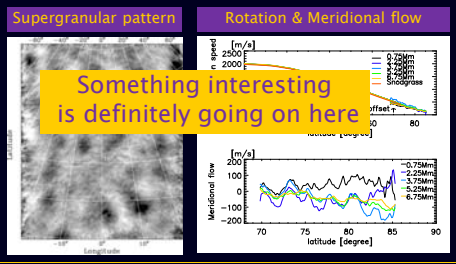
- Why we might think 30 deg is sufficient
  - Meridional flow can be measured from the ecliptic plane up to 60 degree latitude
  - 60+30=90
- Why we would be wrong
  - Among other issues, the longitudinal range over which we can average = cosϕ
    - cos 60° = 0.5, cos 80° = 0.174, cos 85° = 0.09
- We need to go to (30+α) latitude
  - Also to ensure substantial observing time

Helioseimology observations

- There are two main modes
  1. High-latitude local helioseismology
     - Repeat what we do at lower latitudes
     - Can do it solo
  2. Two-vantage-point 'large angle' helioseismology
     - More challenging
     - Needs a partner

Polar flows by Hinode/SOT

- Nagashima (2010)
  - Time-Distance method



A very high-resolution telescope?

- Q. Would that do the job for Plan A?
- A. Partly but not entirely
  - Helioseismology
    - Doppler measurement is preferred: we need a high-inclination orbit
    - A decent FOV is required for probing deeper: a big telescope would not have it
  - Magnetic-field measurement
    - The issue of vertical vs. horizontal components: it would offer complementary view
    - Spatial & temporal coverage

Observational study of dynamo

- We are not yet in position to discuss a few 'key observations' that would pin down the dynamo theory
  - Theory not mature yet
- It is the time for studying SCZ dynamics in general, as an observational approach to the solar dynamo
  - The polar region is by far the least investigated so far

Conclusions

- SOLAR-C Plan A will provide important observational constraints on the solar dynamo/SCZ dynamics
  - Local helioseismology from an inclined orbit is the key
  - …and the polar magnetic field measurement