How Star-like is the Sun;
How Sun-like are the Stars?

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Outline

• **Activity of Sun-like Stars:** middle-aged G-type field stars in solar neighborhood show behavior similar to magnetic cycles, but devil is in the details.

• **The Fainting of Alpha Cen A:** surprising disappearance of solar twin in coronal X-rays challenges our solar experience, or does it?

• **The Solar Oxygen Crisis:** new recommended low-O abundance frustrates helioseismologists, calling into question our understanding of the solar interior; but original driver for oxygen plunge has been challenged recently.
Warning: this talk deals with lower rungs of Drake’s Ladder, where, sadly, sexiness is low, but on positive side, knowledge content was though to be high; even so, a few surprises still were to be found...
Summary: Sun-like Stars

- Activity is Magnetically motivated: most visible and high energy changes of solar spectrum are associated with dynamo inspired surface magnetism; other sources of global variabiliy, like p-modes, are much more subtle.
- Variability is (highly!) wavelength dependent: millimaggs in visible; factors of hundreds in GOES flare bands.
- Comparisons to Sun suffer from instrumental limitations on Both sides: stars rarely observed with useful cadence at high energies (although good time series in Ca II and visible); Sun is missing key irradiance bands and/or sufficient spectral resolution.

(J. Hall, next talk, will cover in more detail)
Changes in the solar spectrum are depicted for the current era. The shortest wavelengths vary the most, whereas the visible and near-IR only show occasional dropouts. The 400--850 nm band will be observed by Kepler.
Solar Ca II “HK” cycle variations (upper) are about 20%, but total irradiance (lower) is only 0.1% (1 mmag), challenging to measure in stars from ground. Nevertheless, the 1 W/m² is 10X entire output of solar chromosphere, and $10^3$ X entire corona. In highly active stars, Ca II variations are erratic and noncyclic, and photometric changes are anticorrelated with HK index; in low activity stars like Sun, cycles are clearly present in about a third, there are “flat activity” objects, and photometric variations tend to be positively correlated with HK.
Solar-Stellar Misconnections

Studies by Lockwood et al. (1997) and Radick et al. (1998) of G-type dwarfs stars found larger cycle variations in visible at solar Ca II activity. Left: solar/stellar astronomer frets over contrary behavior of Sun-like stars in the long-term photometric records:

Is the Sun somehow abnormal in the cosmic scheme of things?
New study by Lockwood et al. (2007) clarifies the situation: similar sample as in previous work, but longer time base (up to 20 yrs, to catch full photometric amplitude). Possibly anomalous subgiants identified, and targets with less reliable check stars eliminated (at 1 mmag, many photometric “standard stars” vary).
“long-term” chromospheric variations in Ca II refer to cycle timescales; “short-term” to rotational modulations: Sun appears perfectly normal for its chromospheric activity level with regard to other G dwarfs of the field.
In cycle associated photometric variations [(b+y)/2~70% TSI], Sun still is a bit low compared with other stars, but not unreasonably so. Lockwood et al. cite relatively small sample size; working at the photometric limit probably contributes, as well. We also have seen at this workshop that narrow wavelength bands can behave contrary to full TSI.
Again, low-activity G stars tend to show positive correlation (open symbols) of photometric variation with HK index; younger more active solar-like stars tend to show anticorrelation (filled symbols). **Sample size is about to increase substantially, about 1000X:**
**KEPLER** will monitor 100’s of thousands of solar-like--or near solar-like--stars, for a period of ~6 years: main focus is to capture Earth-mass planets in transit, but secondarily will detect starspot cycles, rotation, differential rotation, and other dynamo-related processes. Photometric precision in orbit will be about 100X better than from ground: stay tuned!
2nd half: Fainting of Alpha Centauri A, Resolved!
The Alpha Centauri triple system has two solar-like stars separated by about Sun-Saturn distance, and a dim red dwarf about 10,000 au away (toward us). Alpha Cen is slightly metal rich compared with Sun, and slightly older by ~1 Gyr. The G2 V primary (“Alpha Cen A”) is a near twin of our own star.
Alpha Cen first was detected in X-rays by HEAO-I; later resolved by Einstein HRI. Surprising result: smaller Alpha Cen B was twice as X-ray luminous as bigger A. ROSAT HRI could easily separate the two stars during 1990’s, and carried out a long term campaign to measure their coronal activity.
Multi-year *ROSAT* HRI record showed short term “rotational modulations” (active regions rotating onto, and off, the visible hemisphere); long term changes probably analogous to 11-year sunspot cycle; and flares on K dwarf (but not G star).

(Schmitt & Liefke)
Early in Chandra era (Dec 1999), LETGS spectrum of Alpha Cen captured both stars: A is at top, B at bottom in each frame. Companions were similar in coronal temperature, a very solar-like 1-2 MK, B slightly hotter than A. (Raassen et al.)
As in final ROSAT observation, LETGS showed both stars at similar coronal intensities, again somewhat below previous values.
More recent observations of Alpha Cen by XMM-Newton: MOS1 at top and pn at bottom (0.2-2 keV). Primary star (“A”) is clearly visible in first observation, but disappears by mid-2004: behavior unprecedented for its corona, challenging our understanding of stellar magnetic dynamos. (Robrade, Schmitt, & Favata [2005])
Multi-year XMM campaign showed stunning “fainting” of G star by factor of $\sim 50 \times$ in 0.2-2 keV band (6-60 Å).

Sun’s coronal variations over cycle were thought to be only $\sim 5-6 \times$ (Judge, Solomon, & Ayres: 0.1-2.4 keV “ROSAT” band).
Stellar-Solar Misconnections II.

Left: solar physicist frets over curious behavior of Sun’s twin Alpha Cen A in X-rays: Is the Sun somehow abnormal in the coronal scheme of things?
Fe XII 195 (1 MK) images of Sun over recent solar cycle. Significant coronal emission persists at minimum (left). “Fuzzy ball” arises from “magnetic carpet,” small clumps of flux built by convective local dynamo action independent of deep seated big dynamo responsible for major sunspot groups and their decadal ebb and flow (right: solar max).
Since Y2000, Alpha Cen orbit has been closing rapidly and no longer is easily resolvable by XMM-Newton (but still trivial for Chandra). HRC-I exposures beginning Oct 2005 recovered both stars: “A” low compared to 1990’s, but not as low as XMM, and “B” declining. What’s going on? New LETGS spectrum (June 2007) held key. (Note proper motion & parallax of Alpha Cen.)
Chandra LETGS spectrum taken June 2007 (upper spectral panel). B is at top, A at bottom. Note fading of A at short wavelengths; strikingly different appearance than in 1999 (lower panel). But, key longwavelength emissions (carrying bulk of coronal radiative losses) are unchanged.

Upper panel: response curves of XMM Mos1, HRC-I, and HRC-S.
Revised time series for A (1 MK) and B (2 MK), for broad 0.06-6 keV band. Now XMM has moved closer to Chandra, less challenging expectations for stellar cycles. In hindsight, darkening of Alpha Cen in XMM 0.2-2 keV band has precedence on Sun; not obvious in stars during ROSAT era owing to poor energy resolution of PSPC. (Yellow shaded: range of estimated full solar cycle 0.1-2.4 keV from Judge, Solomon, & Ayres.) Note “synchronization” of Alpha Cen cycles.
High-energy Yohkoh imaging, 1996-2006: 2-3 MK emission almost exclusively from active regions.
Although XMM-Newton recorded seemingly stunning decline in 0.2-2 keV $L_X$ of Alpha Cen A, Chandra LETGS revealed X-ray disappearance was due to “global cooling,” not collapse of coronal emission measure (i.e., “heating” didn’t turn off). Has natural explanation in solar cycle: we need not be overly apprehensive concerning “fainting” of solar twin (and what it might have foreboded for our own star).
Over the past decade, or so, solar oxygen abundance has fallen precipitously; Sun is in danger of becoming oxygen free circa 2015...
Consequences

New low oxygen abundance (450 ppm relative to hydrogen, compared with 700 ppm recommended a decade ago) affects other difficult-to-measure species such as C, N, and Ne. Domino effect lowering of solar Z (heavy metal mass fraction) spoils previous excellent agreement with helioseisomology (interior sound speed profile). Compensating changes in metal opacities are outside bounds set by Opacity Project; precipitating an “Oxygen Crisis,” at least among the few of us who care about these things . . . .
Seismology Constraints

Left: noted British helioseismologist frets over low-O, ruining previous excellent agreement with solar interior models. Oxygen accounts for over half of the heavy metal mass fraction $Z$, and is crucial in the interior opacity. Helioseismology prefers $O$ in the narrow range only 640-680 ppm.

3-D model (upper) mimics distortions of [O I] profile with addition of significant Ni I blend; but Oxy on its own (lower) predicts convectively blueshifted core, disagreeing with observed lineshape.
1D thermal profiles of solar photosphere. “COmosph” (red dots) is optimum model of Ayres et al. (2006); warmer than Asplund mean model (blue circles; yellow shading: Trms). New 3D model CO$^5$BOLD is orange curve (flanked by blue dashes; red dot-dashed curves are Trms. The two 3D models are different.
Absolute velocity scale of observed spectrum is vital: only few 100 m/s error can spoil the oxygen abundance. Trick is to “self-calibrate” the wavelength scales using 3D model to simulate Fe I lines near 6300 (top panel, each segment: +/- 10 km/s; dashed lines are rest wavelengths; note convective blueshifts). Blue curve is high quality FTS scan of disk center from NSO Digital Library. Red dots are synthetic spectra.
Simulated [O I] (blue) and Ni I (orange) for various situations:

(a) \(O=500 \text{ ppm, } Ni=100\pm20\%\);

(c) \(O=650\pm50; \ Ni=70\%\);

Best 3D fit is \(O=650 \text{ ppm}\).
Oxygen Crisis Summary

- Asplund and collaborators propose low O based on 3D modeling of atomic oxygen and oxygen bearing molecules (including recently CO).
- Ayres et al. (Aug '06, ApJS) applied thermal “tests” to mean stratification of Asplund et al. model, showing it is too cool in middle photosphere, thereby resulting in low O from molecules like OH (and low C from CO, as in recent work by Scott et al.); what if the 3D models are not perfect??
- More recent studies of additional thermal tracers---especially the Ca II H & K wings---using 3D models support earlier suggestion that these models are too cool in CO-forming layers. O abundance derived from CO is ~650 ppm.
- New analysis of pivotal [O I] 6300 feature (Ayres '08, submitted) does not confirm low-O obtained by Asplund group, but rather value of 650+/−65 ppm. High side of range is compatible with seismic O, but probably still too early for helioseismologists to breathe collective sigh of relief.
• Sun appears to be perfectly star-like, albeit near the middle/bottom of the activity histograms, at least of the legitimate main sequence dwarfs.

• The apparently paradigm breaking coronal cycle dimming of the solar twin Alpha Cen A can be understood in terms of what probably is normal solar behavior, combined with instrumental limitations of, in this case, the XMM-Newton Observatory.

• The whole “Solar Oxygen Crisis” needs to be considered more carefully: there apparently are significant differences in conclusions depending on which specific 3D convection model one utilizes to simulate the key 630 nm O I + Ni I blend.
LETGS spectra of active Alpha Aur (6 MK), low activity Alpha CMi (3 MK), and Alpha Cen stars (normalized at O VII).

Note weakening of A (blue curves, two bottom panels) in 2007 in T> 1 MK features.
Converting to fluxes in broad 0.06-6 keV band (2-200 A), all Energy Conversion Factors, particularly XMM, show strong dependence on T_cor. (Higher values = lower sensitivity: fewer counts per unit energy emitted at source.) Dashed curve depicts % of 0.2-2 keV emission in full 0.06-6 keV band: 0.2-2 keV emission is good proxy for total, but only above 2 MK.
Histogram representation of CO$_5$BOLD 3D model (single snapshot). +Z velocities (upflows) are associated with warmer columns; T’s reverse in high altitude layers.
Owing to relatively poor XMM spatial resolution, psf “background” at A contributed by B sets fundamental limit on detectability of primary.