FUSE Observations of the Unprecedentedly Deep "Quiescent" Magnetic Activity State of α Centauri A

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Abstract

Since 1990 we have been engaged in the "Sun-in-Time" project - a program of coordinated multiwavelength observations of solar-type stars. These stars, which all have similar physical properties (*viz.* mass, radius, temperature, and depth of convection zone), have been selected as proxies for the Sun at stages throughout its main-sequence lifetime, differing only in age, or equivalently, rotation period. An important component of this program is the investigation of magnetic activity cycles that occur within these solar proxies, and the changes in high energy X-ray coronal and FUV transition region (TR) emissions.

Recently, X-ray emission fluxes for one of our program stars, the approximately solar-aged α Cen A, was observed to diminish by a factor of ~25 in only two years' time, a phenomenon never before observed for any solar-type star. The *XMM* observations imply that the chromospheric through coronal regions of α Cen A can be highly variable, with changes in both mean temperatures and the emission measures necessary to address these recent observations. Presented here are *FUSE* Cycle 7 observations obtained during this unprecedented, very deep magnetic inactivity state of this solar proxy. These new observations are compared to the previously existing *FUSE* Cycle 2 FUV spectra, secured before this dramatic magnetic recession began. We find that in this short span of five years α Cen A has exhibited a significant decrease of approximately 2.5-3× in the key FUV emissions, which may indicate an activity cycle. Examination of other high energy measures, such as X-ray (coronal; *Einstein*, *ROSAT*, and *XMM*), UV (transition region; *IUE*), and NUV (chromospheric; *IUE*) emissions of α Cen A, along with comparisons to the Sun (*Solar EUV Experiment*, *Yohkoh*) are presented.

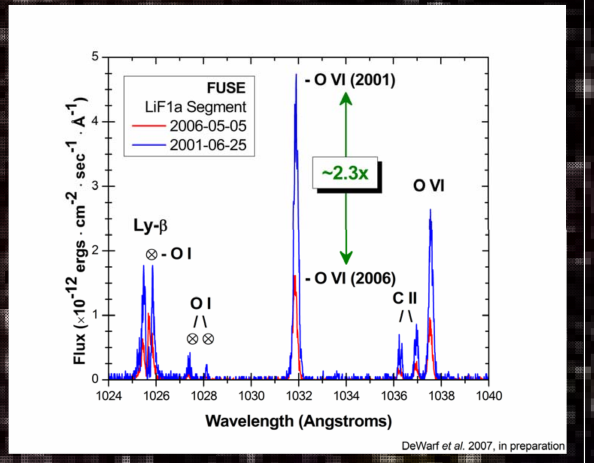
I. Introduction

A long standing problem and a central topic of "solar-stellar" connection studies is that of relating the Sun's magnetic behavior to other stars. Our Sun is used as a fundamental calibration and as a reference point for stellar theory. This requires that the Sun's expressions of activity (distribution of magnetically active regions, coronal densities, emergence of magnetic flux, etc.) are fundamentally "normal" for a star of its age and evolutionary history. Direct comparison with true solar analogs is critical for both understanding the magnetic nature of the Sun as well as magnetic phenomena in other stars. α Cen is the nearest stellar system to our Sun. The G2V primary (α Cen A; HD128620; *V* = -0.01; *(B-V)* = 0.71) is an almost perfect solar analog with regard to its mass, radius, temperature, and convection zone depth, but is slightly older (τ ≈ 5-6 Gyr) than our Sun. These properties are well determined through extensive studies, making it an ideal *Sun-as-a-Star* comparison to test solar concepts. Recently, coronal X-ray emission fluxes for α Cen A were observed to diminish by a factor of nearly 25 in just two years (Robrade *et al.* 2005), a phenomenon never before observed for any solar-aged star. The *XMM* observations imply that the chromospheric through coronal regions of α Cen A can be highly variable, with potential changes in both mean temperatures and the emission measures necessary to address these recent observations. Presented here are the results of a *FUSE* investigation into this phenomenon.

III. *FUSE* Observations

Both α Cen A and B were observed by *FUSE* in Jun 2001 using the MDRS aperture (Program ID: P104; PI: K. Sembach). Examination of these Cycle 2 spectra show excellent S/N for the stronger emission features. At that time, the peak flux of the C III 977Å line was 9.0×10^{-12} for α Cen A and 2.8×10^{-12} (cgs) for α Cen B. These data were serendipitously acquired near maximum magnetic activity for α Cen A, and therefore may well represent its "high-state" FUV emission levels.

FUSE Cycle 7 observations were obtained in May 2006 for α Cen A and B (ID: G081; PI: L. DeWarf). These spectra, acquired during α Cen A's deep quiescent magnetic state, have diminished to 2.9×10^{-12} (cgs) for the peak flux of the C III 977Å line (*see* Figure). As shown in the Table below, the integrated flux level has decreased by a factor of ~3.6 for this important TR emission feature. Similar results were determined for other key TR/chromospheric lines. We also obtained a *FUSE* MDRS exposure of α Cen B to be used both as a reference spectrum for comparison to α Cen A and to look for changes in its activity level. We observe that α Cen B exhibits relatively small variations in its X-ray luminosity, but has very recently diminished by a factor of nearly 4 and may have been "caught" by *FUSE* during an activity cycle minimum.



FUV Integrated Emission Flux Ratios

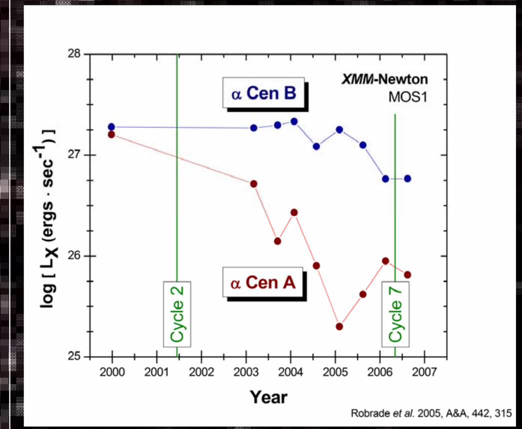
Atomic species	Wavelength (Å)	Temperature (K)	Stellar Region	Integrated Flux Ratio '01/'06
H I (Ly-β)	1025.722	~12,000	Chromosphere	1.81
C II [a]	1036+7	~20,000	Chromosphere/TR	2.60
C III	977.02	~50,000	TR	3.55
C III [b]	~1176	~50,000	TR	2.48
O VI	1031.925	~300,000	TR	2.34
O VI	1037.614	~300,000	TR	2.31

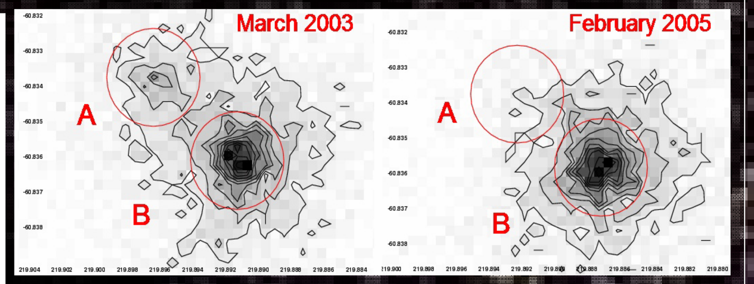
Analysis of the *FUSE* Observations:

Emission lines in the *FUSE* wavelength range allow a critical probe of hot plasmas from the upper chromosphere, TR, through the low corona. This corresponds to over three decades in temperature - from 10^4 K (H I Lyman series; chromosphere), 3×10^5 K (O VI; TR), and 6×10^6 K (Fe XVIII; corona). Several of the strongest emission features, such as C III (977Å, 1176Å) and O VI (1032Å, 1038Å), originate in TR plasmas and are pivotal for understanding the mechanisms for chromospheric and TR heating in stars with convective zones.

IV. *XMM* Observations

Recently, Robrade *et al.* (2005) observed the X-ray luminosity for α Cen A to diminish from $L_X = 5.2\times10^{26}$ ergs/sec to $L_X = 0.2\times10^{26}$ ergs/sec - a factor of ~25 in only two years' time! The Figure below (right) shows two *XMM* MOS1 snapshot images taken about 2 years apart. Note that, relative to α Cen B, α Cen A has diminished in X-ray luminosity significantly. Indeed, the Figure below (left) diagrams this remarkable decline of α Cen A from Mar 2003 Feb 2005. For a solar-type star, changes this large have not been reported.



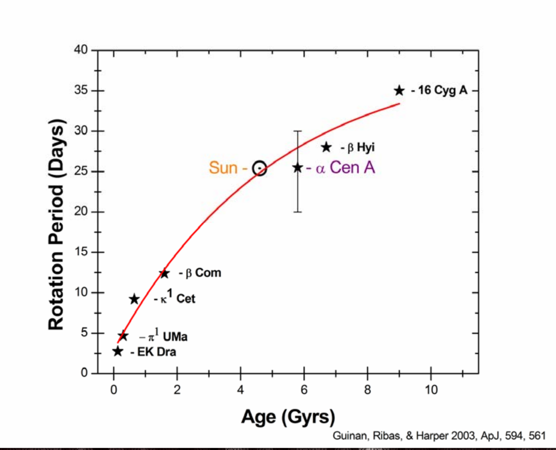


***Above**: Images of the α Cen system obtained with XMM MOS1 showing the Mar 2003 and Feb 2005 exposures. Note that the darkening of α Cen A is striking (Robrade et al. 2005). **Left**: Long-term X-ray light curve of α Cen A (red) and B (blue). The green vertical lines show when FUSE Cycle 2 and 7 observations occurred.*

These *XMM* observations of α Cen A imply that the chromospheric through coronal regions are highly variable, with changes in both mean plasma temperatures and, to a larger extent, changes in the emission measures necessary to explain this large L_X variability. Also included in the Figure above (left) are the L_X values for α Cen A and B secured in Dec 1999 with *Chandra* LETG (Raassen *et al.* 2003). At that time, α Cen A appears near the maximum of a potential activity cycle with an L_X of ~1.6×10^{27}. This behavior is consistent with a solar-like ~10-11 year activity cycle. Unpublished *XMM* observations of α Cen A, obtained in Aug 2005, Feb 2006, and Aug 2006 (kindly communicated by J.H.M.M. Schmitt), indicate a small increase in L_X from its apparent minimum in Feb 2005. From this same data, it appears that the L_X of α Cen B is strongly decreasing.

II. The Sun in Time Project

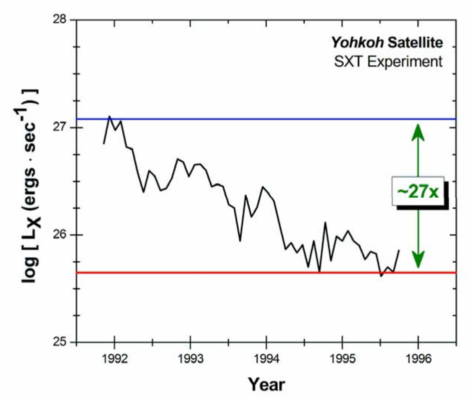
Since 1990 we have been engaged in the "Sun in Time" project - a program of coordinated multiwavelength observations of solar-type stars (*see* Dorren & Guinan 1994a/1994b; Dorren *et al.* 1994; *and more recently*, Guinan *et al.* 2003; Ribas *et al.* 2005). These stars have been selected as proxies for the Sun at stages throughout its main-sequence lifetime, and are single, main-sequence G0 - G5 stars of ages from ~70 Myr (representing the ZAMS Sun), to stars of approximately solar age like 18 Sco and α Cen A, together with older solar analogs with ages up to ~8.5 Gyr (16 Cyg A). These stars all have similar physical properties (mass, radius, temperature, and depth of convection zone), differing only in age, or equivalently, rotation period. The connection between age, rotation period, and magnetic activity is well established for such stars (Skumanich 1972; Simon *et al.* 1985; Ribas *et al.* 2005). Specifically, we use these stars to investigate the decline in the level of solar magnetic activity as the Sun spins down, and also changes in the activity cycle with age. More generally, by examining stars of fixed properties, including convection zone depth, we isolate and examine the role that rotation plays in a stellar dynamo.

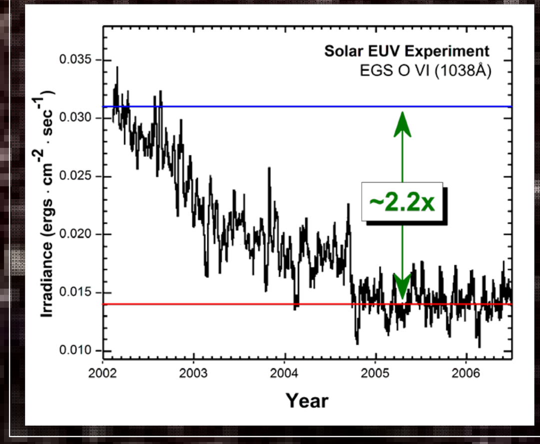


This investigation has utilized many resources and spanned much of the electromagnetic spectrum from radio through X-ray. An important component of this "Sun in Time" project is the investigation of magnetic activity cycles that occur within these solar proxies, and the changes in the high energy coronal and transition region (TR) emissions.

V. The Present Sun

For comparison with the Sun, *Yohkoh* SXT (0.3-3.0 keV band) observations from Nov 1991 (near solar maximum) to Sep 1995 (near solar minimum) show a decline in the full disk X-rays of greater than a factor of ~25, with an accompanying change in average coronal temperature of only 3.3 to 1.5 MK (Acton 1996). α Cen has dropped in X-ray luminosity by a factor of ~80.

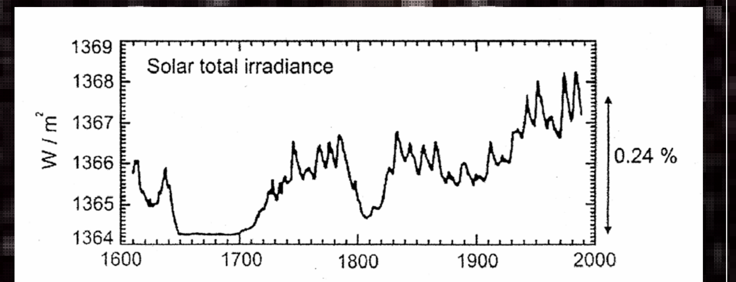




Solar EUV observations from 2002 to 2006 show a decline in the O VI emission feature of greater than a factor of two. We measure this same feature to have declined by a factor of ~2.5 (about 3.5x overall) for α Cen A.

VI. The Maunder Minimum

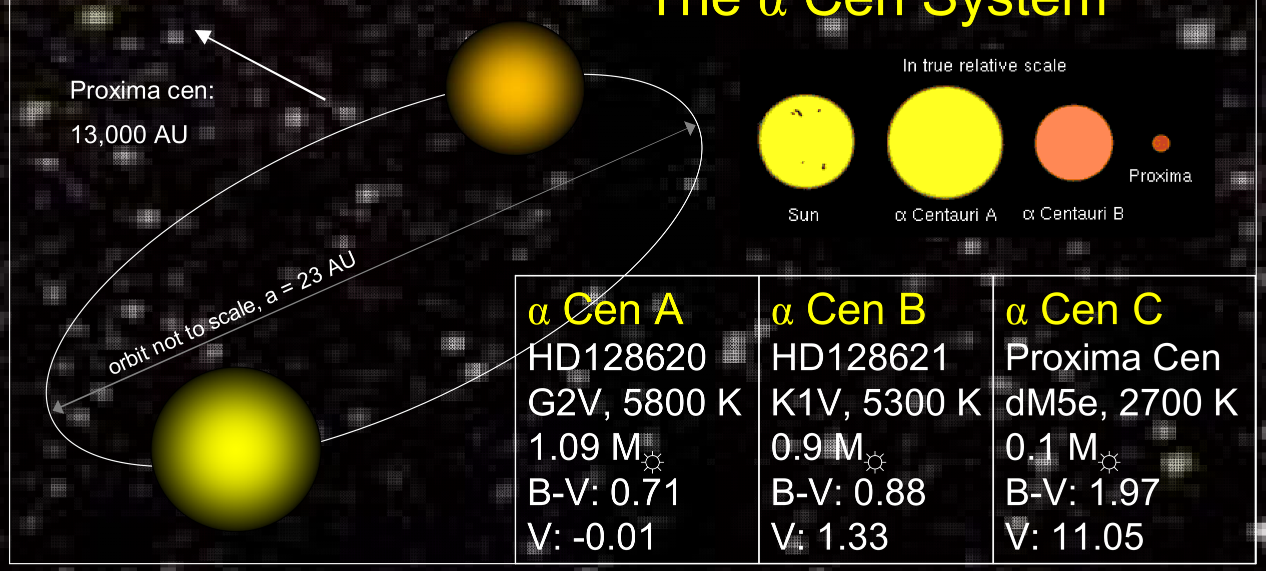
During the extended period from 1645 - 1715 the Sun's expressions of activity (number of sunspots, auroral frequencies, etc.) were nearly nonexistent. Overall, the total solar irradiance is estimated to have diminished by about 0.2% (Lean *et al.* 1995; Bhatnagar *et al.* 2002). The high-energy (X-ray through UV) measures, which are significantly more sensitive to changes in magnetic activity, are believed to have declined by much greater margins. For example, the FUV Ly-α emission feature, stemming primarily from the solar chromospheric region, is estimated to be a 25% decrease relative to current solar minimum conditions (Woods 2004). Using current *Yohkoh* data, we estimate that the coronal X-ray levels for our Sun were down by about a factor of 10 from current average irradiances during the Maunder Minimum.



Precisely how the Earth's climate can be affected by these changes is extremely complex, but notwithstanding, global temperatures were typically lower by about one half of one degree during the Maunder Minimum. Among other things, this "Little Ice Age" resulted in failed crops and associated human starvation.

The exact cause of the Maunder Minimum remains unclear, but our slightly older solar cousin may be entering a similar, but a much deeper, quiescent state.

The α Cen System



α Cen A	α Cen B	α Cen C
HD128620	HD128621	Proxima Cen
G2V, 5800 K	K1V, 5300 K	dM5e, 2700 K
1.09 $M_\odot$	0.9 $M_\odot$	0.1 $M_\odot$
B-V: 0.71	B-V: 0.88	B-V: 1.97
V: -0.01	V: 1.33	V: 11.05

References

- Acton, L.W. 1996, in Cool Stars, Stellar Systems, and the Sun (ASP Conf. Ser. 109), eds. R. Pallavicini and A.K. Dupree, 45
- Bhatnagar, A., Jain K. & Tripathy, S.C. 2002 astro-ph/0201025
- Dorren, J.D. & Guinan, E.F. 1994a, in The Sun as a Variable Star: Solar and Stellar Irradiance Variations (IAU Coll. 143), eds. J.M. Pap et al. (Cambridge: Cambridge University Press), 143, 206
- Dorren, J.D. & Guinan, E.F. 1994b, ApJ, 428, 624
- Dorren, J.D., Guinan, E.F. & DeWarf, L.E. 1994, in Proc. Eighth Cambridge Workshop: Cool Stars, Stellar Systems, and the Sun, ed. J.-P. Caillault (Dordrecht: Kluwer), 64, 399
- Guinan, E.F., Ribas, I., Harper, G.M. 2003, ApJ, 594, 561
- Raassen, A.J.J., Ness, J.-U., Mewe, R., van der Meer, R.L.J., Burwitz, V., Kaastra, J.S. 2003, A&A, 400, 671
- Lean, J., Beer, J., Bradley, R. 1995, GeoRL, 22, 3195
- Ribas, I., Guinan, E.F., Güedel, M. & Audard, M. 2005, ApJ, 622, 680
- Robrade, J., Schmitt, J.H.M.M., Favata, F. 2005, A&A, 442, 315 (astro-ph/0508260)
- Simon, T., Herbig, G. & Boesgaard, A.M. 1985, ApJ, 293, 551
- Skumanich, A. 1972, ApJ, 171, 565
- Woods, T. 2004, in the Earth Observer, vol. 16, no. 5

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