LETG

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Getting Cross: Calibration

It all sounds simple enough. All the different instruments on the satellite should agree on the flux they measure from an astrophysical source were it to be observed by them all at the same time. The euphemism for engineering such an amicable concord is "cross-calibration." If the source of X-rays is constant, it is childs' play: just rack up a few observations, grasp all the effective areas between both hands and squeeze together until no lumps or protrusions pop out from between your fingers and write out the FITS files. Frustratingly, the innocuous little word "constant" proves to be a bit of a sticking point. Adult intervention is required and inevitably, until it finally bursts, the calibration balloon can never quite be squashed down without some part of it sticking out somewhere. Lacking a well-defined calibration at launch, the instrument left wearing the "Why Always Me?" T-shirt is, of course, the LETGS.

A frequent lament in these pages is that the only cosmic sources of X-rays that can be considered constant from a calibration standpoint are either very soft or very faint (hot white dwarfs and isolated neutron stars) or else quite large and diffuse (supernova remnants and clusters of galaxies). Being a slitless spectrometer, the LETGS cannot observe large diffuse sources without a lot of confusion in unravelling the origin of the photons dispersed all over from different regions of the source: essentially we get a source image smeared out continuously in the dispersion direction. *Chandra*'s imaging spectrometer, ACIS, can observe these in great detail, however, and with nice energy resolution. Scientists in charge of those instruments have no excuse whatsoever not to have an absolutely perfect cross-calibration between ACIS-I and ACIS-S.

So, what can we do to get LETGS in line with the other instruments? In *Chandra* Newsletter 19, we documented the process of re-calibrating the low-energy quantum efficiency (QE) of the primary LETGS readout detector, the HRC-S, relying heavily on the hot white dwarf HZ 43. While it is indeed on the hottish side for a white dwarf, 51,000 K is only tepid in X-ray terms. Consequently, its Wien tail tends to peter out around 50 Å or so, and only by adding together all the yearly calibration observations of it were we able to calibrate down to the Carbon edge near 44 Å. But it *is* constant—at least to well beyond the percent precision we need it to be—and it does provide an absolute calibration. Well, truthfully, absolute relative to a fairly decent model of the emission from a pure hydrogen atmosphere. At shorter wavelengths, we need to appeal to petulant, harder X-ray sources, none of which can be described by models of absolute flux, and all of which have a tendency to vary well beyond the percent precision level on the several hour timescales it takes us to observe them to acquire sufficient signal.

Blazingly bright X-ray binaries might sound like appealing calibration sources, but they tend to be piled-up in HETG+ACIS-S and LETG+ACIS-S spectra that we need to cross-calibrate with. They also generally reside near the Galactic plane, where intervening gas and dust lies in wait to plunder the softer X-ray photons on their way through. At higher Galactic latitudes, less blazingly bright blazars come in handy, and Mkn 421 and PKS 2155-304 have been perennial calibration favourites. Both lie behind modest absorbing columns of about 10^{20} hydrogen atoms per cm^2 and their relatively featureless spectra stretch observably into what might be called the Extreme Ultraviolet, getting up to the vicinity of 100 Å.

To get around the problem of the source spectrum changing from an observation using one instrument configuration to another, we adopt the cunning tactic of observing them in one long session, switching between the instrument configurations in the hope that the blazar does not notice. Even if it varies a little, we can adjust the calibration so as to get the smoothest transitions in derived fluxes when switching between instruments. The best way would be to switch gratings and detectors, oh, about once every few minutes or so. Unfortunately, we are not allowed to do this—something about potential hardware failure and the inability of the gratings to flap in and out of the optical path like hummingbirds' wings (a design flaw hopefully eradicated in future missions). So, we do it every 10ks, with a pretty pattern that goes HETG+ACIS-S, LETG+ACIS-S, LETG+HRC-S, LETG+ACIS-S, LETG+HRC-S, LETG+ACIS-S, LETG+HRC-S, HETG+ACIS-S. Not only does this harmonise perfectly with the chord progression of Pachelbel's Canon in D (D, A, Bm, F#m, G, D, G, A, of course), but also makes for colorful plots that under certain types of source behaviour can reproduce the national flag of the Seychelles.

The thing is that the blazars *do* notice, and, like an impish boy sticking his tongue out just at the moment the family Christmas photo is taken, they like to mess it up for us. Fig. 1 illustrates the combined light curve from the Canon in D performance from the beginning of 2013 July when Mkn 421 did a convincing impression of the outline of the original Tacoma Narrows Bridge at its moment of collapse. Note the clever inflection points timed to coincide perfectly with the HETG-LETG switches, rendering the data useless for grating cross-calibration. Patience, then, is the only recourse: if we take enough photos, surely one of them will not exhibit the offending tongue. Perhaps, but we have only been doing this for 8 years, and they all have cheeky tongues sticking out at us at different angles. Instead, we have to resort to the airbrush, and use the variety of tongue portraits to construct the tongueless one: while the variations in a single set of observations might render the calibration corrections ambiguous or uncertain, the required adjustments *should* just pop out of the ensemble of data, like a fearless, leaping salmon, or a tongue.

OK, this particular salmon would not have made it past the first modest fish ladder, but by insisting on the smoothest possible curve through the data it did manage to poke its head above water and bubble "HRC-S down by 7%." Since we are absolutely calibrated at wavelengths longward of the C edge, the QE shortward of the C edge was then lowered by a grey 7%, tapering to zero correction by 44 Å. Just so the longer wavelengths did not feel left out, we also applied some few percent time-dependent QE tweaks to the HRC-S QE in the vicinity of 100 Å to reflect the recent more rapid loss of QE in detector regions of lower gain—see *Chandra* Newsletter 19 for a description of the ungainly effects of aging on the instrument.

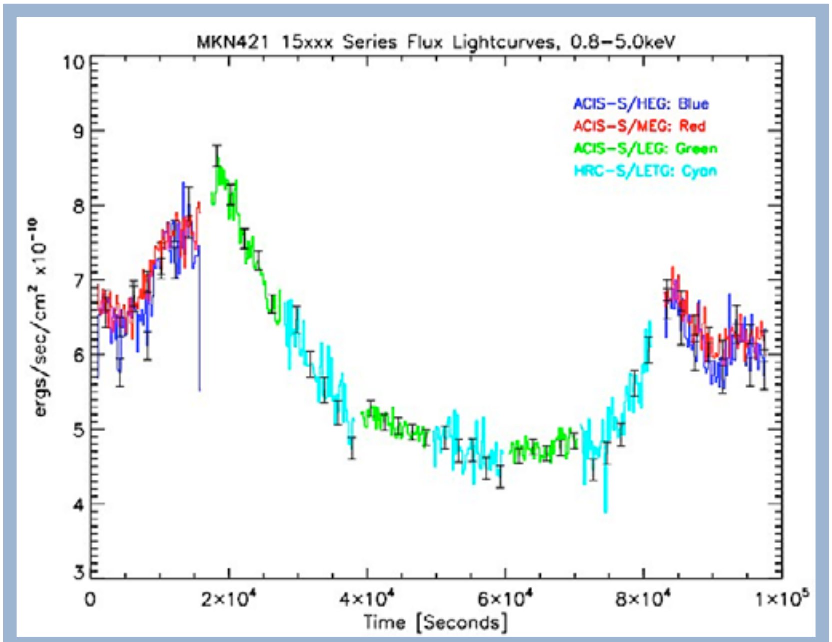

Fig. 1 — The light curve of the blazar Mkn 421 as seen in the sequence of grating combinations designed for foolproof cross-calibration. Inflection points at the HETG-LETG grating changes were an ingenious flux variation stunt the source produced to sabotage our best efforts to cross-calibrate between gratings.

Star Cyclist

The unbiased observer of scientific progress would be hard pressed to reach any other conclusion than that it has proven quite tricky to understand the details of our closest cosmic source of X-rays, the Sun. Since sunspots were first reported—as far back as 2000 years ago by those precocious Chinese observers—it took until the early 1900's and Hale's spectroheliscope to realize they were regions of strong magnetic field. A century later, we still do not really have a fully successful start-to-finish model for the dynamo that generates the solar magnetic field, and continue to debate even where exactly in the solar interior most of the field originates. It has been about 70 years since it was realized that the solar corona comprises a plasma with a temperature of a million degrees, and 50 years since coronal X-ray emission was found to be clearly associated with sunspots in "active regions." A detailed understanding of how the solar corona is heated is still lacking.

Given the rate of progress on our closest astrophysical body that we can spatially resolve, one might wonder what everything we cannot resolve is really like (it would be inappropriate to point fingers at a particular field, like, say, anything dealing with purported black holes)! In an effort to unmask the complex physics involved, solar instruments have striven to reach higher and higher spatial resolution, often limiting studies to small patches of the solar surface with the unintended consequence that the global "Sun as a star" behavior has sometimes been overlooked. Including stumpers like how much does the solar soft X-ray output vary through the solar cycle? Researchers have struggled to shoehorn the data from, well, let's just say it, often poorly-calibrated, disparate solar instruments into tidy agreement. The litany of impending

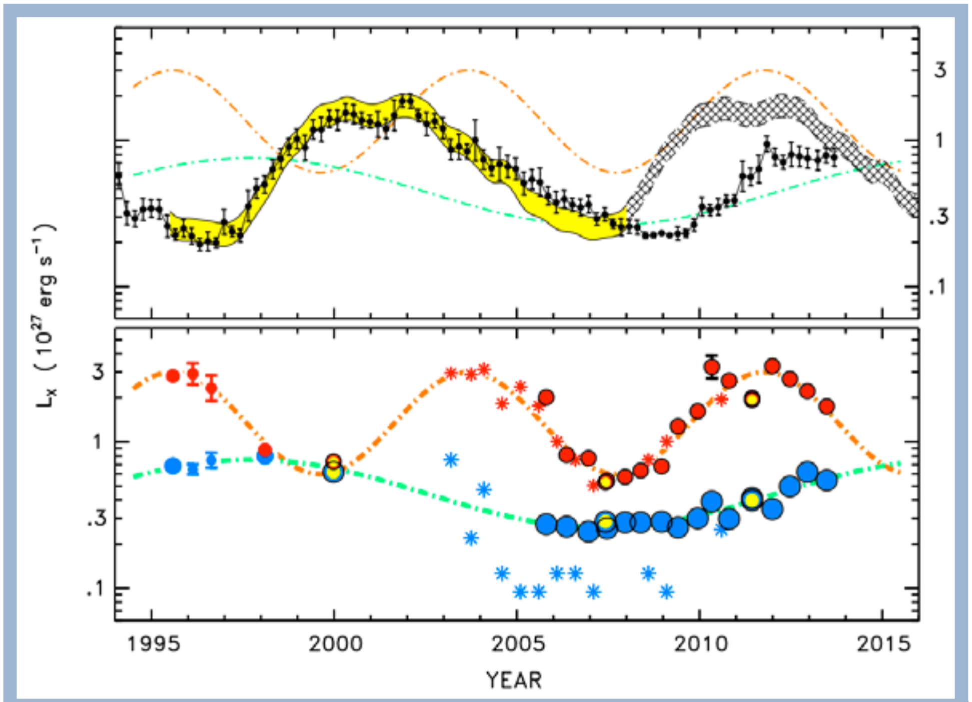

Fig. 2 — Damien Hirst-like spot representation of the coronal cycles of α Cen. Top: solar 0.2–2 keV luminosities inferred from GOES data, overplotted on the three-cycle average shown in yellow and the hatched region. Bottom: HRC fluxes of α Cen: blue for solar-type primary (α Cen A); red for K-type secondary (α Cen B). Pre-2000 dots are based on ROSAT HRI observations. LETGS exposures are shown by yellow dots. Asterisks are scaled XMM-Newton X-ray luminosities. Dot-dashed curves are log-sinusoidal fits to Chandra and ROSAT for α Cen A, including also XMM-Newton data for α Cen B. From Ayres (2014).

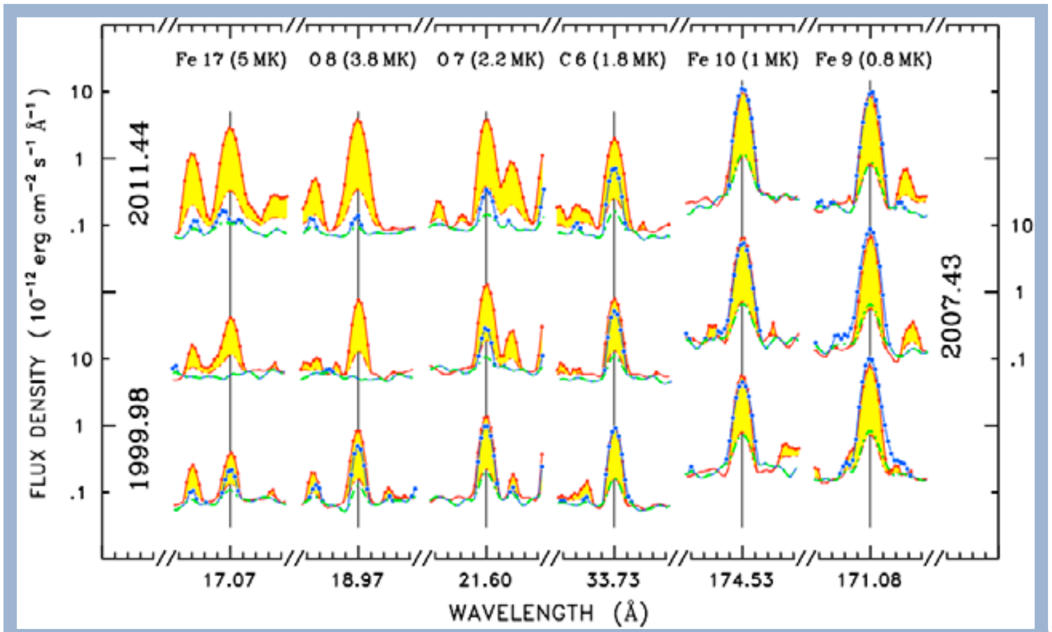

Fig. 3 — Spectra of selected lines from LETGS observations of α Cen A. The use of strong primary colors is designed to separate out behavior of the K star (shaded yellow and red dots) from that of the G star (blue dots). Delicate pastels indicate 1σ photometric errors for B in orange and A in green. Approximate line formation temperatures are listed. Note the dramatic differences between the two stars at the shortest wavelengths (< 20 Å) compared to the rather similar fluxes at the longest wavelengths (> 170 Å). From Ayres (2014).

ecological catastrophes to be precipitated by *Homo sapiens* messing up their sandbox a bit too much has meant the influence of solar variability and ionizing flux on the Earth's atmosphere and climate has got a bit more attention than the usual solar physics story over the last few years. Can the cliché "solar-stellar" connection come to the rescue? Probably not, but it's a reasonable place to start to understand solar behavior we cannot observe at the present time.

Fortunately, we only have to go a parsec or so to get to a star reasonably close to the Sun in age and mass—to the α Centuri system, containing a G2 dwarf and sibling K dwarf. Tom Ayres, of the University of Colorado has, since 2005, been using *Chandra* to carry out observations of the binary every six months. He has mainly used the High Resolution Camera for its efficient soft X-ray response, and has also made two observations with the LETGS to get to grips with how the spectra might be changing. The separation of the stars on the sky varies from about 22 down to 2 arcseconds and *Chandra* is therefore able to fully resolve the binary throughout its orbit and measure the soft X-ray flux of both stars. Combining the *Chandra* data with earlier ROSAT observations, Ayres (2014) has been able to identify a definite 8 yr cycle in α Cen B over which the soft X-ray output changes by a factor of 4.5—about half of the solar amplitude—and a tentative, weaker 19 yr cycle in α Cen A. Alternatively, Ayres speculates that the more solar-like α Cen A could be climbing out of a Maunder Minimum type of magnetic slump. With a plot technique clearly grounded in the Seurat neo-impressionist school, and with an obvious nod to the more recent Damien Hirst Spot Paintings, Ayres' illustration of the the α Cen AB coronal cycles features in Fig. 2. Inference based on *XMM-Newton* data suggesting a "fainting" of α Cen A around 2004 to very low X-ray fluxes never seen on our own Sun appear to have been spurious. This is probably good news: if it happened on α Cen A it can happen on the Sun and large changes in the solar ionizing flux could have unforeseen consequences for our homely terrestrial environment.

LETG spectra, snippets of which are shown in Fig. 3, were able to tease apart the spectral variations, showing that at longer wavelengths, in the light of Fe IX and Fe X lines formed at temperatures of about 1 MK, both stars have very similar fluxes. The differences are more striking at shorter wavelengths, with B dominating in lines formed above 2 MK. Both stars vary largely through changes in the hotter plasma emission. Again, reassuring, because similar behavior is seen on the Sun.

No need to worry too much about the Sun going crazy based on α Cen then. But those enormously giant flares on solar-like stars seen by Kepler are another matter…

JJD thanks the LETG team for useful comments, information and discussion.

References

Ayres, T. R. 2014, AJ, 147, 59