# Separating Local and Cosmic Soft X-ray Emission in the Chandra Deep Field-South

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**Abstract.** The *Chandra* Deep Field-South (CDF-S) observing program, comprising 2 Ms of data collected near Solar Maximum (1999 and 2000) and during Solar Minimum (2007), provides a uniquely rich and informative data set for investigation of solar wind charge exchange (SWCX) and the soft X-ray background (SXRB). When combined with data on solar wind composition from the ACE satellite, these observations permit studies of the effects of solar wind stratification (fast versus slow wind) and viewing geometry (through the heliosphere and geocorona) on SWCX emission. We discuss preliminary results from our analysis of these data, including an upper limit on the true cosmic (non-SWCX) SXRB in the 3/4-keV band in the direction of the CDF-S.

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## INTRODUCTION

Several papers in this volume have discussed soft X-ray emission from solar wind charge exchange (SWCX), including its discovery, the physical mechanism, spectra, spatial distribution, dependence on the solar wind, and its contribution to the observed soft X-ray background (SXRB). The SWCX contribution is a subject of great importance and great uncertainty, with estimates for the 1/4-keV band ranging from much less than half to essentially 100%, at least in some directions. This article briefly summarizes the difficulties in trying to measure SWCX emission observationally, and also presents some preliminary results from analysis of *Chandra* Deep Field-South (CDF-S) data. The CDF-S data span both Solar Minimum and Maximum, and offer a rare opportunity to quantify the contributions of both local and cosmic emission to the SXRB.

## SWCX AND THE SXRB

The four components of the SXRB are: (1) absorbed extragalactic emission (roughly following a power law), (2) absorbed thermal emission from the Galactic halo ($\sim 2\times 10^6$ K), (3) unabsorbed thermal emission from the Local Bubble ($\sim 10^6$ K), and (4) SWCX from the geocorona and heliosphere. With the moderate energy resolution typical of X-ray CCDs, the SWCX spectrum looks much like that of the Local Bubble, and the spectra are indistinguishable to the *ROSAT* proportional counters.

Observationally separating the cosmic emission (components 1, 2, and 3) from local SWCX contamination thus requires some effort, preferably with a bit of luck. Unlike the cosmic SXRB, which varies with position on the sky but is constant in time, the observed SWCX emission varies not only depending on where one looks, but also when,

**TABLE 1.** CDF-S Observations. All observations use ACIS chips I0–I3 and S2.
Galactic lon, lat: 223.58, -54.44 Ecliptic lon, lat: 41.13, -45.19

| ObsID | Start Date | ACIS Mode | Expos. (ks) | ObsID | Start Date | ACIS Mode | Expos. (ks) |
|---|---|---|---|---|---|---|---|
| 581 | 1999-10-14 | VF$^{*}$ | 21$^{\dagger}$ | 8591 | 2007-09-20 | VF | 46 |
| 1431 | 1999-10-15 | VF | 30$^{**}$ | 9593 | 2007-09-22 | VF | 47 |
| 1431 | 1999-11-23 | VF | 95 | 9718 | 2007-10-03 | VF | 50 |
| 441 | 2000-05-27 | F | 57 | 8593 | 2007-10-06 | VF | 50 |
| 582 | 2000-06-03 | F | 132 | 8597 | 2007-10-17 | VF | 60 |
| 2406 | 2000-12-10 | F | 30 | 8595 | 2007-10-19 | VF | 118 |
| 2405 | 2000-12-11 | F | 60 | 8592 | 2007-10-22 | VF | 88 |
| 2312 | 2000-12-13 | F | 125 | 8596 | 2007-10-24 | VF | 118 |
| 1672 | 2000-12-16 | F | 96 | 9575 | 2007-10-27 | VF | 110 |
| 2409 | 2000-12-19 | F | 70 | 9578 | 2007-10-30 | VF | 47 |
| 2313 | 2000-12-21 | F | 132 | 8594 | 2007-11-01 | VF | 151 |
| 2239 | 2000-12-23 | F | 132 | 9596 | 2007-11-04 | VF | 113 |

$^{*}$ 1999 observations were with ACIS temperature of -110 °C instead of standard -120 °C.
$^{\dagger}$ 44 ks for I3, $\sim$18 ks for other chips.
$^{**}$ ObsID1431 comprises two separate observations.

and where one is looking *from*. In this paper we use the last two dependences to tease apart the local and cosmic SXRB.

## THE *CHANDRA* DEEP FIELD-SOUTH

The CDF-S observations, comprising 2 Ms of exposure time using the ACIS-I CCD array, are unique among X-ray deep fields in that they were collected both near Solar Maximum (peak $\sim$2001/2002) and during Solar Minimum ($\sim$2007). Note that the *ROSAT* All-Sky Survey (RASS) occurred in 1990, during the previous Solar Max. In this preliminary analysis we exclude the three earliest observations (late 1999, with non-standard ACIS operating temperature), leaving 9 observations totalling 836 ks in 2000, and 12 observations in 2007 totalling 981 ks (see Table 1). The CDF-S lies in a low-background region of the sky, at an ecliptic latitude of -45°.

The ecliptic latitude matters because during Solar Min the solar wind is stratified, with the more highly ionized slow wind confined to within $\sim$20° of the ecliptic plane. During Solar Max, a mix of slow and fast wind occurs at most latitudes [1]. One therefore expects the 2000 observations to show, on average, a relatively high X-ray background level because the line-of-sight (LOS) traverses a large fraction of slow wind. In contrast, in 2007, the LOS traverses mostly fast wind, yielding less SWCX emission.

In addition to these solar-cycle effects, seven of the nine 2000 observations were conducted from inside the He focusing cone (see Fig. 1-left), a region of relatively high neutral-He density downwind of the Sun created as the Sun moves through the Local Interstellar Cloud [2], which further enhances SWCX emission. The 2007 observations, on the other hand, were made when the Earth was outside the He cone and look downwind through a region of low H density.

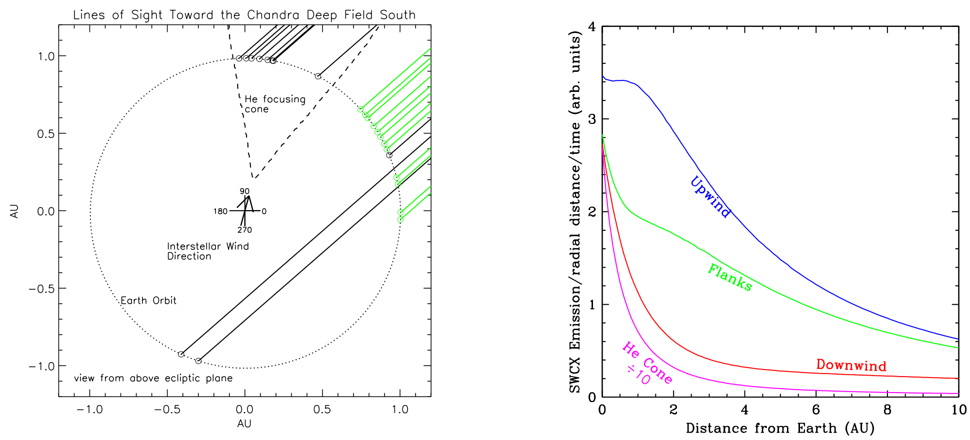


**FIGURE 1.** *Left*: Lines of sight in the ecliptic plane for all CDF-S observations (2007 in green). All lines angle down into the page at 45°. The 2007 observations look through mostly the less ionized fast solar wind, from outside the He cone. *Right*: Modeled SWCX emission distributions as observed from Earth for various anti-Sunward look directions. In the downwind direction (looking from outside the He focusing cone), SWCX emission is weak and mostly originates from several AU away. When observing from within the He cone, emission is much higher (note the ÷10 scaling) and arises from relatively nearby.

The 2000 observations should therefore show higher average SWCX emission than those in 2007. There should also be a much tighter correlation between the observed X-ray rate and the flux of highly charged ions measured by the Solar Wind Ion Composition Spectrometer (SWICS; data available from `http://www.srl.caltech.edu/ACE/`) on *ACE* in the Earth's vicinity (0.01 AU toward the Sun), particularly ions such as $O^{7+}$ and $O^{8+}$ that give rise to most of the SWCX emission seen by *Chandra*. This is again because the 2000 observations were made from inside the He cone; as shown in Fig. 1-right, when inside the cone, most of the observed SWCX emission arises from relatively nearby.

Outside the cone (as for the 2007 observations), and particularly when looking toward regions of the heliosphere with low neutral density, most of the observed emission comes from several or many AU away, so temporal variations in the observed SWCX emission arising from solar wind fluctuations tend to be smoothed out by spatial averaging [3]. Most of the SWCX emission seen in the 2007 observations is therefore coming from a region of the heliosphere where solar wind properties are not known, so one expects little correlation between local solar wind conditions and variations in the apparent SXRB.

## Analysis

After registering all observations to a common coordinate system and removing periods of high background (only 10 ks), data from all 21 observations from 2000 and 2007 were combined and a 7.7'-radius region covering most of the four ACIS-I chips was extracted. 246 sources were detected and removed, with exclusion areas adjusted as

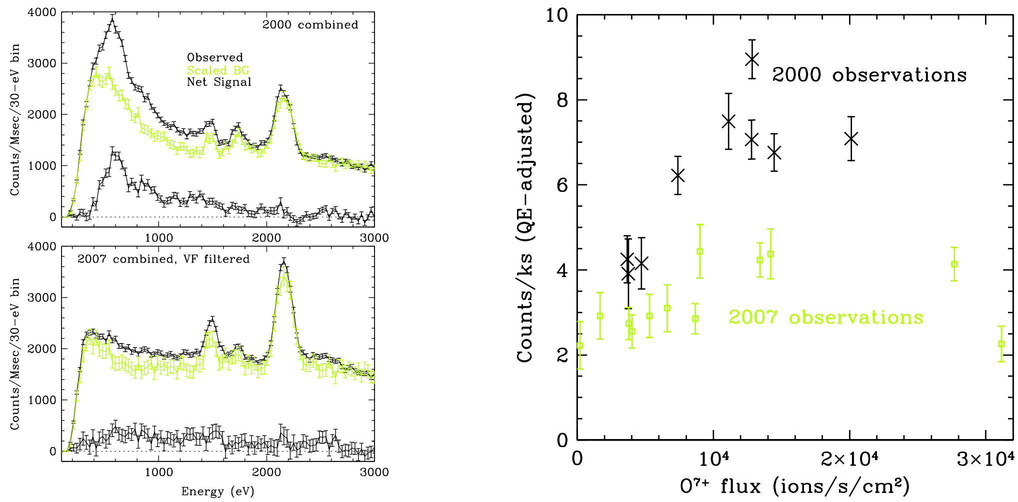


**FIGURE 2.** *Left*: BG-subtracted spectra from combined 2000 and combined 2007 data. VF filtering was applied to the X-ray and background data for the 2007 analysis. ACIS QE around 600 eV is ∼40% lower in 2007 than in 2000, but it is still obvious that the SXRB in the CDF-S was on average much higher in 2000. *Right*: Average X-ray event rate (520–710 eV) versus locally measured solar wind $O^{7+}$ flux, by ObsID. X-ray rates for 2007 have been approximately corrected for changes in ACIS QE. Rates in 2000 are generally higher, have more relative variation, and are more correlated with O ion flux than in 2007, as expected from the SWCX model.

a function of source intensity and distance from the telescope aimpoint. Of the remaining X-ray events in the final field (7.5’ radius), fewer than 2% come from point sources.

The data were then divided into two sets to assess general differences between the 2000 and 2007 observations, and VF filtering was applied to the 2007 data to reduce the particle background (which was much higher than in 2000 because of the Solar Cycle). After extracting the spectra, background spectra from the ‘ACIS-stowed’ calibration data set were scaled appropriately and subtracted from the CDF-S spectra.

## Results

As seen in Fig. 2-left, the X-ray event rate is much higher in 2000 than in 2007. This is partly due to a ∼40% decrease in ACIS QE at energies around 600 eV during the intervening 7 years, but the SXRB level is clearly higher in the 2000 data, most noticeably around 600 eV where SWCX emission from He-like and H-like O dominates.

Further evidence that the enhanced X-ray emission comes from SWCX is found when comparing observed X-ray rates between 520 and 710 eV with $O^{7+}$ solar wind ion fluxes measured by *ACE* (see Fig. 2-right). As expected for the 2000 observations, most of which were conducted from inside the He focusing cone, there is a clear correlation of X-ray rate and the flux of highly charged O ions. In contrast, there is essentially no such correlation for the 2007 observations, again in agreement with the SWCX model.

If one extrapolates the 2000 data to zero oxygen ion flux, the X-ray rate approximately matches the lowest rates seen in 2007. After doing some quick and dirty fits to the combined spectra of the 3 lowest-rate 2000 observations and 8 lowest-rate 2007 observations, convolving the results with the *ROSAT* PSPC response matrix, and scaling down the 2000 results to reflect the estimated zero-SWCX level, we obtain a *preliminary* *ROSAT*-equivalent intensity of roughly $35 \times 10^{-6}$ cts/sec/arcmin$^2$ in the R45 band.

This provides an upper limit to the cosmic SXRB in the CDF-S. Unfortunately, no direct comparison with RASS results can be made because the CDF-S lies right on the edge of a gap in the RASS coverage, and nearby regions are contaminated by Long-Term Enhancements that could not be removed from the data. Nevertheless, the $35 \times 10^{-6}$ cts/sec/arcmin$^2$ estimate, if it holds up, would indicate that very roughly half of the R45 emission typically found in low-rate regions of the RASS comes from SWCX.

## CONCLUSIONS AND EXPECTATIONS FOR PROGRESS

Observationally constraining the SWCX contribution to the SXRB is a challenging problem, requiring careful selection of targets (such as "on/off" observations of dark clouds), multiple observations of a single field preferably with different observing geometries, and luck in catching the solar wind in a particularly quiet or active state. Despite these problems, we have seen at this conference that good progress is being made, supported by similarly intense efforts at theoretical modeling.

The SWCX problem will only be solved, however, by high-resolution spectra from microcalorimeters, with resolutions of one or a few eV. SWCX spectra differ from thermal spectra, with unique signatures such as enhanced emission from high-*n* Lyman lines and He-like forbidden and intercombination lines. Those lines can be used as diagnostics and compared with CX spectra measured in the lab or computed theoretically (although much more work is needed in both fields) to spectrally separate the SWCX and cosmic components. Note, also, that a solar wind velocity of 500 km/sec corresponds to a Doppler shift of 1 eV at 600 eV. Microcalorimeters on missions such as *Spektrum-Roentgen-Gamma* and the *International X-ray Observatory* will finally disperse the SWCX fog that we have been looking through since the beginning of X-ray astrophysics.

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## REFERENCES

1. E.J. Smith, et al., Science 302, 1165 (2003).
2. J.G. Michels, et al., Ap. J. 568, 385 (2002).
3. T.E. Cravens, I.P. Robertson, and S.L. Snowden, J. Geophys. Res. 106, 24883 (2001).