INTI
Processing guide : the sun corona

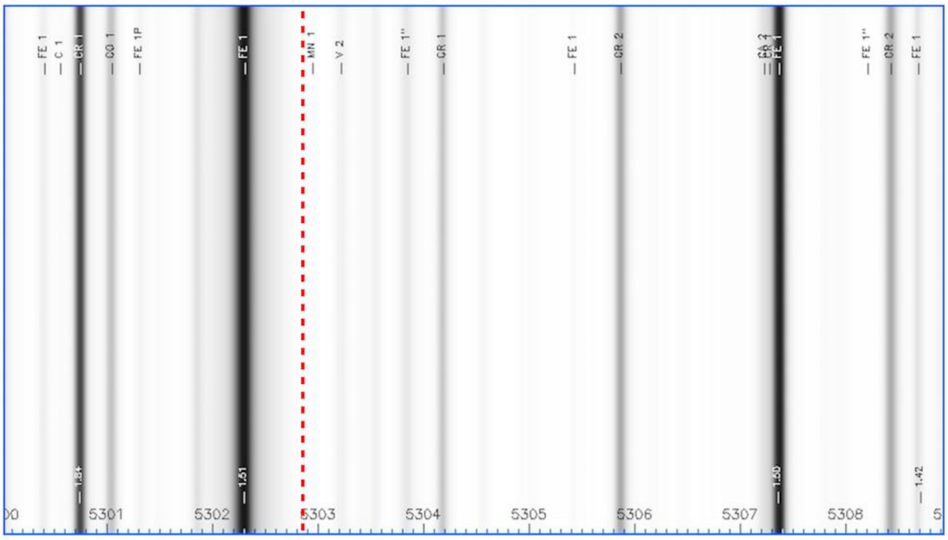
1. Introduction

Observing the corona is possible using the Sol'Ex instrument and the tools provided by the INTI software.

It's not the most spectacular observation if we focus solely on the aesthetic aspect, but it is on the other hand an emotionally powerful observation when we consider that it's possible to see the corona outside eclipses, under skies that aren't necessarily very coronal. We speak of coronal skies when, by hiding the disk with a finger, the scattering from the atmosphere is so weak that it's hard to pinpoint the location of the day's star. This condition can be encountered at high altitude, but the author and others have nevertheless managed to see the corona at the seaside with Sol'Ex, so...

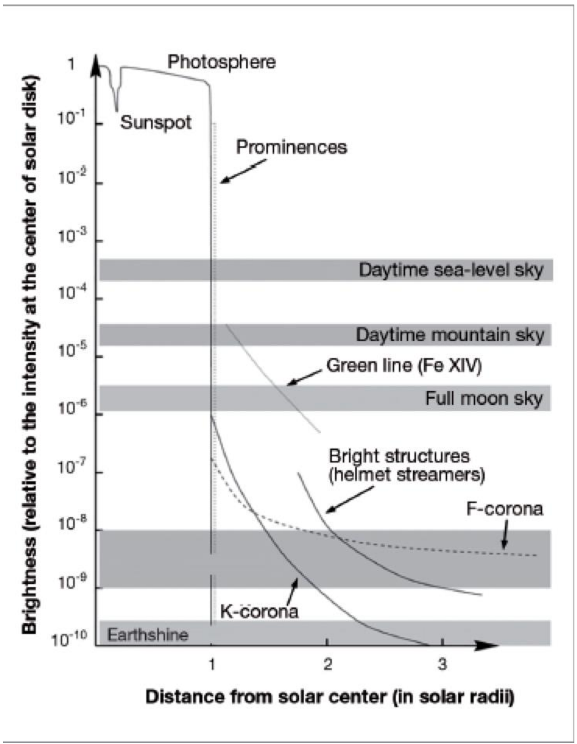
We're going to take advantage of the fact that the corona emits light in specific spectral lines, in particular in highly ionized iron lines. This ionization is caused by the very high temperature in the corona (over a million degrees). Here, we're using a line in the green part of the spectrum, the Fe XIV line, precisely at a wavelength of 5302.86 A. We refer to this as an "E" corona observation, to indicate that it corresponds to viewing the corona via emission lines.

Here's a highly magnified image of the solar spectrum (Meudon Observatory), showing the location of the Fe XIV line in relation to its neighbors:



The position of the line is indicated by a vertical dotted red line. To its left, on the blue side, is a deep photospheric line, Fe I, at a wavelength of 5302.30 A. This line will be of great value to us in the future, but it is also a potential nuisance, given its proximity to the Fe XIV line.

Of course, the intensity of the coronal lines is considerably lower than that of the solar photosphere - around a million times less intense! This is shown in the following graph, where we note that what we wish to observe is at the level of the full Moon sky, but at the edge of the solar limb!



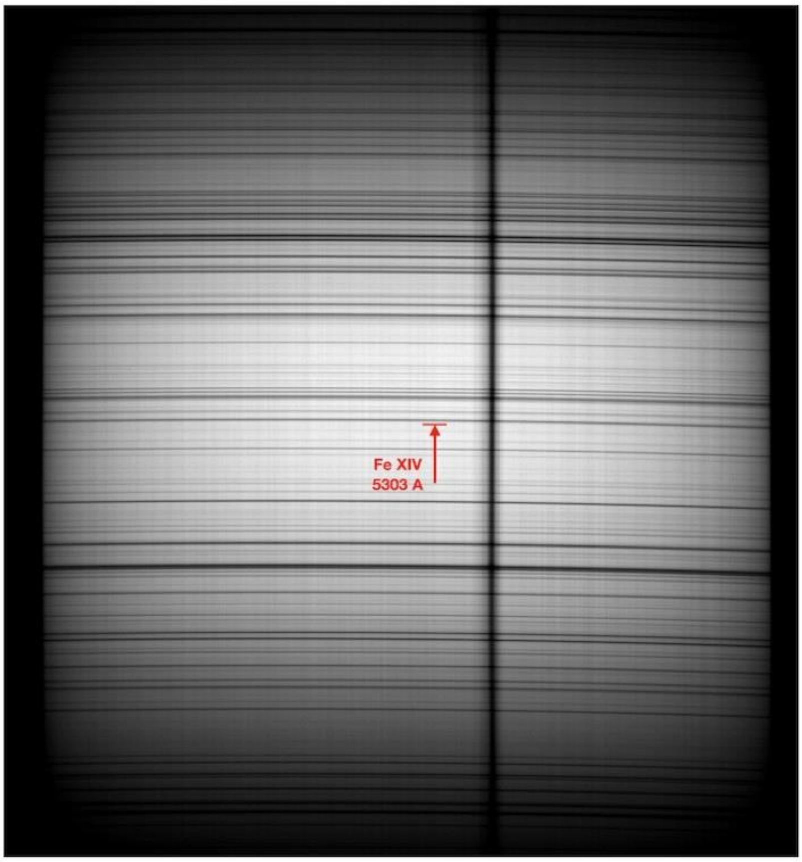
This is a difficult observation, especially when the observatory is located on a plain, with an atmosphere full of aerosols that scatter the intense light of the star of the day. We also need to minimize instrumental scattering, which is a source of spurious background. An effective weapon here is the use of a bandpass-type interference filter, which isolates the Fe XIV line region in the spectrum. This filter, centered on the length of our line, unfortunately doesn't exist as such, but it is possible to adapt the length of a bandpass filter centered on a nearby wavelength, at 540 nm: this is the 10 nm wide Baader Solar Continuum filter, well known to solar observers and relatively inexpensive. To shift the bandwidth around 530 nm, which is just right for us, all we need to do is tilt the filter at an angle of around 25° to the incident beam. The operation is facilitated by a small accessory available from Azur3DPrint, enabling the filter to be mounted in front of the Sol'Ex slit and tilted to the desired angle.

Finally, to facilitate the reading of what follows, we recommend that you first read the processing guide dedicated to observing the Sun in the yellow helium line. It describes how to use INTI's "Free Line" tab, which you should be familiar with.

2. Observation recommandations

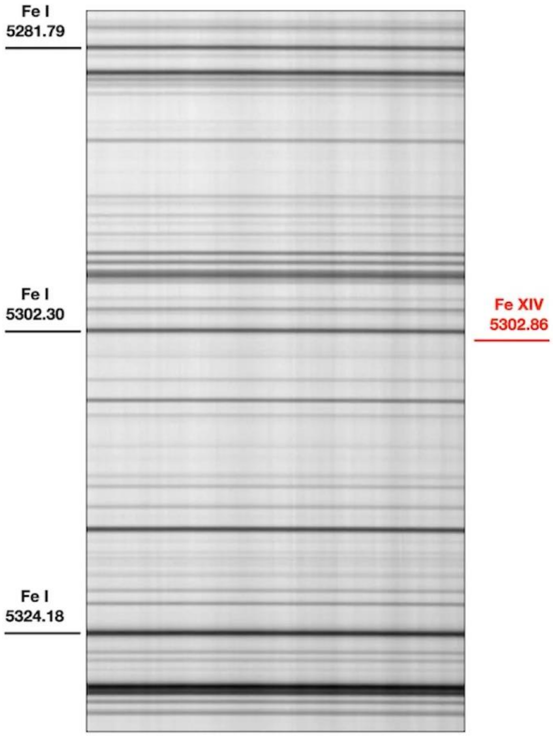
A small telescope with a focal length of between 200 and 400 mm is ideally suited to this observation, to capture the overall image of the solar disk with Sol'Ex.

Of course, you need to locate and center the Fe XIV line in the middle of your sensor. This is made easier by the interferential filter, which isolates the desired region of the spectrum. In the following image, we see the spectrum as it should be for observations, with the spectral lines horizontal in order to optimize the acquisition frequency of the SER file frames:



Note the presence of a sunspot at the entrance slit (the vertical dark band). In this document, we can clearly see the effect of band-pass filtering: the intensity of the spectrum decreases on either side of the Fe XIV line (the filter's inclination must be adjusted for this to happen).

Here's another, closer view:



The question arises of the binning factor (pixel addition) to set when reading the sensor. Intuitively, one would expect to work with 1x1 binning to obtain the most resolved spectrum possible, and thus better isolate the coronal line from the light background. In practice, however, 2x2 binning is recommended, for two reasons:

- SER file size is considerably smaller with 2x2 binning than with 1x1 binning. When you realize that to detect the corona properly, you need to add up several dozen successive scans of the solar disk, or even a hundred, you'll understand that the argument for 2x2 binning is very strong when it comes to your storage capacity.
- Coronal lines are not purely monochromatic. Their natural width is typically 0.8 A and given the speed of gases guided by the magnetic field, this line can move by +/-2 A (Doppler shift of +/-100 km/s). Working with 2x2 binning enables us to integrate this enlarged signal much more effectively, and thus increase the signal-to-noise ratio.

With this binning, the close presence of the Fe I 5302 line forces us to point precisely to the Fe XIV line. Locating the wavelength in the spectrum sometimes must be defined to within a fraction of a pixel.

Here's a view of a typical instrument layout:

Sol'Ex, the Solar Explorer, is at the focus of a 300 mm telescope. Here, we're using an ASI462MM camera in 2x2 binning, with its relatively large pixels (2.9 microns, although this does not prevent detection of the corona). It's a modernized version of the ASI290MM camera (better performance). The sensor is small, but the entire solar disk is captured in a single scan, thanks to the telescope's short focal length. A more conventional Sol'Ex ASI178MM camera, with its finer 2.4-micron pixels, is also perfectly suitable.

At the front is a dense ND16 HOYA. A diaphragm has also been added to the front of the telescope, to increase the aperture to f/7, in the hope of further reducing instrumental scattering (reduction in the geometric extent of the optical beam, but the true gain of this operation has not been evaluated):

This diaphragm is also a variable for adjusting exposure time, the idea being to avoid over-saturating the image of the solar disk - we'll see why later - while working with a camera gain of less than 100, which is always preferable (better image dynamics and optimal signal-to-noise ratio).

Here, we've opted for a scan along the declination axis, as allowed by the ZWO AM5 mount used. This is unusual. The aim is to reduce the effect of the Sun's rotation around its axis, which causes a Doppler shift in spectral lines between the eastern and western edges. However, given the natural width of the Fe XIV line, a classic right-ascension scan is also satisfactory.

3. Observation recommandations

Processing SER videos to extract a corona image is simple with INTI. Once you've made an important decision at the time of acquisition, it's all in the "Free line" tab...

The natural tendency when observing is to force the camera gain to try and get a better view of what's going on around the solar disk. This is pointless, because (1) the corona is far too faint to be seen directly, (2) increasing the camera gain does absolutely nothing to improve the signal-to-noise ratio in our case (we're dominated by photon noise) and (3) worst of all, by heavily saturating the continuum, we can no longer see the background spectral lines.

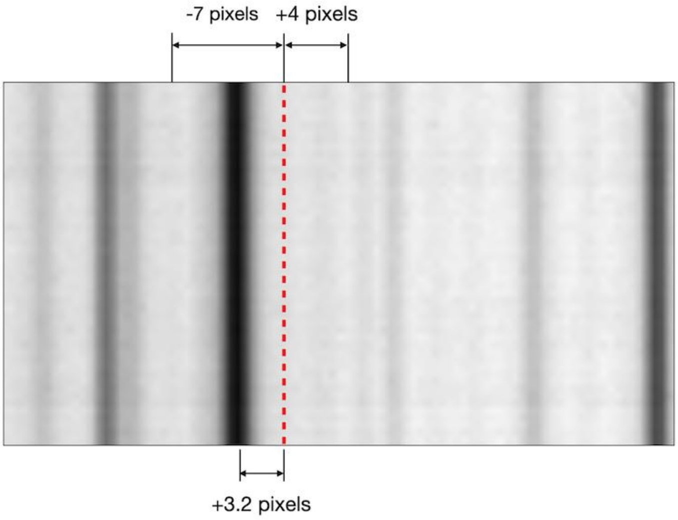
These spectral lines will be useful for identifying the position of the coronal line, and even compensating for deformations of the Sol'Ex over time.

So, you need to choose a camera gain that may saturate the continuum very slightly, but still allow the absorption lines to be seen, at least the strongest at 5302.30 A. Here's how it looks on the "_mean" image produced by INTI:

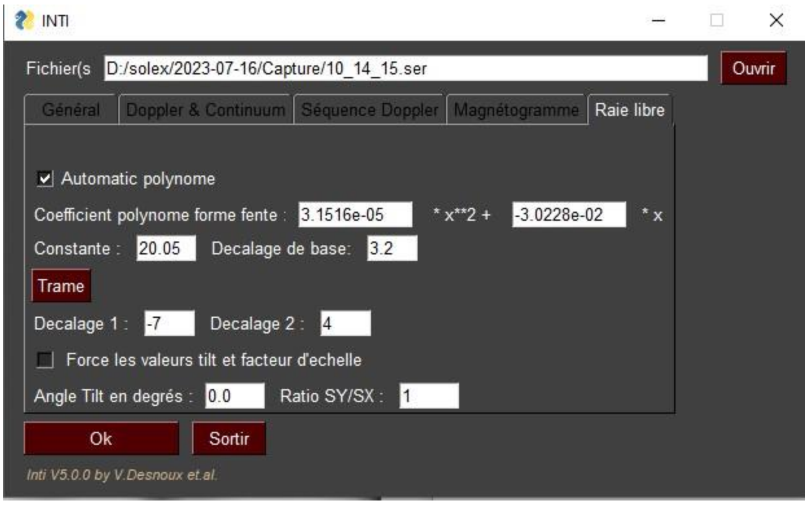
Note: for this observation, we created a 1920 x 28 pixel crop using SharpCap software, thus isolating a fraction of the overall image. The above document shows only a portion of the spectrum range thus obtained.

Next, we need to tell INTI the pixel spacing between the Fe XIV line and the neighboring Fe I line, as the latter will serve as a reference point (visible because the images are not saturated, once again). With 2.4 microns pixel (and a 2x2 binning camera), the spectral dispersion delivered by Sol'Ex is 0.145 A/pixel in this region of the spectrum. Since the wavelength difference between the two lines is 5302.86 - 5302.30 = 0.56 A, we deduce that they are separated by 0.56 / 0.145 = 3.86 pixels. With a camera equipped with a 2.4 microns pixel detector, this gap is only 3.20 pixels.

Here's how things look graphically for the latter situation:



The -7 and +4 pixels offsets identify the continuum zones whose intensity will be averaged by INTI and subtracted from the raw image of the corona to eliminate as much as possible of the background light around the Sun. We're therefore calculating an image difference, so it's a good idea to use the "Free line" tab (as when extracting an image in the helium line). Here's how this tab is filled in for the example described:

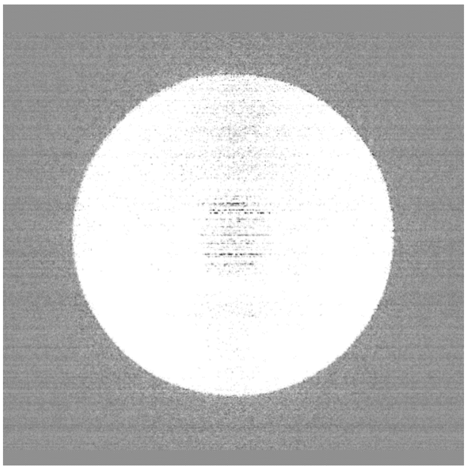


Note that the "Automatic polynomial" option is selected. This is very important here. It means that for each SER file processed, INTI will recalculate the most appropriate polynomial. So, in this mode you don't need to enter the line distortion polynomial terms, or the constant - INTI does the work for you. And if Sol'Ex becomes distorted by heat, INTI recognizes this and compensates (as it were, following the displacement of the spectral lines).

One thing remains unchanged: the distance between the Fe I reference line, which is used to calculate the polynomial, and the estimated position of the Fe XIV line, here at +3.2 pixels. We also recognize the offset values adopted for the continuum measurement, (-7, +4) pixels.

Let INTI calculate the solar disk deformation parameters, by unchecking the "Force tilt and scale factor" option.

Press Ok to process the designated SER file. The result of interest is the image file xxxx_free.fits, which contains the difference between the image in the Fe XIV line and the sky background.:

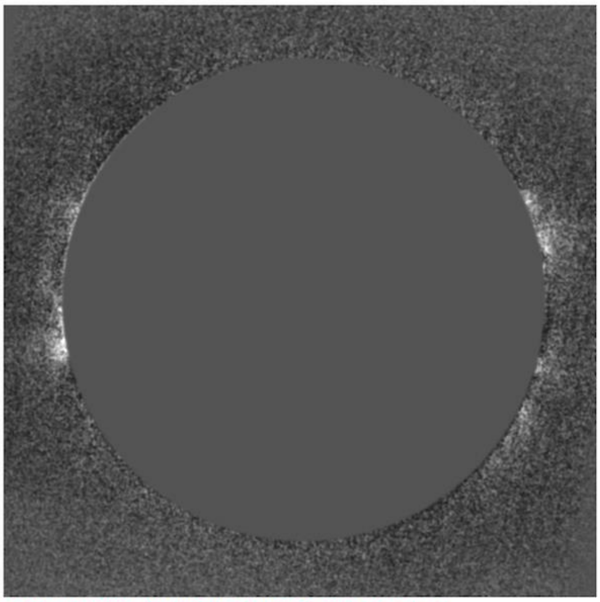


You may be disappointed with the result. There's little chance of seeing the corona from a single SER file. You can barely make out the corona. You'll need to add up several of such images for the faint corona to emerge from the noise.

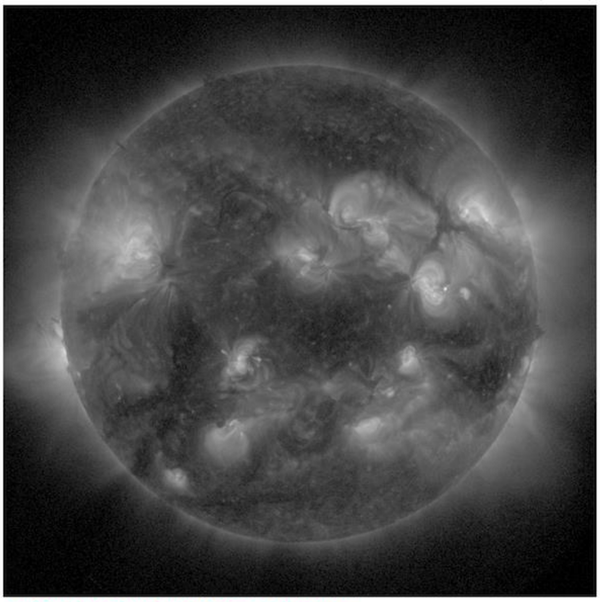
You can automatically process a large number of SER files in sequence, selecting them as a group (dozens at a time if you like), and displaying their names in the input box at the top of the "Free line" tab. Then Ok.

From version 5.0 onwards, INTI offers some very interesting possibilities for such massive data processing: the format of the images produced is always the same, and the solar disk is always centered to the nearest pixel. If you've made 100 SER videos, you can add up the 100 extracted images of the corona directly with your favorite image processing software, without any further transformations. The whole process takes just a few minutes, effortlessly and with very little human intervention.

Here's the result for 100 summed scans, taken on July 22, 2023, when the sky was far from coronal (compare on the right with an SDO image for the date):



Solar Explorer Fe XIV 5303 A line Coronal Emission



SDO Fe XVI 335 A line Coronal Emission

You can easily resume processing by tweaking the parameters, which is both instructive and enjoyable. For example, I've often obtained a higher-contrast image of the corona by using a base offset of 4.0 to 4.4 pixels rather than the 3.2 pixels (for pixels of 2.9 microns, and therefore 4.8 to 5.3 pixels with a camera like the ASI178MM). Don't forget to select the noise reduction option from the advanced settings in the "General" tab, which will give you a significantly less noisy result (by a factor of two, in theory). You'll also better cover the spectral range of the Fe XIV line, which, as you'll recall, is wider. You also have the option of adding together several images of the corona obtained by changing the value of the base offset between them, in 1-pixel steps for example.

INTI output images, even if framed and centered - which is a big plus - may require additional processing to remove some residual bias, the presence of which is not surprising given the weakness of the signal you wish to highlight. Here are just some of the typical processing operations that may be required: