Simulations of the images expected from UVIT

By

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Under the supervision of

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Certificate

This is to certify that this dissertation titled "***Simulations of images expected from UVIT***", submitted by Arya Dhar, JRF, IIA is original and bona fide record of the project work carried out by under my guidance and supervision.

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Abstract

The project involves numerical simulations with archival images from GALEX, exploring the effects of various parameters on the reconstructed image. The input image as would be recorded by the UVIT is simulated, taking into the effects of optics, resolution of the detectors, image frame acquisition rate, etc. Then, by using one or more centroiding algorithms, photon events in image frames are detected for image reconstruction. The reconstructed image shows photometric-distortions in and around bright sources. An iterative method is used to correct these distortions.

Contents

Introduction

Ultra-Violet Imaging Telescope (UVIT) is one of the five payloads aboard the Indian Space Research Organization (ISRO)'s ASTROSAT mission. UVIT records images simultaneously in three channels: Far Ultra-violet (FUV, 1300-1800 Å), Near Ultra-violet (NUV, 1800-3000 Å), and Visible (VIS, 3200-5300 Å), simultaneously with ~ 0.5 degree field of view. Like other UV missions (FUSE, GALEX, etc.) the UVIT Detectors are of photon counting nature based on Micro Channel Plate (MCP) image intensifiers Technology as shown in the Figure 1.

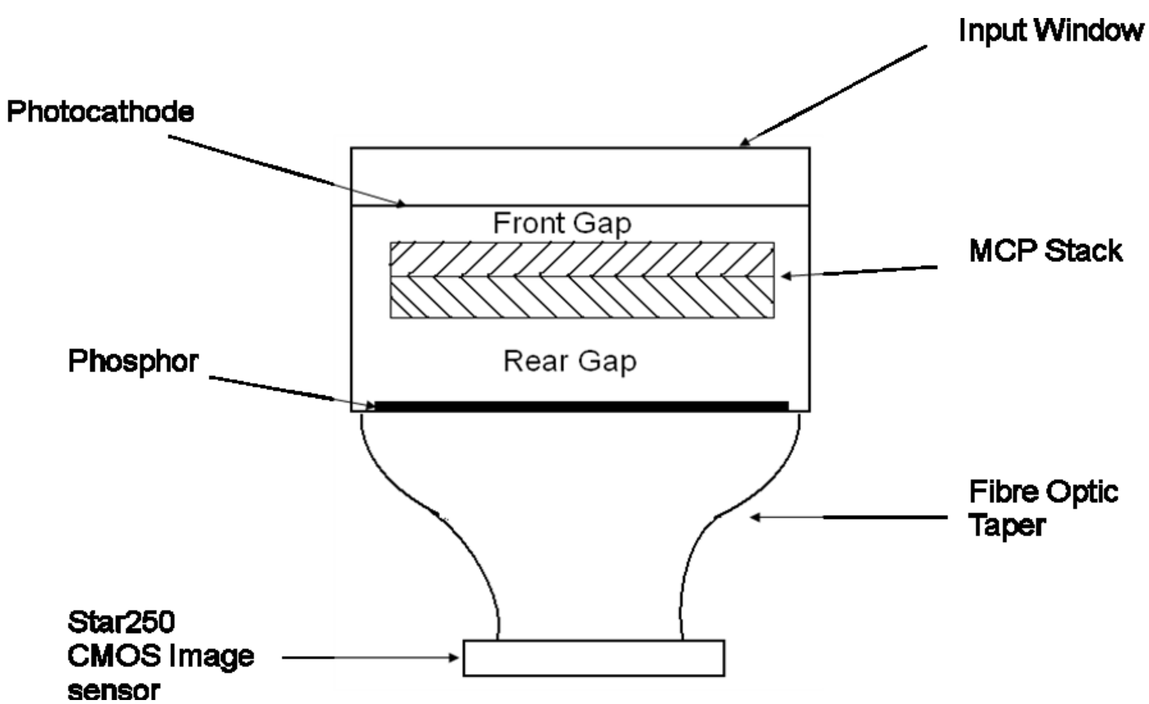


Figure 1: Sketch of the Detector System.

The photocathode deposited on the inside of a 40 mm window lies at the focal plane of the optical system. The photoelectrons released are accelerated across a gap (typically 100-200 μm) to a stack of two microchannel plates. The resulting electron shower illuminates a phosphor with a fast decay time. The light from the phosphor is fed through a fiber-optic taper that is bonded to the surface of a Cypress Star250 CMOS detector, with 512 X 512 pixels. Each pixel is square in size with 25 μm a side. Each pixel extends ~ 3 arc-sec X 3 arc-sec on the sky. This will be referred to as CMOS pixel-scale in the future. In our simulations, we will use this value of the pixel-scale as the UVIT pixel-scale. A detected photon event produces a splash of light on the CMOS that covers several pixels. The exact coordinates of the photon event would later be estimated through some centroid algorithm using the pixel values of the detector, to much higher resolution than one CMOS pixel.

The experimental studies done by Hutchings et al. (2007) shows that one photon event produces a light splash whish follows roughly a Gaussian distribution with Full Width at Half Maximum (FWHM) of ~ 1.5 pixels. The resolution of the detector is set by the gap between the photocathode and first MCP (Michel et al. 1997). The UVIT detectors are designed with the gap of 0.1 – 0.15 mm to obtain a resolution of ~ 1".

Generating the UVIT Data Frames

Data frames were simulated from input images of extended sources from the GALEX data archive. The GALEX image had an input-pixel scale of 0.5 arc-sec. This was done by converting the image from GALEX to an image equivalent to the same galaxy, but kept at a distance 3 times farther and a resolution of 1/3rd thus converting the pixel-scale from 1.5”/pixel to 0.5”/pixel. Given the total integration time and UVIT parameters (mirror diameter, CMOS pixel scale, frame acquisition rate, etc.) each input pixel would produce an average number of photons during the whole integration time. The actual photons in each input-pixel are then generated using the Poisson Statistics as the arrival of photons are a Poisson events. These photons are later randomly distributed in to total number of data frames. The blurring due to optics and detectors (i.e. due to spread of photoelectrons between photocathode and MCP) was approximated by a 2-dimensional Gaussian function with standard deviation (σ) of 0.7 arc-sec (on either axis) and spatial position of a photon in a data frame was determined by this function. The exact position of the photon in any data frame was recorded with accuracy of 1/8th of an input-pixel.

To simulate UVIT photon counting detector, each of the photons were converted to a bunch of photoelectrons i.e. a photon event. The number of photoelectrons in each bunch is obtained from a Gaussian distribution having 30000 photoelectrons as average with σ of 6000 photoelectrons. These photoelectrons were then distributed over the face of the CMOS detector. The footprint of each of photon events (i.e. the photoelectrons) were distributed over the area of 5 X 5 CMOS pixels following a 2-D symmetric Gaussian probability distribution with σ of 0.7 CMOS pixel. Another Poisson distribution was invoked to obtain actual number of photoelectrons in a CMOS pixel. This number of photoelectrons was then divided by 20 to convert the photoelectrons in the unit of counts. Hence a photon event would correspond to a Gaussian distribution of average 1500 counts with sigma of 300 counts.

To describe a data frame, suppose the frame acquisition rate is 20 frames/ second. So for $1/20^{th}$ of a second, the detector will be exposed and the counts stored. Then this information is read out and an image is formed. This is a single data frame. After the entire observation time, centroids in all such data frames are found out. These centroids correspond to the position of the incoming photons. The final image is constructed with all these locations of the photons. A data frame is basically an array with array positions corresponding to the pixel and the number stored there are counts.

Reconstruction of the image

The reconstruction of the image from UVIT data frames involves two critical steps:

i. Detection of the photon events within a data frame.
ii. Calculation of the event centroid for the detected events.

Three event detection algorithms or windows were used for this purpose namely, 3-Cross, 3-Square and 5-Square. These algorithms scan the data frame and compare value of each pixel to its surrounding pixels. The definition of surrounding pixel varies for these algorithms as shown in the following figures:

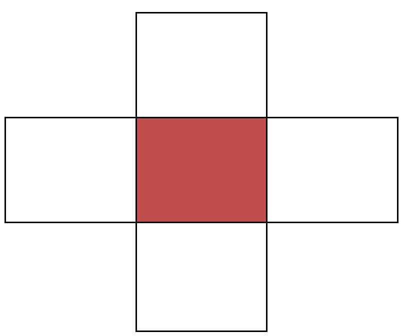


Figure 2: 3-Cross algorithm uses the adjacent single pixels along rows and columns from the shaded central pixel.

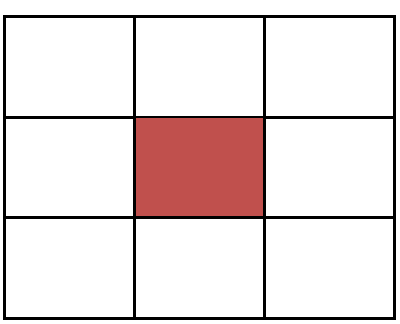


Figure 3: 3-Square algorithm uses the surrounding 8 pixels in the shape of a 3X3 matrix

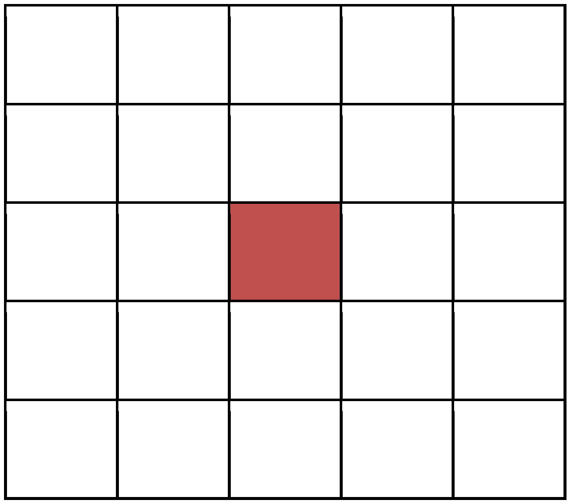


Figure 4: 5-Square algorithm takes surrounding 24 pixels in the shape of a 5X5 matrix.

Detection of photon events

To detect photon events in a data frame, each of the previously mentioned algorithms applies the following three criteria:

- A pixel may be a candidate of a photon event if its value is larger than surrounding pixels contained in centroid window as shown below.

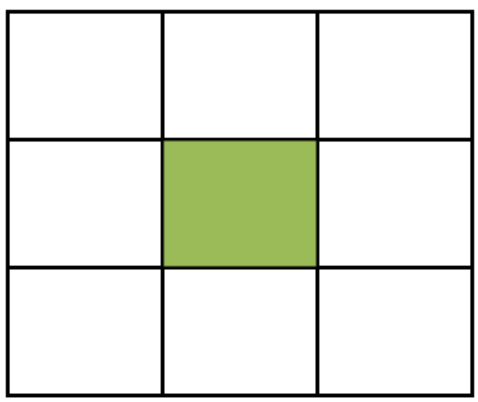


Figure 5: The shaded pixel would be the candidate if its value is greater than all the other 8 pixels in this 3-Cross window.

- The value of this central pixel must exceed a minimum energy threshold to discard the fake events due to random variation in the background.

- The total energy of the photon event i.e. the sum of all the pixel values in the respective algorithm shape, should also exceed some threshold depending on the window.

Too low a threshold will find non-real "events" in the non-illuminated parts of the detector. On the other hand, too high a threshold will begin to eliminate legitimate counts that make up the desired image. So we had to optimize this, and the minimum threshold value of 150 for the central pixel and 450 for the shape-summed value was adopted.

In case if two central pixels of a photon event candidate have equal values, it would not be considered as a photon event, even if it were a genuine footprint. This would lead to a loss of 0.6% of the total events. Event centroids are later calculated using the centre of gravity method (Michel et al. 1997) following the various algorithm pixel configuration. Just as we find the centre of gravity by the following method:

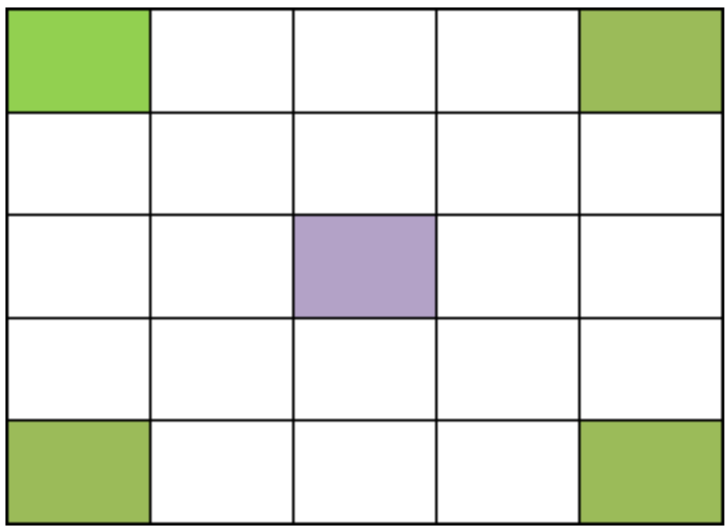
$$C.G. = \frac{\sum m_i x_i}{\sum m_i}$$

where x_i are the positions of the *i*-th body with mass m_i . Similarly we can define the centroid of the photon event in the following manner:

$$C = \frac{\sum c_i x_i}{\sum c_i}$$

where c_i are the counts in the pixel number x_i. The limits of the summation will depend on the algorithm shape.

Another important factor that would affect the imaging performance of the system is the presence of another photon event in the neighborhood of one event in a data frame. The situation is referred as "*Double Photon Events*". In such cases, the footprints of the two events would mix up and this would lead to a miscalculation of the event centroid, thus affecting the angular resolution. Moreover, if the second event is very nearby to the first one, then one of them might remain undetected. These multiple overlapping photon events would b a major source of concern especially in the case of extended sources and it is highly desirable to keep trace of such events. For this purpose, another threshold is imposed called the ***Rejection Threshold***. It is defined as follows:



We have the central shaded pixel as the event centre. We would then create a 5 X 5 square matrix and locate the four corners as shown in the green shade. Out of these four corner pixels, the difference between the highest and lowest pixel counts is defined as the Rejection Threshold. For genuine single photon events, this difference would be expected to be very low, however the presence of another photon in the vicinity would raise this value. Hence the high value of the rejection threshold, i.e. "*Corner Maximum – Corner Minimum*" would be a fair indication of double photon events.

Errors in Centroid Determination

In addition to random errors, associated with the noise and background variation (Michel et al 1997), this method also put a systematic bias over the calculated values of the centroids in the form of "***Fixed Pattern Noise*** *(FPN)*" (Dick et al. 1989; Michel et al 1997). The FPN is visible in the reconstructed images in the form of a regular grid structure superimposed on the image with a periodicity of one CMOS pixel. There are various factors that can cause FPN, however the main reason of FPN in reconstructed UVIT images is the exclusion of wings of footprint of a photon event by pixel configuration used by various centroiding algorithms. As the simulated photon event footprints have FWHM of ~ 1.65 CMOS pixel, the wings of the energy distribution would be left out by 3-Cross and 3-Square algorithms while 5-Square algorithm would collect almost all of it. Therefore FPN is clearly visible in 3-Cross and 3-Square images but not in 5-Square image.

To remove this error, we used a correction table provided by Mudit Srivastava from IUCAA for the images reconstructed using 3-Cross and 3-Square algorithms.

Simulations

For the simulations, we used the image of M51 galaxy from the GALEX data archive as our input image. The image had a input-scale of 0.5 arc-sec per pixel. We took a frame acquisition rate of 30 frames per second with an integration time of 3300 seconds. Hence we had a total of 99000 data frames in which the photons were randomly distributed. As stated earlier, the CMOS pixel-scale was taken as 3 arc-sec and it had a total of 512 X 512 pixels. The reconstructed images had a pixel-scale of 0.5 arc-sec. To find the centroids, we used a software provided to us by Mr. Joe Postma, University of Calagary, Canada. The input image, the reconstructed images and the ratio images are shown below. One thing should be kept in mind is that before taking the ratio of two images, both of them was convolved with a Gaussian function of sigma equals to 1.0 arc-sec. Colored circles are marked in the images around three of the bright sources to compare with the subsequent images and see the effects of photometric distortion, if there are any. The following steps are executed to remove the photometric distortions:

1. The image of the M51 galaxy is taken as shown in Figure 6. Let it be IG

2. But the actual positions of the photons are found out after applying the Poisson statistics (Figure 7). Let it be IG0.

3. From the IG0, we reconstruct the image I_UVIT using the centroid finding software. (Figure 8)

4. To compare IG0 and I_UVIT, we convolve both of them with a Gaussian of sigma 1 arc-sec. (Figure 9, 10)

5. The ratio of these two convolved images is taken (Figure 11). In the ratio image, the presence of structures with ratio values deviating from unity clearly suggests the presence of photometric distortions. The regions around the circled areas clearly shows values much greater and less than one showing the effects of bright sources in their neighborhood. So we proceed in the following manner to reduce these distortions.

6. The reconstructed image in the first phase, i.e. I_UVIT, is taken as the input image now and the entire simulation procedure repeated.

7. After applying the Poisson distribution, the actual positions of the photons are found out (Figure 12). Let it be I0.

8. From this I0, using the centroiding software, I1 is reconstructed. (Figure 13).

9. We now convolve I0 and I1with a gaussian of sigma 1 arc-sec and get I0C (Figure 14) and I1C (Figure 15) respectively.

10. We now take the ratio of I0C and I1C and call it IR1 (Figure 16). This is the correction matrix.

11. Now to see whether this correction matrix is the real one or not, we form another image called I2 = IR1 X I1 (Figure 17).

12. We expect this image to be similar to I_UVIT. So we convolve I2 and I_UVIT and take the ratio (Figure 18). We observe that the structures which were present in the previous ratio image, are missing and the values are closer to unity throughout the image.

13. So we are now confirmed that the ratio IR1 is the right correction matrix. We now multiply I_UVIT with IR1 to get I3 (Figure 19).

14. To check whether this reconstructed image I3 is similar to our input image IG0, we convolve each of them with a gaussian of sigma 1 arc-sec and then take the ratio. We see that the values are more or less unity with very less structures thus decreasing the photometric distortions.

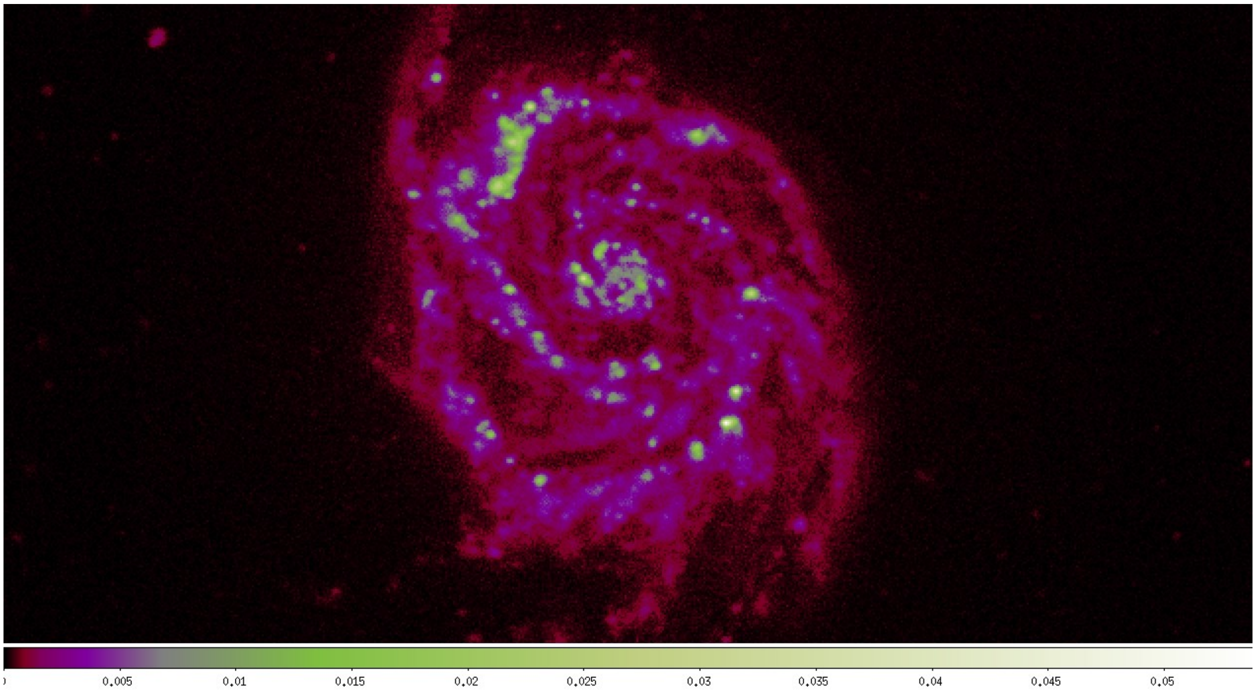


Figure 6: GALEX image of M51 galaxy which was used as input image. Let this be IG.

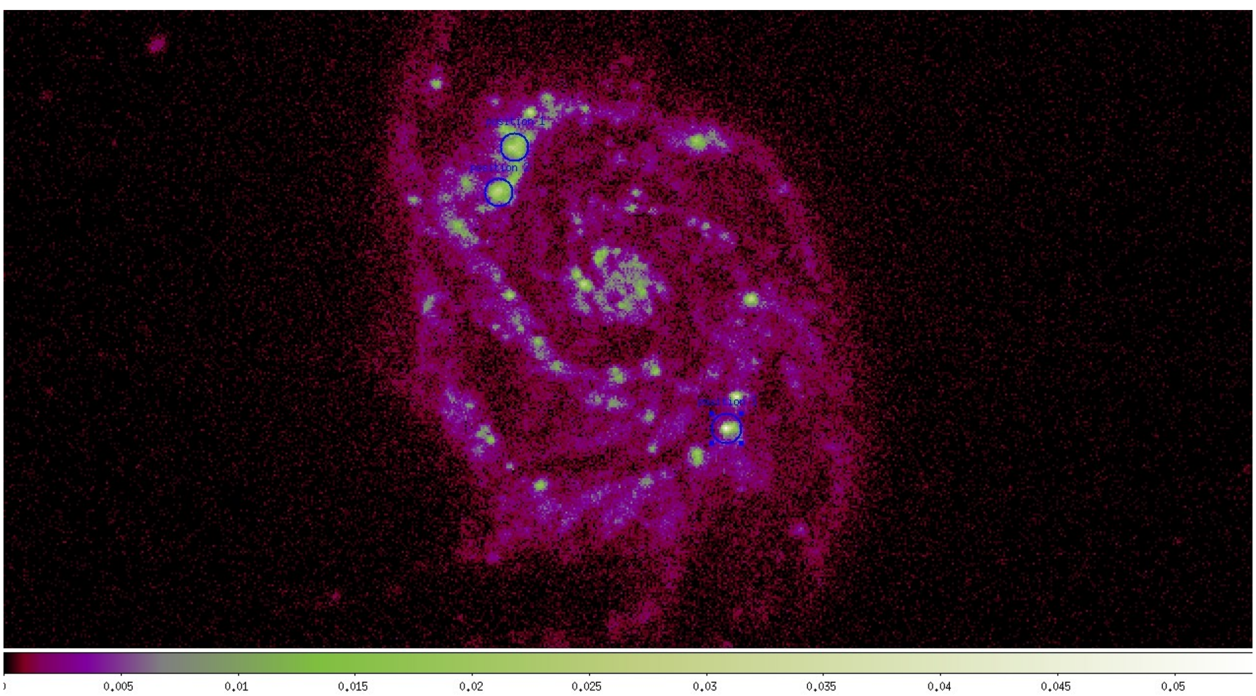


Figure 7: After applying Poisson statistics to Fig 6, the actual position of the photons is this. Let this be IG0.

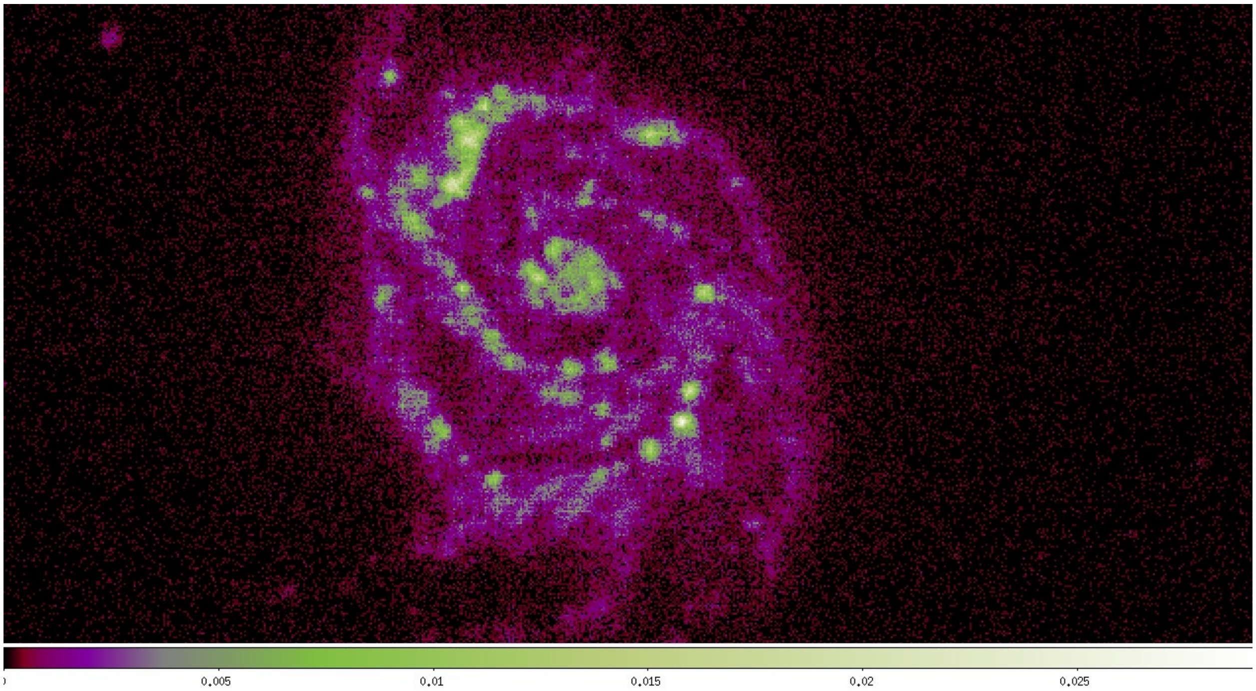


Figure 8: Using the centroid finding software, we reconstruct the image. Let this be I_UVIT.

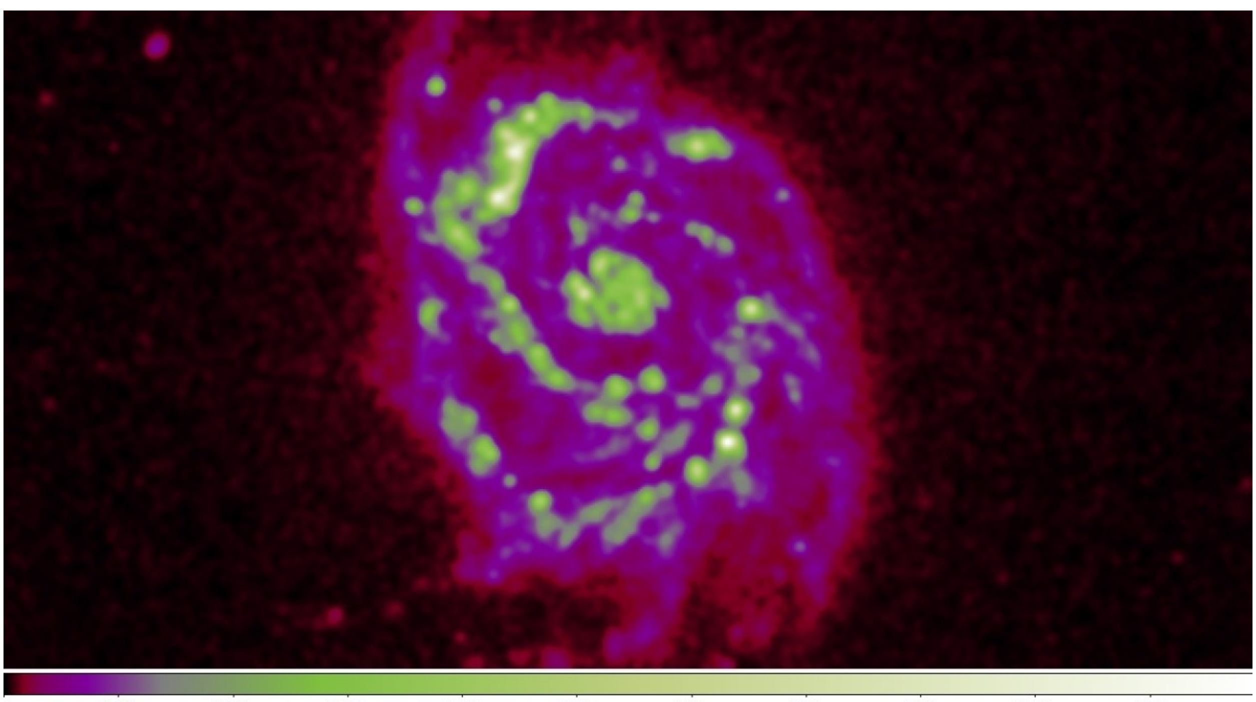


Figure 9: IG0 (Fig 7) convolved with the Gaussian.

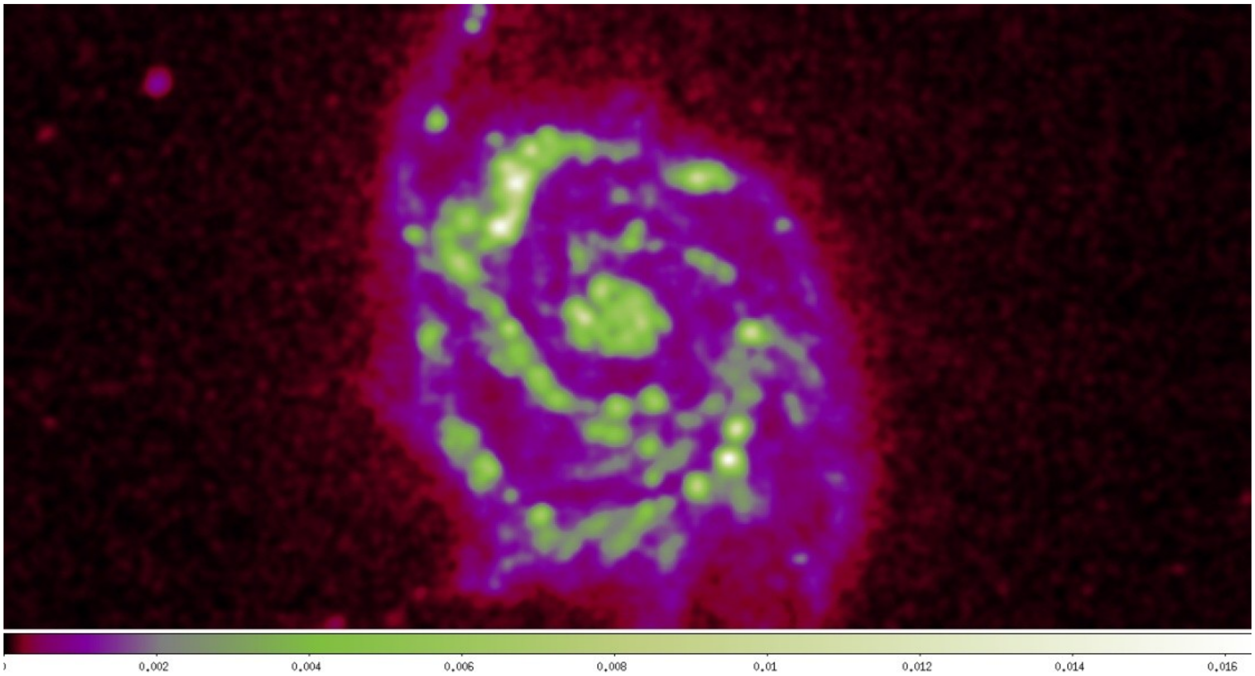


Figure 10: I_UVIT (Fig 8) convolved with Gaussian

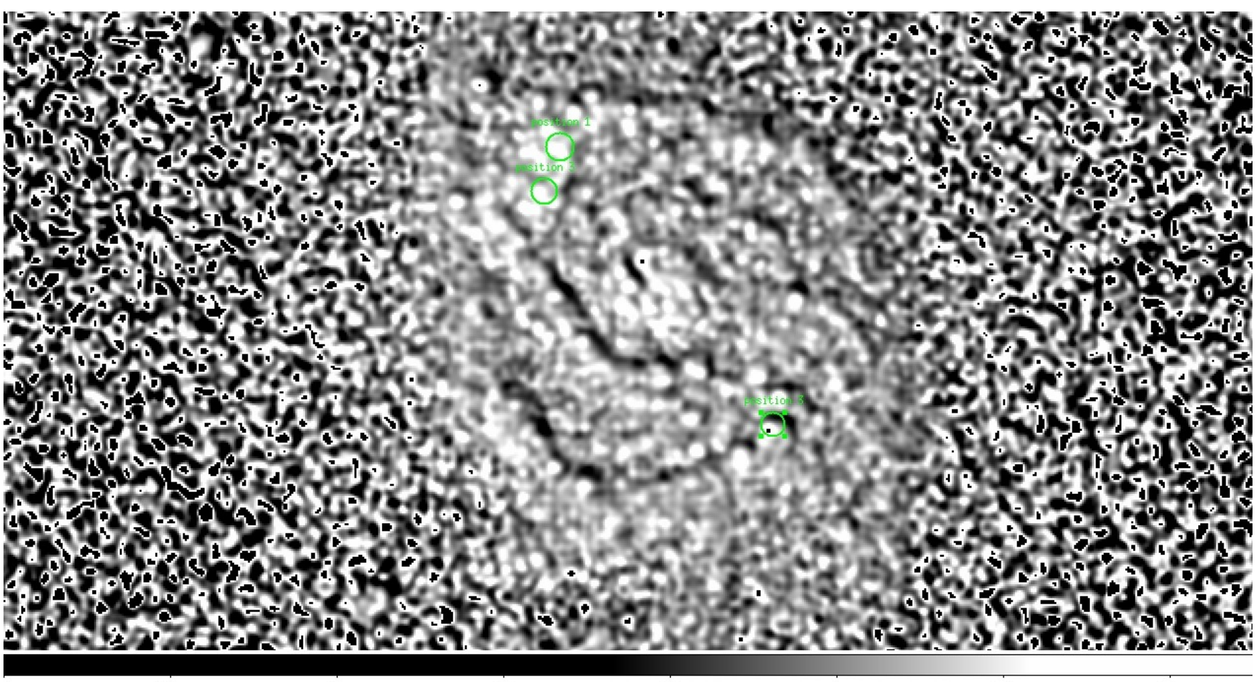


Figure 11: This is the ratio of the above two images (Fig 9 & 10).

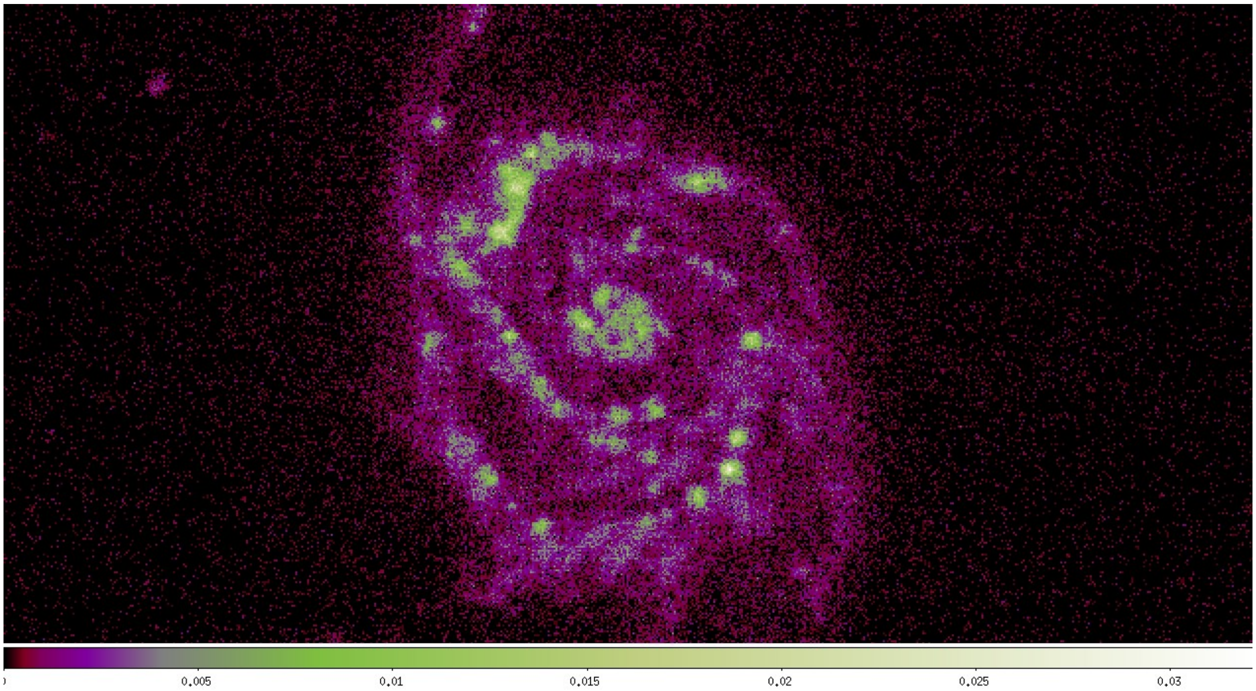


Figure 12: After applying Poisson statistics to Fig 8, we get this image, I0.

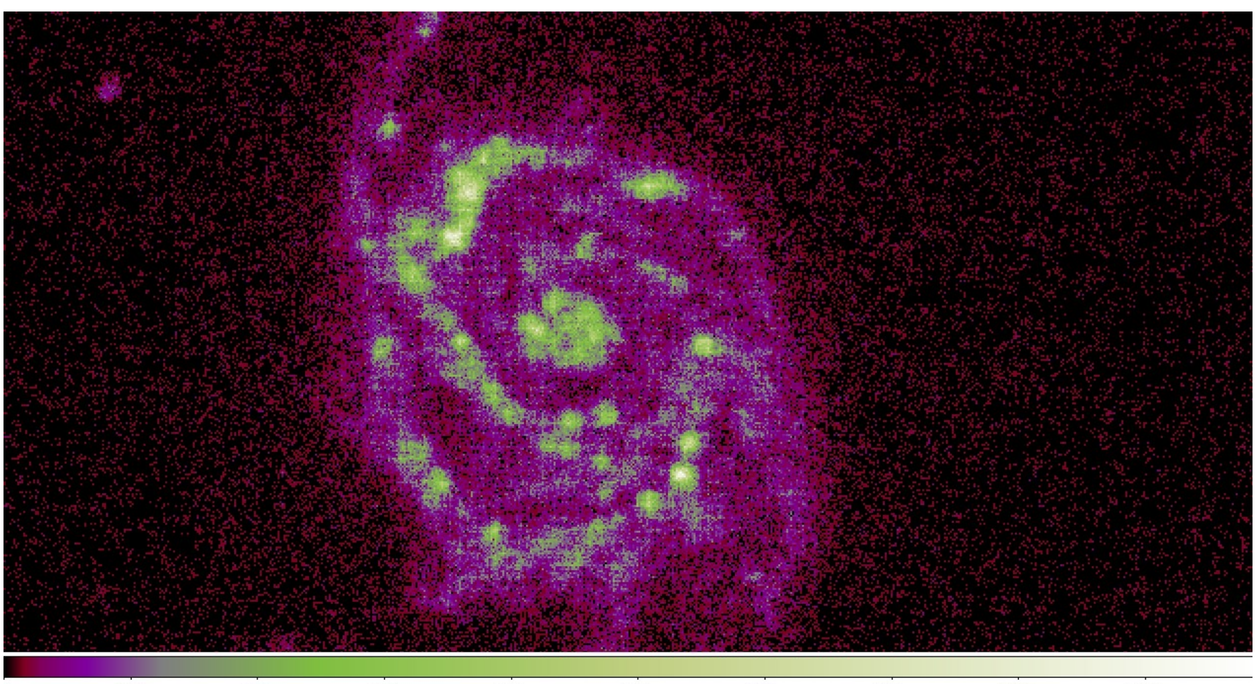


Figure 13: Reconstructed image using centroiding software, I1.

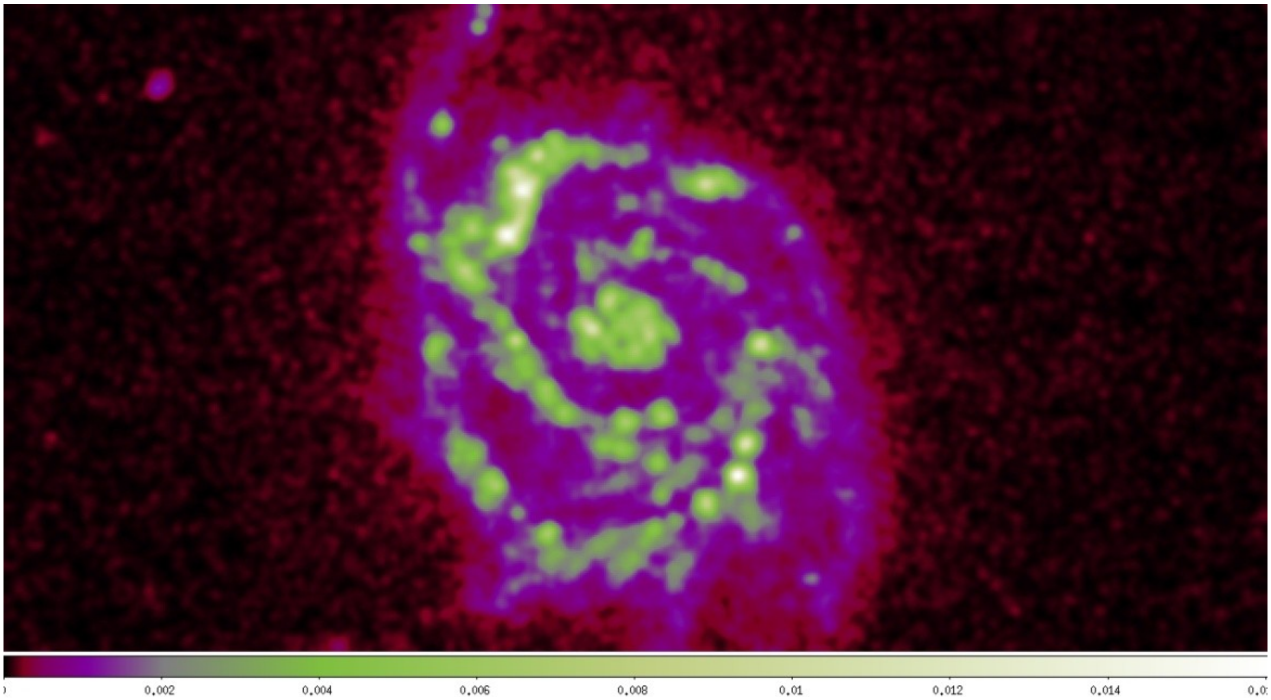


Figure 14: Fig 12 convolved with Gaussian : I0C

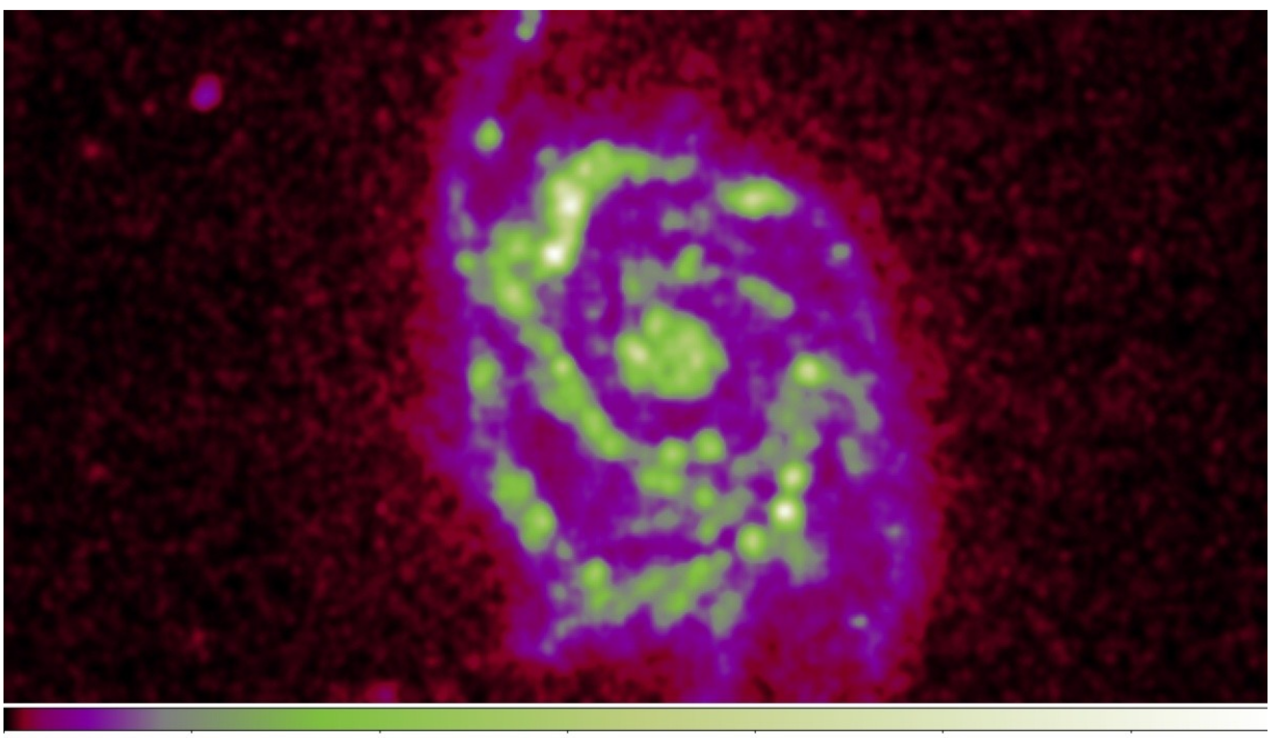


Figure 15: Fig 13 convolved with Gaussian : I1C

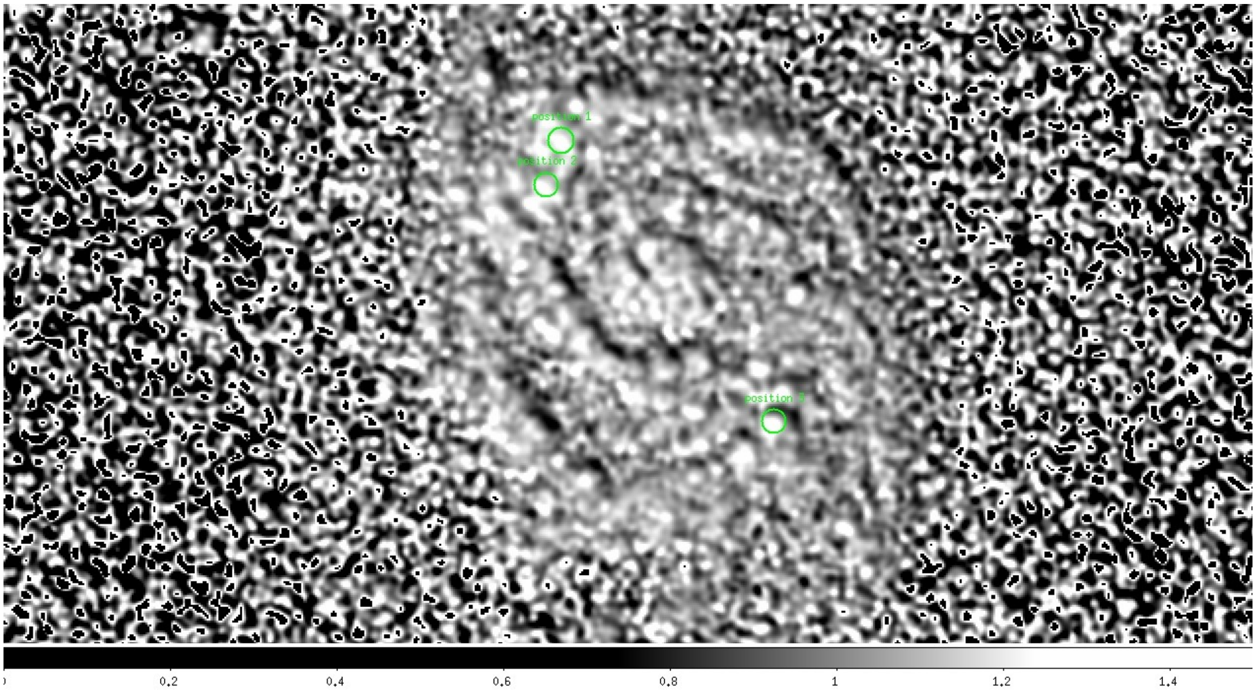


Figure 16: IR1 = ratio of I0C (Fig 14) and I1C (Fig 15)

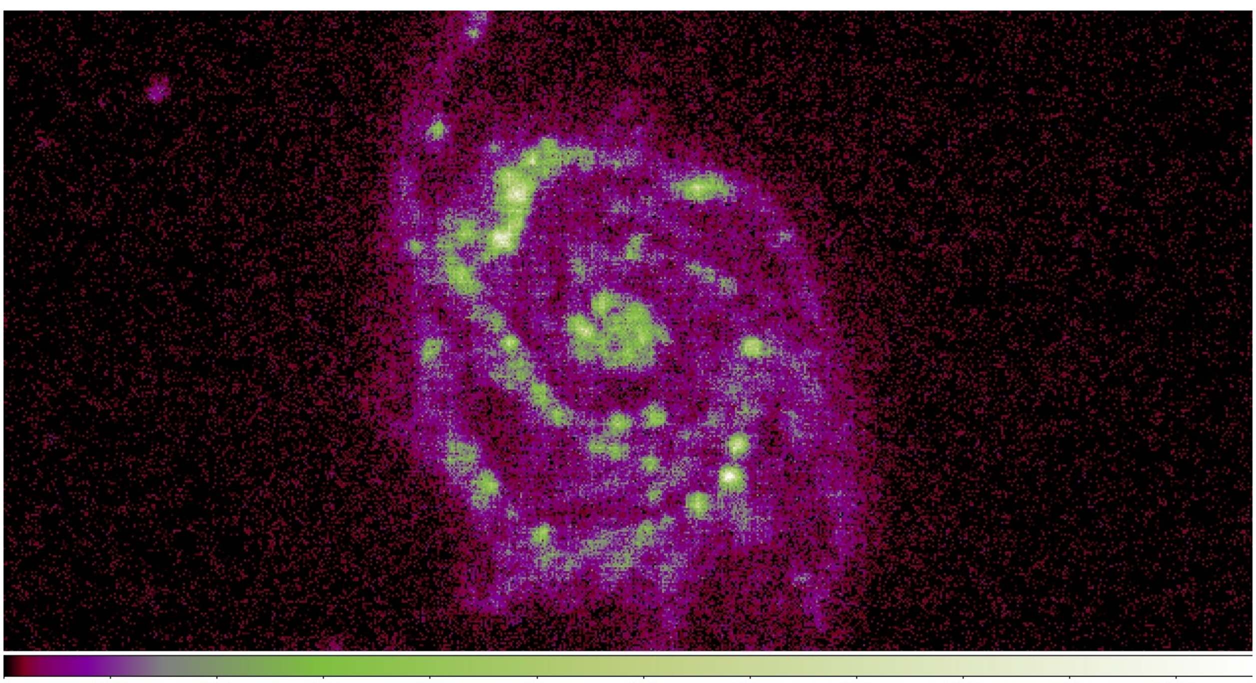


Figure 17: Image I2 = IR1 (Fig. 16) X I1 (Fig. 13)

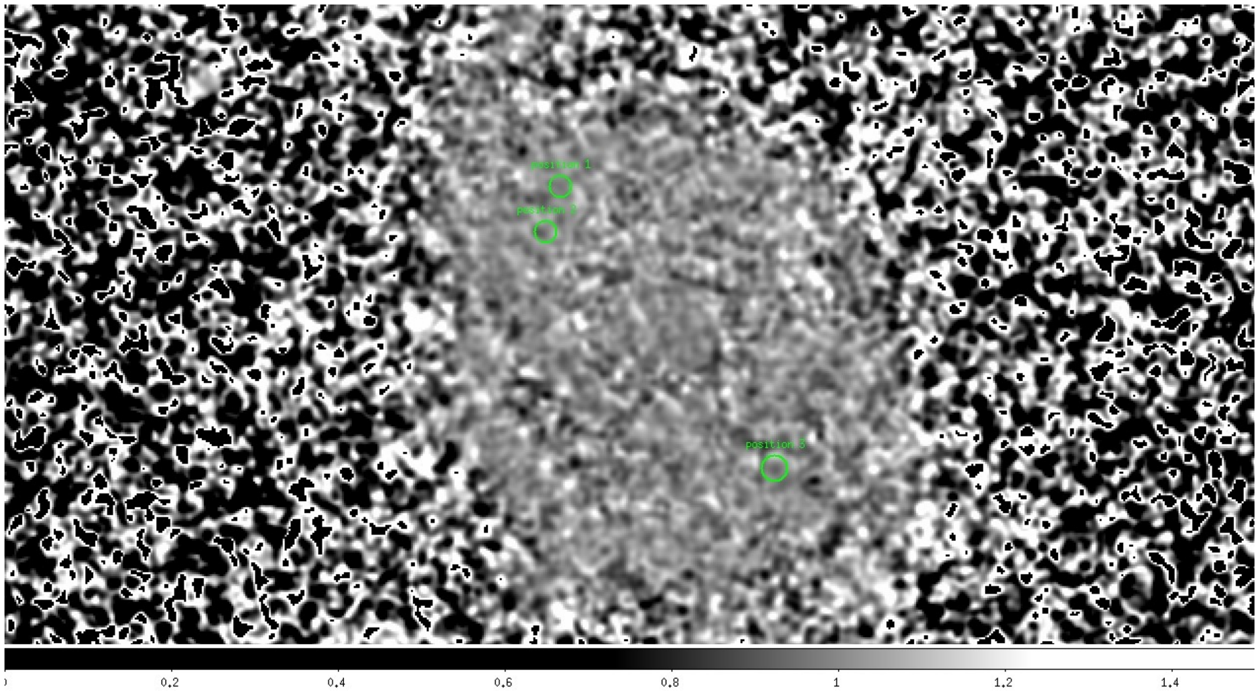


Figure 18: Ratio of I2 (Fig. 17) and I_UVIT (Fig. 8) after convolving each with a Gaussian.

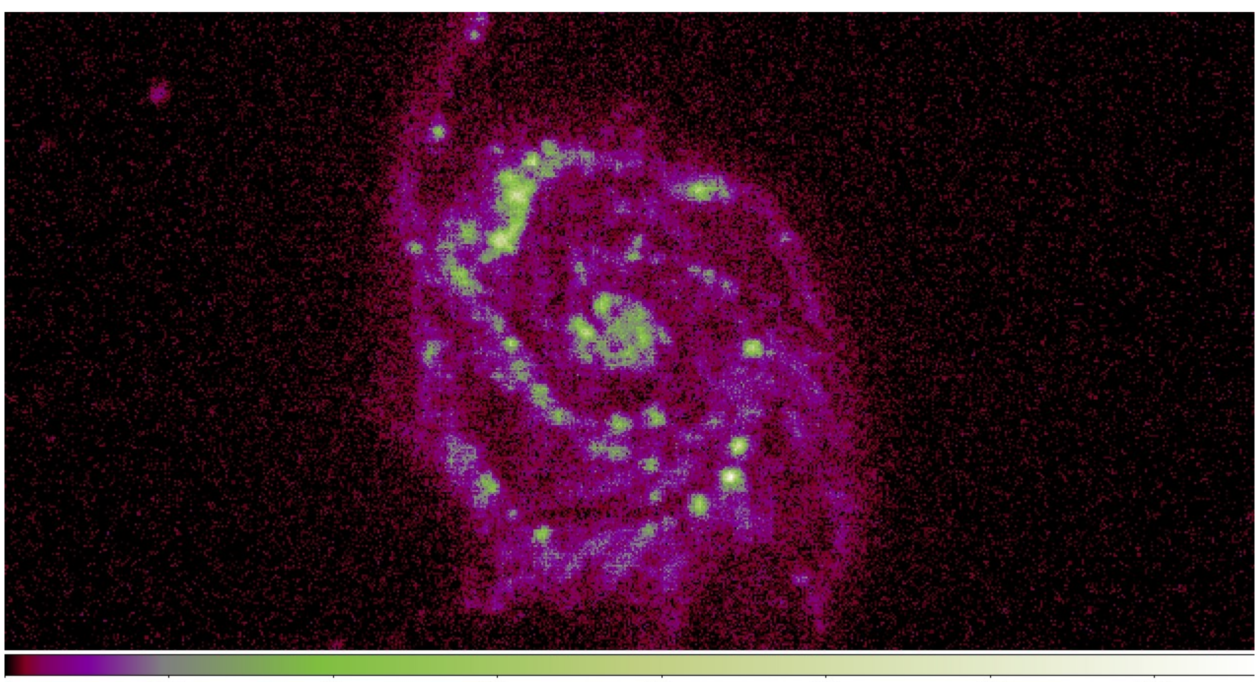


Figure 19: I3 = IR1 (Fig. 16) X I_UVIT (Fig. 8)

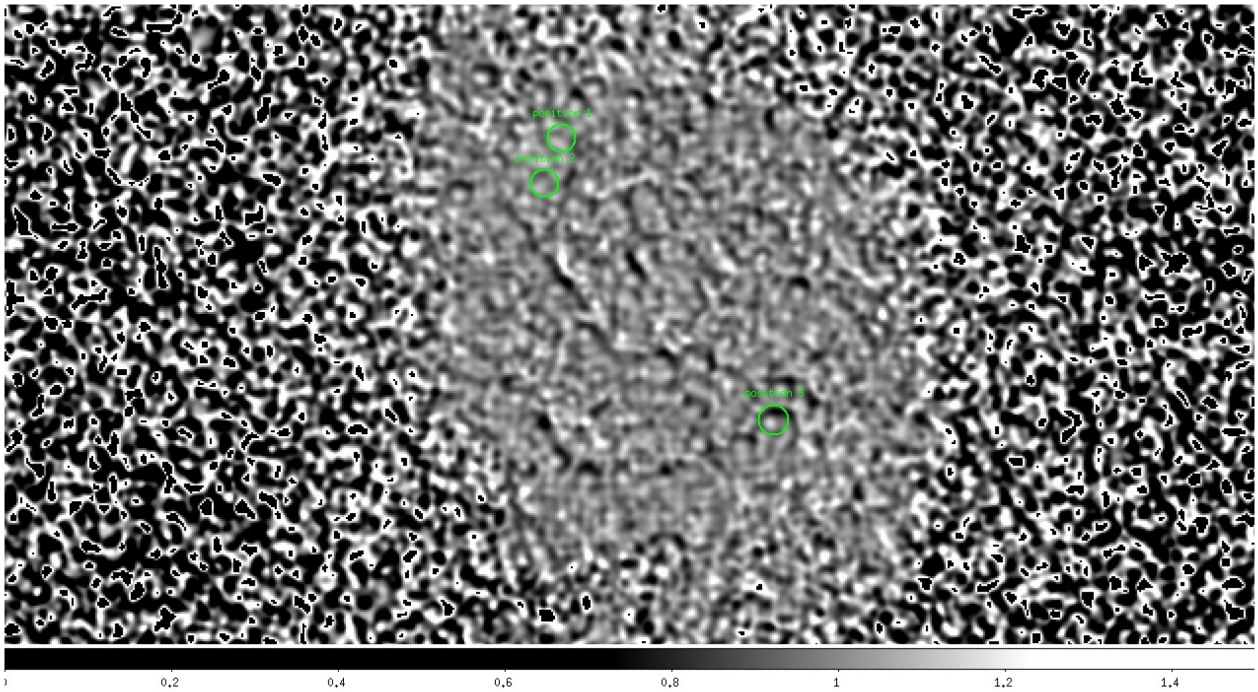


Figure 20: Ratio image of I3 (Fig. 19) and IG0 (Fig. 7) after convolving each with a Gaussian.

Conclusions

The following conclusions can be drawn:

- Initial reconstructed image had a high level of photometric distortions.

- The reasons for photometric distortions can be attributed to Poisson fluctuations as well as the presence of bright point sources. So, a correction matrix was formed by taking the ratios assuming that the effect of fluctuations are the same on IG0 and I0 respectively.

- Final reconstructed image had a lower level of photometric distortion.

So the procedure we used might well be applied to obtain a faithful image from UVIT.

As a plan for future work the following can be done:

- The simulations from the given observed image can be done with 10 times the exposure done here, which would be the actual observation time-scales. It is expected that this would reduce the effect of fluctuations.

- To check that with the "corrected image" as the input, the simulated output image is the observed image. This is the most direct verification of the procedure.

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