The H II Region 30 Doradus

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August 8, 2006

Abstract

A mosaic image of the 30 Doradus nebula was created from SOAR data. Using this mosaic along with data from HST, a map of the emitting layer thickness of 30 Doradus was created. The thickness of the emitting layer at the brightest parts of the nebula was found to be 0.301 pc, and the star cluster R136 was found to be 44.7 pc in front of the nebula along the line of sight. A fortran program was modified and expanded to provide a faster and easier way to see what kind of HST data are available.

1 Introduction

Astronomers endeavor to answer the big questions: what happened early in the universe, how things came to be how they are. One major part of this is the formation of early stars in distant galaxies. How did they form, from what, and why? Unfortunately, it is extremely difficult to view this phenomenon first-hand, as the distant galaxies in which early star formation occurs are too far and too small to image in sufficient detail. Thus astronomers must look closer to home in their effort to understand distant processes. Fortunately, stars are still forming nearby in regions where it is possible to look at the process.

The Milky Way contains thousands of giant molecular clouds within its spiral arms, which provide the necessary location and materials for star formation [2]. These clouds have masses on the order of $10^4 - 10^5 M_{\odot}$, span 100s of lightyears, and have temperatures on the order of 20K [3]. Stars form when portions of the gas in these clouds collapse [2], and the entire cloud converts into stars after $10^7 - 10^8$ years [3].

Once stars have begun forming in a cloud, the state of the gas changes. High mass stars emit radiation at energies above 13.6eV, which breaks up molecules and ionizes hydrogen, forming ionized H II regions [2]. Equation 1 describes the state of ionization equilibrium at each point in the gas [3].

$$N_{H^0} \int_{\nu_0}^{\infty} \frac{4\pi J_{\nu}}{h\nu} a_\nu(H^0) \, d\nu = N_e N_{H^+} \alpha(H^0, T_e)$$ (1)
where \( N_{H^0} \) is the density of neutral hydrogen atoms, \( J_\nu \) is the mean intensity of radiation, \( a_\nu(H^0) \) is the ionization cross-section of neutral hydrogen, \( N_e \) is the density of electrons, \( N_{H^+} \) is the density of ionized H II, and \( \alpha(H^0, T_e) \) is the recombination coefficient. However, stars do not emit infinite amounts of radiation, so the H II region only extends as far as the ionizing photons can reach.

Stars emit their radiation in all directions, thus H II regions form spherically around stars, creating aptly named Strömgren spheres. The edge of these spheres is the barrier between ionized and neutral hydrogen, and their radius is the distance at which the number of ionizations per unit time, integrated over the whole nebula, equals the number of recombinations. This is found by

\[
\int_{\nu_0}^{\infty} \frac{4\pi L_\nu}{h\nu} = \frac{4}{3} \pi R^3 N_e N_{H^+} \alpha(H^0, T_e),
\]

where \( L_\nu \) is the luminosity of the star per unit frequency interval [3].

Strömgren spheres embedded in a molecular cloud are hidden by the gas and dust surrounding them, and cannot be observed in optical wavelengths. However, stars sometimes form near the edges of molecular clouds, and their Strömgren spheres will have a radius that extends beyond the edge of the cloud. These H II regions are known as blister type H II regions, because they have “popped” and are spewing gas and radiation out into space.

Blister type H II regions that are on the near side of molecular clouds allow study of star formation and the environment in which it occurs. Astronomers look at the radiation from different ionized elements to determine the temperature of the gas, the electron density, the reddening, and various other factors that are a part of understanding the process of star formation.

Nearby H II regions include the Orion Nebula, the Omega Nebula, and NGC 3603, all within the Milky Way. These nebulae provide a close-up look at what happens as stars are created, however galactic nebulae cannot compare in size to the vast structures that formed early stars and galaxies. 30 Doradus, a star-forming region in the nearby Large Magellanic Cloud, is close enough to yield detailed images and spectra, thus allowing for comprehensive study. However, at 587 lightyears across, it is larger than any galactic nebula, and since it is in between galactic nebulae and starburst galaxies, it is the next step in the effort to understand larger and larger star-forming regions [1].

2 Mosaic Image of 30 Doradus

Michigan State University is a partner in the Southern Astrophysical Research (SOAR) Telescope, located in Cerro Pachón, Chile. SOAR is a 4.1 m optical telescope, with capabilities
reaching into the near infrared [4]. SOAR captures the sharpest images after Hubble, making it the most precise telescope on the ground [5].

The SOAR Optical Imager (SOI) instrument has a detector comprised of two CCDs and four amplifiers. This configuration yields a gap in the image, requiring multiple images, slightly offset, to fully cover a region. SOI has a field-of-view of 5.26’ at 0.0767” per pixel. Images can be taken using any of the filters mounted in the two filter wheels [4].

In December 2005 and January 2006, Eric Pellegrini and Jack Baldwin took 11 images of the 30 Doradus HII region using the Hα (λ = 6563Å) filter on SOI. In December 2005, they also took three images of 30 Doradus using a continuum filter with a central wavelength of 6115Å [6]. These images were compiled into two mosaic images during summer 2006, a larger one comprised only of the data from the Hα filter, and a smaller one which also included the data from the continuum filter. The larger mosaic was submitted to the Astronomy Picture of the Day (http://antwrp.gsfc.nasa.gov/apod/astropix.html).

Creating the mosaic image was a multi-step process. The individual images had to be reduced, lined up, scaled, and subtracted before they could finally be put into one image. The reduction was done in the Image Reduction and Analysis Facility (IRAF), using a script by Nathan DeLee. Reducing an image is an important step in preparing an image for analysis, as it removes irregularities in the image arising from telescope abnormalities and subtracts from the image a background due to extra current in the CCD. The raw data are split into four frames, one for each amplifier, and during the process of reduction these four frames are combined into one image.

Once the individual images have been reduced, it is important to check that light has been recorded uniformly across the detectors, and that there is not any unseen gradient. The program daophot assists in checking this. It finds the same stars in multiple images, and calculates their photometry. Thus, if a star looks different when recorded in different places on the detector, the chips add an extra effect that must be accounted for when combining the images. This also serves as a warning system if the chips begin to malfunction. daophot was ran on the images, and no such effect was found, showing that the chips were recording data as they should.

After the images are ascertained to be free of strange effects coming from the chips, they must be lined up so that the same features lie in the same place in each image. This requires a reference image to be chosen from the data, around which all the others are placed. The reference image must be somewhat centralized, and share as many stars with the surrounding images as possible. It must be placed in a blank image with the same dimensions as the final mosaic. Then, the other images can be lined up around the reference image using an IRAF package called alinear. This package takes a list of stars from the reference image and fits them to the image that needs to be lined up, using the first two stars on the list, which the user identifies. The newly transformed image it outputs has the same coordinates
as the reference image. This must be done for each image.

The lined up images must be scaled so that the stars have the same brightness in each image and the background is as uniform as possible. This is done in two steps: scaling the stars then subtracting the background. To scale the stars, their magnitude can be determined using the IRAF task `imexam`. With `imexam`, the ‘a’ key will print the aperture photometry of the star, including its magnitude and flux. Doing this for at least six stars will allow an average ratio to be determined for an image. The image can then be scaled with the IRAF task `imarith`. Each image must be scaled to the reference image so that their average ratio is 1.

The scaled images are almost ready to be made into the mosaic, but the final step is making the background uniform. The background level includes light both emitted and scattered by the Earth’s atmosphere, which changes from image to image depending on atmospheric conditions. Another IRAF task called `imstat` can be used to determine the amount of subtraction necessary to bring the background to the level of the reference image. `imstat` will print statistics on a specified region of an image, including something it calls “midpt,” which is the estimate of the median of the pixel distribution. Subtracting the “midpt” of the image from the “midpt” of the reference image for several small sections across the image will determine the amount that needs to be subtracted from each image so that all images have the same background level at the same point on the sky. This subtraction can also be done with `imarith`.

The accuracy of both the scaling and the subtraction can be checked by using `imexam` and `imstat` on the scaled and subtracted images, respectively. It can also be checked by using `imarith` to physically divide the scaled images from the reference image then check if the average flux of the stars is 1, or to subtract the subtracted images from the reference image then check if the average of the background values is 0.

Because the images have abundances of blank space that should not be included in the mosaic, bad pixel masks must be created. Bad pixel masks use 0's to indicate good data to include and 1's to indicate bad data to leave out. Masks can be created with the IRAF task `imcalc`, which will make the masks given the good and bad regions.

After the images have been lined up, scaled, and subtracted, they are ready to be put into one mosaic image, taking into account the bad pixel masks. The IRAF task `imcombine` will combine all the images into one, given certain parameters. The command used to create the mosaic was

```
imcombine @images Mosaic.fits masktype=goodvalue maskvalue=0 outtype=real \
combine=average bpmasks=Mosaic reject=none
```

where `@images` was the list of images to combine, `combine=average` meant to create the mosaic by averaging overlapping images rather than finding their median, and `bpmasks=Mosaic` created a bad pixel mask for the output mosaic, called Mosaic.pl. In the end, the mosaic only
Figure 1: The final mosaic of 30 Doradus, created from 10 SOAR images taken in December 2005 and January 2006.
Figure 2: (a) The transmission curve for the Hα filter for the SOI instrument, centered at 6559Å, with a bandwidth of 64Å. (b) The transmission curve for the continuum filter used in December 2005, centered at 6115Å, with a bandwidth of 135Å. Figures courtesy of [6].

included 10 of the 11 images. The first image taken in January was very blurry, and after some investigation, it was discovered that the telescope had jumped during the exposure. The final mosaic of 30 Doradus is shown in figure 1.

While the mosaic shown in figure 1 is a gorgeous example of SOAR’s imaging capabilities, it is not an image that can be used for science. It was taken with a narrowband filter centered at 6559Å, with the intention of capturing the Hα emission from 30 Doradus [6]. However, the image is contaminated by background radiation including light from Earth’s atmosphere, light from nearby stars scattering off dust particles that are present among the gas of 30 Doradus, and by bremsstrahlung and bound-free emission from the hot gas. In order to use the mosaic for science, this background must be subtracted. Thus, three images covering a smaller area were taken in December using a broadband filter centered at 6115Å [6]. This filter was chosen because it is close enough to the 6563Å emission line from hydrogen that the intensity of the continuum light should be about the same, but far enough that it does not include the line in its bandwidth. The transmission curves from these filters are shown in figure 2.
Figure 3: The mosaic of 30 Doradus with the continuum subtracted. This image can be used for science. While the stars do not subtract perfectly, the scaling of the continuum was done so that the stars were subtracted on average.

The continuum subtraction was a two-step process. First the continuum images were mosaicked in the same way that the Hα images were. Then the continuum mosaic was scaled to the Hα mosaic using the flux from the stars, as the radiation from the stars should be approximately equal in the two different filter ranges. Some stars are hotter, and thus brighter in the continuum range, and some are cooler, thus brighter in the Hα range, but they average out to be equal, and this is the principle on which the scaling is done. The final image produced is not as visually appealing as the larger mosaic, as the subtraction of the stars is never perfect, rather done as an average. In the continuum-subtracted image, shown in figure 3 the average flux from the stars is 0, and the light is coming solely from the nebula.

3 Hubble Space Telescope Archives

Another important tool for studying 30 Doradus is Hubble Space Telescope (HST) data. HST produces the most precise optical images available, thus access to HST data is key...
to getting the most information about an object. In order to utilize HST data, or submit a proposal for observing time on HST, it is necessary to know what currently exists: how many images, what they look at in relation to SOAR images, what instruments they were taken with, and what filters and wavelengths they used.

In an effort to ascertain what kind of HST data are available, a list of datasets, along with information on their target name, RA, Dec, exposure time, instrument, instrument configuration, apertures, filters, central wavelength, bandwidth, proposal ID, and position angle of aperture was downloaded. Each of these pieces of information yields a different, and useful, insight into what is out there:

- **Target name:** Name, if any, of what the proposer was imaging. This can indicate whether the dataset was intended to be used for science or calibration.
- **RA, Dec, position angle of aperture:** Indicates exactly what region of the sky was imaged, including the angle of the telescope.
- **Exposure time:** Important for discerning if image reaches faint enough levels that the faint nebular emission is detected, or whether only the brighter stars will be visible.
- **Instrument:** The individual instrument on HST that was used to take the data.
- **Instrument configuration:** Which camera, if a specific one, on the instrument was used.
- **Apertures:** The setting of the camera, which can alter the area of the sky that was imaged.
- **Filters, central wavelength, bandwidth:** Can be used to determine whether the individual dataset covers specific emission lines of interest.
- **Proposal ID:** Can be used to find the proposal for which the data was taken, which can be used to determine whether the proposer might be interested in a similar analysis.

However, this information comes in list form, which can be difficult to use in a situation where often hundreds of images are included. Thus, an existing fortran program was modified to help visualize this information. The original program took the RA, Dec, position angle of aperture, and instrument, and plotted the location and shape of the dataset for use as an overlay over an image of the nebula. However, the program did not include all available instruments on HST, nor did it take into account the instrument configuration or the aperture used.

As part of this REU project, the program was modified to include all the instruments available on HST, as well as to correctly plot each different instrument configuration and aperture. This provides a more accurate representation of the location of HST datasets on
the sky. A sample plot produced by the program is shown in figure 4. In addition, a feature has been added that allows the user to specify a wavelength that they are looking for, and the program will plot only data that include that wavelength. If the user does not care about this information, they can enter “0” and the program will not use wavelength as a criterion when plotting.

This information helps determine what to propose, if anything, to study with these existing HST datasets. It shows whether current data adequately cover the nebula, or if they leave large gaps unimaged. It also shows if the available data has been taken using filters and wavelengths that can be used for analyzing the nebula. Finally, it can be used to determine where the data are in relation to existing SOAR data, whether they complement each other, or if they are redundant. Since access to SOAR is far easier to obtain, SOAR data can be taken to work with existing or future HST data that becomes available.
4 Analysis of Mosaic

The final SOAR mosaic can be used to analyze the 30 Doradus nebula. It was used to measure the thickness of the emitting layer of Hydrogen. It can also be used to find the reddening of the nebula, which indicates the amount of absorption by dust. This can be found by looking at certain ratios that do not depend on electron density or temperature. After being de-reddened, this image could also be used to find $Q(H)$, or the amount of ionizing photons emitted by the central star cluster.

HST data, especially in the H$\alpha$ range, do not cover the nebula very completely. As figure 5 shows, there are many gaps between datasets that have not been viewed by HST. The SOAR mosaic image of 30 Doradus covers a more complete field of view, and is thus a good tool for studying the nebula as a whole. However, it is not flux calibrated, and this must be done prior to any analysis. For this, the HST data is a useful tool. HST data are calibrated extremely well, because there are no problems due to absorption, scattering, or image smearing by the Earth’s atmosphere. Scaling the mosaic data to HST data will calibrate the mosaic to units of intensity.

To scale the mosaic, it must be compared with HST data that overlaps with its field of view and was taken with an H$\alpha$ filter. Thus, four datasets were downloaded from the HST
Figure 6: The throughput efficiency for the F656N filter on WFPC2 as a function of wavelength.

archives, two of which were taken with an emission-line filter centered at 6564 Å. The other two datasets were taken with a medium band filter with a central wavelength of 5483 Å, which provided continuum information that was subtracted from the Hα data, just as was done for the SOAR mosaic.

Once the HST data were continuum-subtracted, it was necessary to convert them from units of counts s$^{-1}$ to units of intensity; erg s$^{-1}$ cm$^{-2}$ arcsec$^{-1}$. The conversion to intensity was done using the relation [7]

$$I = \frac{P_{\text{object}}}{2.3 \times 10^{10} (QT) \lambda},$$

(3)

where $P_{\text{object}}$ is the image, QT is the quantum efficiency, or total throughput of the telescope and filter, and λ is the wavelength of the light in question. The QT for the F656N filter on WFPC2 is shown in figure 6.

To convert the data to intensity, the parameters for 30 Doradus were substituted into equation 3, and the final scaling factor was

$$I = \frac{P_{\text{object}}}{2.3 \times 10^{10} (0.105) (6568.9)}.$$  

(4)

With the HST image converted to intensity, it was ready to be compared with the SOAR mosaic.
In order to scale the SOAR mosaic to the HST data, the two images needed to be lined up and resampled to the same pixel size on the sky. Thus, the HST image was rotated to match the SOAR image using the `alinear` task used while creating the SOAR mosaic, which also rebinned HST data to match the pixel size of the SOAR mosaic. The data were then blurred to match the resolution of the SOAR image so that a proper scaling could be performed. The SOAR mosaic and the HST data are shown in figure 7.

Once the HST image was rotated and blurred, scaling for the SOAR mosaic could be found by simply dividing the HST image by the SOAR image. This yielded a rather constant scaling factor of $1.85 \times 10^{-17}$. Multiplying the SOAR image by this factor calibrated it and made it ready for analysis.

With the calibrated mosaic image, the thickness of the emitting layer could be found by following the method used by Wen & O’Dell [8]

$$S(H\alpha) = N_e^2 \alpha^{eff}_{H\alpha} \frac{hc}{\lambda} L \frac{1}{4\pi(206265)^2}$$

where $S(H\alpha)$ is the surface brightness of the image and $\alpha^{eff}_{H\alpha}$ is the recombination coefficient for H\(\alpha\). This follows from the right-hand side of equation 1, which gives the rate of recombinations per unit volume. Equation 5 simply shows that the total light emitted in H\(\alpha\) from a unit area on the glowing face of the nebula is the integral, over the depth of the ionized region, of the rate at which recombinations produce H\(\alpha\) photons times the energy per photon. It is also assumed in equation 5 that $N_e = N_{H^+}$. Solving this equation for $L$ and applying it to the image yields a map of the thickness of the emitting layer of hydrogen. The emitting layer thickness of the brightest points was $L = 0.301$pc. The electron density of 30 Doradus was not known, but a typical density of $N_e = 450$ cm$^{-3}$ was assumed, as well as a typical H II temperature of 8,000 K.

With this map, the distance $R$ from the star cluster to the layer of emitting gas directly
Figure 8: Different views of the thickness of 30 Doradus. Note that the taller regions correspond to the bright areas of the nebula, and are concentrated around the central star cluster.
behind it can be calculated. By averaging the thickness of the area directly around the cluster, the thickness of the emitting layer can be interpolated. It is possible to then calculate $R$ by solving

$$\frac{Q}{4\pi R^2} = S(H\alpha) \frac{\lambda}{hc} \frac{\alpha_B}{\alpha_{H\alpha}}$$

(6)

where $Q$ is the total number of ionizing photons emitted per second by the ionizing star(s), $\alpha_B$ is the recombination coefficient for $H$ II to all excited energy levels. The left-hand side of equation 6 is the number of ionizing photons per second striking a unit area on the illuminated surface of the gas cloud. The right-hand side is the number of recombinations per second through the total thickness of the ionized gas layer behind that unit area. In a steady state situation, the recombination rate must equal the ionization rate. The distance was found to be

$$R = 44.7 \text{ pc.}$$

This analysis yielded a map of the nebula which can be displayed as a surface plot. Figure 8 shows the map from a few different angles. It shows the bright regions of the nebula above and to the right of the star cluster. The star cluster is the peak in the center of the plot. As would be expected, the regions experiencing the most ionization are those closest to the star cluster.

With more data and time, a more detailed analysis could be performed. The geometry shown in figure 8 shows the emitting layer thicknesses as though they are resting on a flat surface. The next step in creating the map would be to calculate the shape of the emitting layer, not just its thickness. This would provide a 3-dimensional view of the nebula. In addition, the electron density, a key factor in calculating the emitting layer thickness, was assumed here rather than calculated. With access to spectroscopic information covering either the entire nebula or large regions of the nebula, the electron density could be calculated, as could the temperature of the nebula.

5 Conclusion

A mosaic image of 30 Doradus was created from SOAR data. Using this mosaic along with data from HST, a map of the thickness of the emitting layer in 30 Doradus was created. This is the first step towards understanding the intricate structure of the nebula. With more time and data, a great deal more information could be extracted about the nebula. In addition, a fortran program was modified and expanded in order to provide a faster and easier way to see what kind of HST data is available.
References


