M63 From the Macalester Observatory

Alyssa M. Bulatek

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1 Introduction

M63 (NGC 5055), colloquially called the Sunflower Galaxy for its floral appearance, is a well-studied spiral galaxy at a distance of about 8.58 Mpc measured using the TRGB method by McQuinn et al. (2017). It is located at an RA of $13^{\mathrm{h}}15^{\mathrm{m}}49.3^{\mathrm{s}}$ and a declination of $+42°01'45.4''$. M63 has a warped spiral structure in neutral hydrogen that begins at the edge of the optical disk, where the rotational gradient goes from having little structure at small radii to having cohesive structure at large radii (Battaglia et al. 2006).

M63 is a good candidate for study with the Macalester Observatory because it is relatively bright (9.31 mag in the V band) and reaches a maximum elevation of approximately 87 degrees. Although its structure is not as magnificent as the grand design spiral galaxies that are often chosen as computer backgrounds, I think that the Sunflower Galaxy is small but mighty, as far as spirals come.

My scientific goals for this project were to perform a multiwavelength analysis of M63 using images from the Macalester Observatory in together with archival images of the source. Although there is certainly more quantitative analysis that could be done with these data, some basic yet insightful qualitative analysis can be performed simply by comparing the images of M63 taken with the Macalester Observatory to the images in the literature.

2 Data Acquisition

In order to do robust science with the Macalester Observatory, we need to take images that we can use to calibrate the science images we wish to present. The first of these types of images are dark frames, which are taken with the camera shutter closed and allow us to read out the noise that accrues in the detector for a given integration time. We can subtract the dark frames from our science frames to remove this intrinsic noise. The second type of calibration image is a flat frame, which is used to remove artifacts due to imperfections in the surface and consequent performance of the detector (for example, dust that has fallen onto a filter that causes nonuniform responsivity to photons across the detector). To account for these imperfections, we uniformly illuminate the detector with light scattered into the sky by the setting Sun and thus get a useful measure of the relative sensitivity of each of the pixels in our detector. From these flat frames, we can create flat field images that we can use to remove these artifacts from our science images. After this processing, our science images are ready to be analyzed.

I collected useable data several times throughout the semester. The science images I took on the nights of February 20 and April 6 of this year were the data I included in my analysis. I took corresponding dark frames for each of these observations as temporally close to the observations as possible, though the night of April 6 was plagued with camera issues and darks were taken in the two days following the observation. I also utilized flat frames taken by my classmates in the B and Hα filters on March 22 and April 4 respectively.

In order to compare broad-band to narrow-band observations, I took images of M63 in the B, V, R, and I filters as well as in Hα. I took useable images in the B filter on February 20 and April 6. The V, R, I, and Hα images I used were from April 6. My flat frames for the R and I filters were also taken on April 6; in the V filter, I took flat frames on February 16.

I also took images in the U filter, the SII filter, and the OIII filter, but the robustness of the images in these filters was not significant, and M63 was barely visible over the noise. I began my analysis with 60 images, but I was only able to use 30 of them (five per filter, with the B filter having ten images) in concert for my final images.

I used exposure times of 90 seconds for all broad-band filters and 150 seconds for my narrow-band filters. These were the longest integration times I could use without the foreground star in the field becoming saturated.

3 Data Reduction

For my data reduction, I followed the methodology presented in the "Accelerated Image Handling" manual used in our analysis sessions as well as some basic guidelines from the CCD Quickstart activity. I utilized SAOImage DS9 and `kvis` for visualization of my data, and I used IRAF for the reduction steps.

In order to calibrate my data, I followed several discrete steps, which I will describe in brief detail in the following verbose list.

1. Average dark frames together for each integration time using `imcombine` with outlier rejection above 3σ to remove cosmic rays from the images.
2. Subtract dark frames from science images and flat field images with `imarith` to get rid of the background noise level in these images.
3. Combine dark-subtracted flat field images for a given filter with no outlier rejection.
4. Normalize these flat field images by calculating the mean of the central regions (using `imstat`) and dividing the flat field images by this value.
5. Apply the flat field corrections to the dark-subtracted science images by dividing the science images by the flat field images.
6. Subtract the mean sky background (calculated using `imstat` on regions that have no signal) from each of the science images. (At this point, I noted that there was a significant gradient across almost half of my images that flat-fielding did not seem to resolve.)
7. With the remaining 30 images that seem viable, calculate the difference in position between all of the images using `imexam` to find the center of a specific star, and using `imshift`, shift the images into alignment.
8. Combine aligned images of a single filter together to produce a deeper image of M63 in each filter.
9. Trim off any edge effects, change the pixel type of science images for manipulation in `kvis`, and enforce a WCS (World Coordinate System) solution for the final five science images using a reference image of the field from the Digitized Sky Survey to match as many stars as possible.

With my final images, I was able to experiment with using different filters to make tricolor images in `kvis`. I also experimented with a rudimentary method of continuum subtraction to isolate the line emission present in my Hα image. These fully-reduced images allow me to make scientifically useful conclusions about the physics at work in M63.

4 Results

4.1 Broad-band Imaging

Figure 1 is a tricolor image in R, V, and B of M63. Though not as impressive as an image from a space-based telescope, I think that the general shape and flocculent nature of M63 is preserved in this observation from our telescope. The nuclear region of the galaxy is prominent in all filters as is the foreground star to the lower right. The nuclear region seems to be the brightest in the R and V filters, as can be observed by the yellower center of the galaxy, while the radial extent of the galaxy seems to be brightest primarily in the V and B filters. Much of the central-most portion of the disk can be seen, as well as some of the more sparse emission at slightly larger radii, though this emission is faint compared to the central parts of the galaxy.

4.2 Continuum Subtraction

In an attempt to glean more useful information from my narrow-band image, I performed a first-pass continuum subtraction using my image in the R filter to subtract the continuum level from my Hα image. I created a scaled-down version of my image of M63 in the R filter. I determined the correct scaling factor for these particular images by testing scales of my R image between 0.1 and 0.9, with a separation of 0.1 on each trial, then repeating with more precision until a sufficient subtraction was achieved and no difference could be determined between one precision step and the next. In theory, one should measure the correctness of the subtraction by subtracting the continuum image from the Hα image and seeing if the stars in the field are oversubtracted or not.

This ended up being a particularly difficult way of measuring the quality of the subtraction, as the stars did not evenly disappear (as can be seen in Figure 2). To circumvent this, I chose the scale factor where the emission in the most central region of the galaxy becomes about the background value. I chose this by eye while glancing at the values in the image, so it is not the most robust way of measuring the goodness of the subtraction. Once I settled upon a scale factor of 0.13, I used the continuum-subtracted Hα image in a tricolor image with R and B as red and blue respectively. In Figure 2, we can see that much of the emission in the Hα image near the nuclear region of the galaxy must have been continuum emission, as it seems to have mostly disappeared with the subtraction. However, some emission can be seen in green at large radii from the center of the galaxy. In an ideal world, this is line emission from the galaxy.

The bad subtraction could be caused by several things, the most avoidable of which is poor alignment of the WCS solutions of the Hα and R images. This could be resolved by matching coordinates with a reference frame more carefully. Another potential cause of this poor stellar subtraction could be a difference in the PSFs (point spread functions) between the Hα image and the R filter continuum image used. This is able to be fixed by using a PSF-smoothing function in an image reduction package (for example, in IRAF, the function `gauss` could be used to do this).

4.3 Comparison with Archival Data

Figure 3 shows a comparative view of M63 from the Macalester Observatory and GALEX. The image on top is a tricolor image with R as red, Hα as green, and B as blue. As in the RVB tricolor image, the nuclear region of the galaxy as well as the foreground star are the most prominent parts of the image. However, in this image, the Hα emission at larger radii is much more prominent and localized than the broad-band emission. This indicates that there are regions of active star formation in the optical arms of M63. Comparing this image taken with Macalester's telescope to the image taken with GALEX in the far ultraviolet, we see similar localized regions of emission at large radii. Since both Hα and FUV are tracers of active star formation, it makes sense that we would see both types of emission in the same regions of the galaxy.

I also compared my RVB image with archival HI data from the THINGS survey by Walter et al. (2008), as shown in Figure 4. The extent of the HI emission that is not shown in the figure is great: there is low surface-brightness emission up to 40 kpc from the optical center of the galaxy as measured with WRST (Battaglia et al. 2006). The contours are shown as indicated in the figure caption; there is less-bright emission towards the center of the galaxy as well as at large radii. This could be due to the fact that M63 is part of the M51 group of galaxies, and much like in the M82 group, the extended HI gas could indicate interaction between it and its companions.

There also seems to be coupling between the Hα emission, which marks star formation in HII regions, and the densest part of the galaxy in neutral hydrogen.

5 Conclusions and Next Steps

The Macalester Observatory is able to recover a fair amount of the central flux of M63. Using continuum subtraction with Hα images taken with the Observatory allows us to see HII regions at moderate radii from the galactic center. Comparing the Hα images taken with our Observatory to

FUV images from GALEX reveals similar localizations for both types of emission, which both trace star formation. In another logical coincidence, there seems to be coupling between Hα and neutral hydrogen emission, which makes sense, as it is more likely for stars to be actively forming in regions where there is material out of which they can form. Similar incidences of co-spatial Hα and HI emission can be seen in the analysis of UGC 8245 and UGC 11411 by Bralts-Kelly et al. (2017).

If I could do further work on this project, I would take and combine more images to get a higher signal to noise ratio in my final images. I did not anticipate the quantity of images I would need in the end, and having to exclude several nights of data because of poor flat-field corrections added to this problem. Part of the reason I decided to exclude my SII data was because I did not take dark frames for my SII flat frames, and I thought that taking darks for these flats in such a temporally-detached fashion would introduce enough noise into the resulting image to essentially drown out the already-dim galaxy. I would focus on taking images in Hα and SII next time, as well as in their corresponding continuum filters, in order to really be able to focus on the scientific results from this project.

I would also like to flux calibrate my images to be able to compare my observations of M63 in a useful way to observations in the literature. Converting my images to units of counts per second instead of counts would be an easy task and would allow me to compare the recovered flux in my images to flux values in the literature to measure the abilities of the Observatory and of my particular observations.

In comparing my narrow-band images with my broad-band images, I would also like to perform a better continuum subtraction using PSF smoothing to see if I could find a more accurate scale factor and have the stars subtract out nicely. If this were to be done, we could conclude that any remaining flux in the Hα image should be entirely from line emission.

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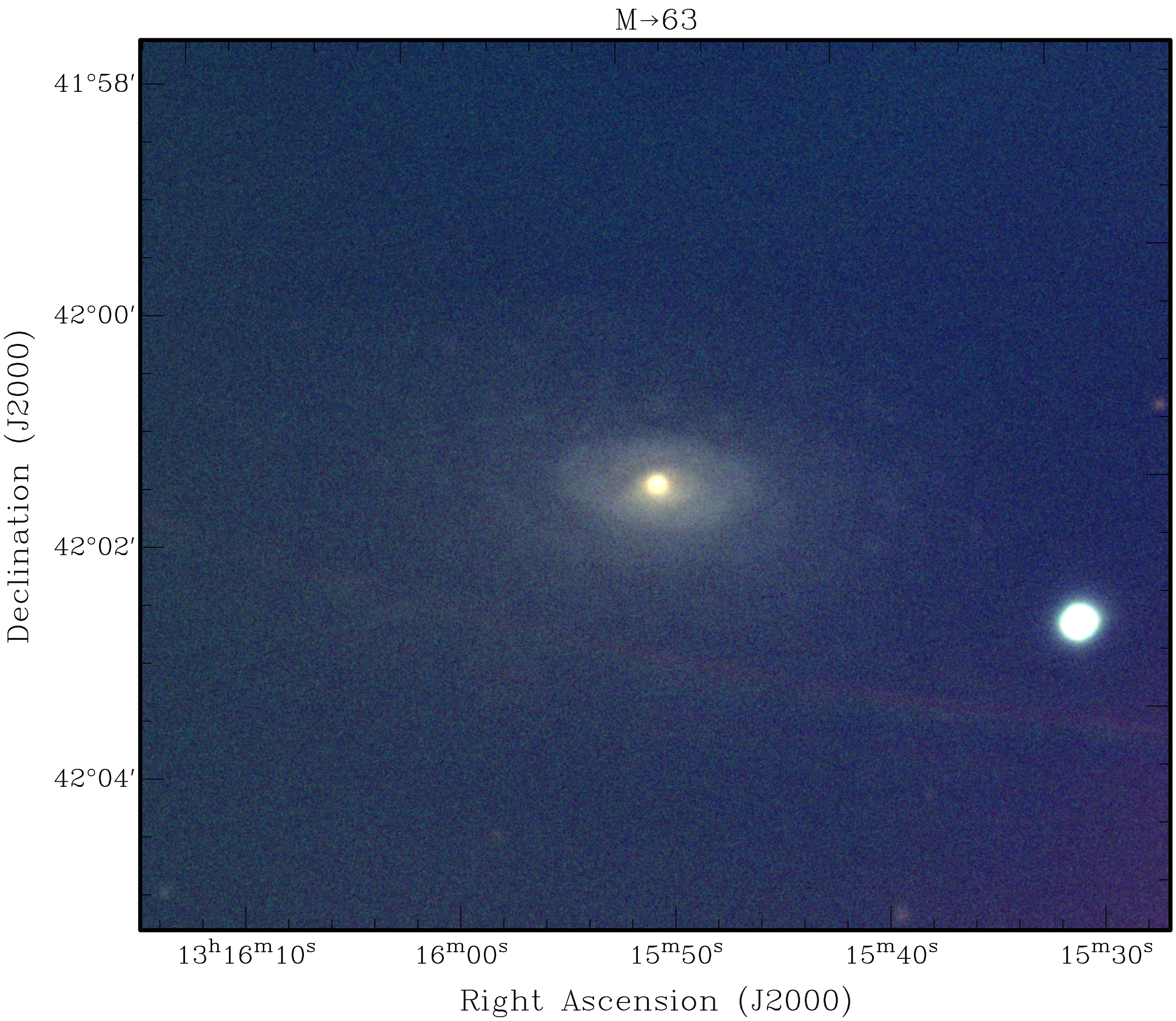


Figure 1: A tricolor image of M63. Here, red is the R filter, green is the V filter, and blue is the B filter.

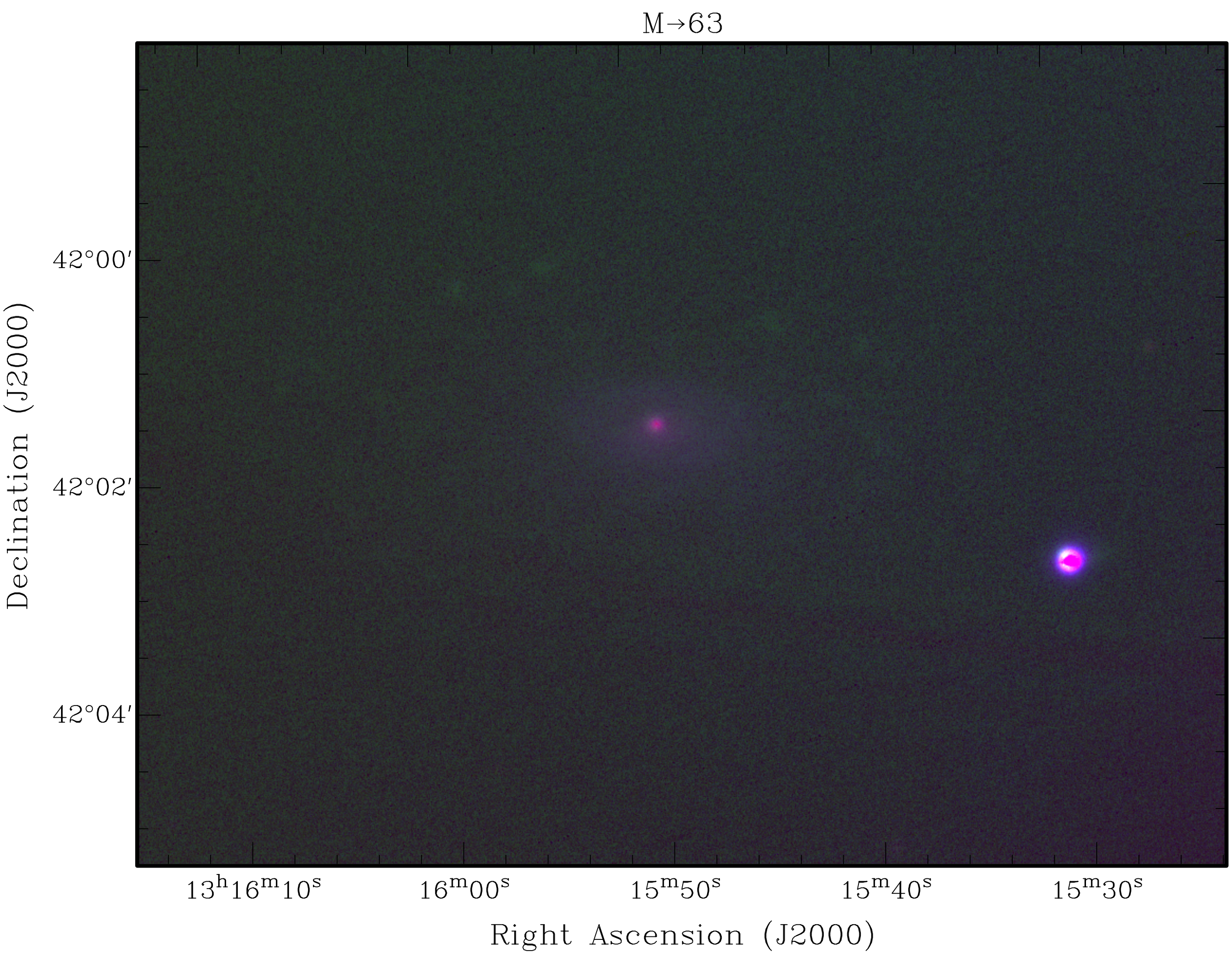
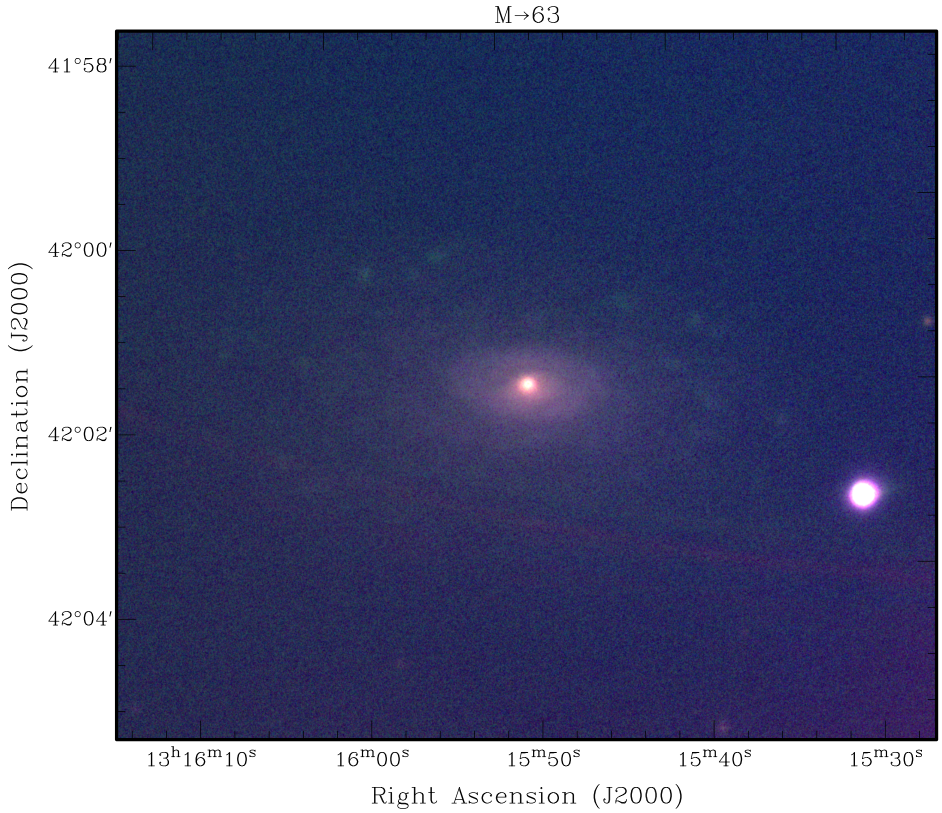


Figure 2: A tricolor image of M63 with continuum-subtracted Hα emission. Here, the R filter is red, the Hα filter with continuum subtraction is green, and the B filter is blue. Though the background noise is high, one can clearly see several HII regions at large radii from the center of the galaxy. Because of the continuum subtraction, these regions shown in green should solely mark the presence of Hα line emission. The foreground star in the image is poorly subtracted, which is why it appears very pink.



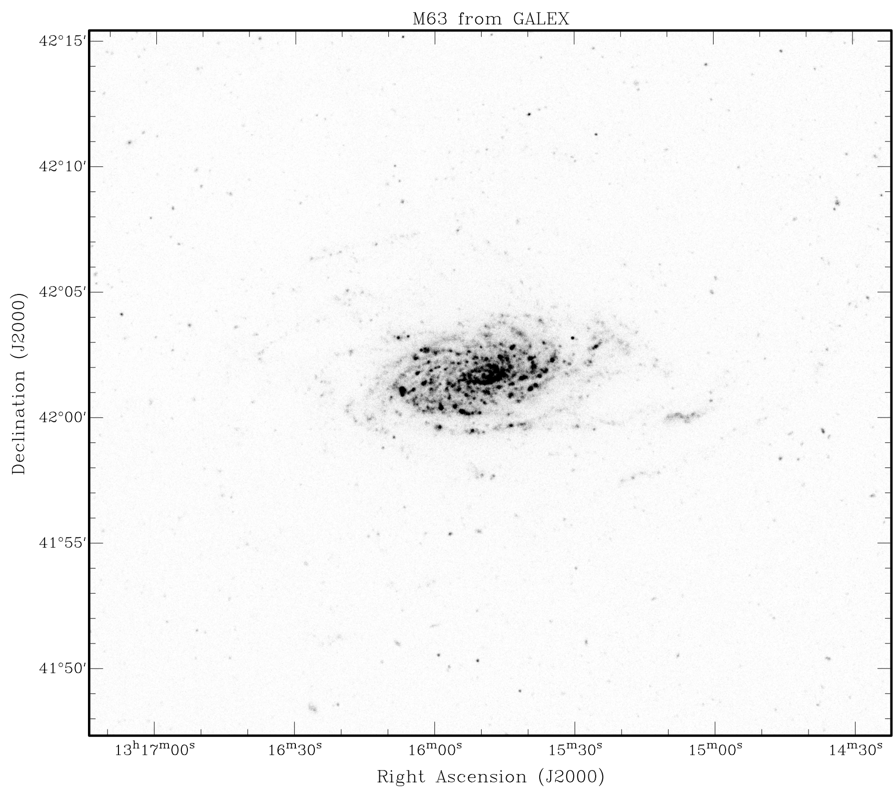


Figure 3: *Above:* a tricolor image of M63 with the R filter as red, the Hα filter as green, and the B filter as blue. *Below:* a far-UV observation of M63 from GALEX, flipped on the declination axis from the image above.

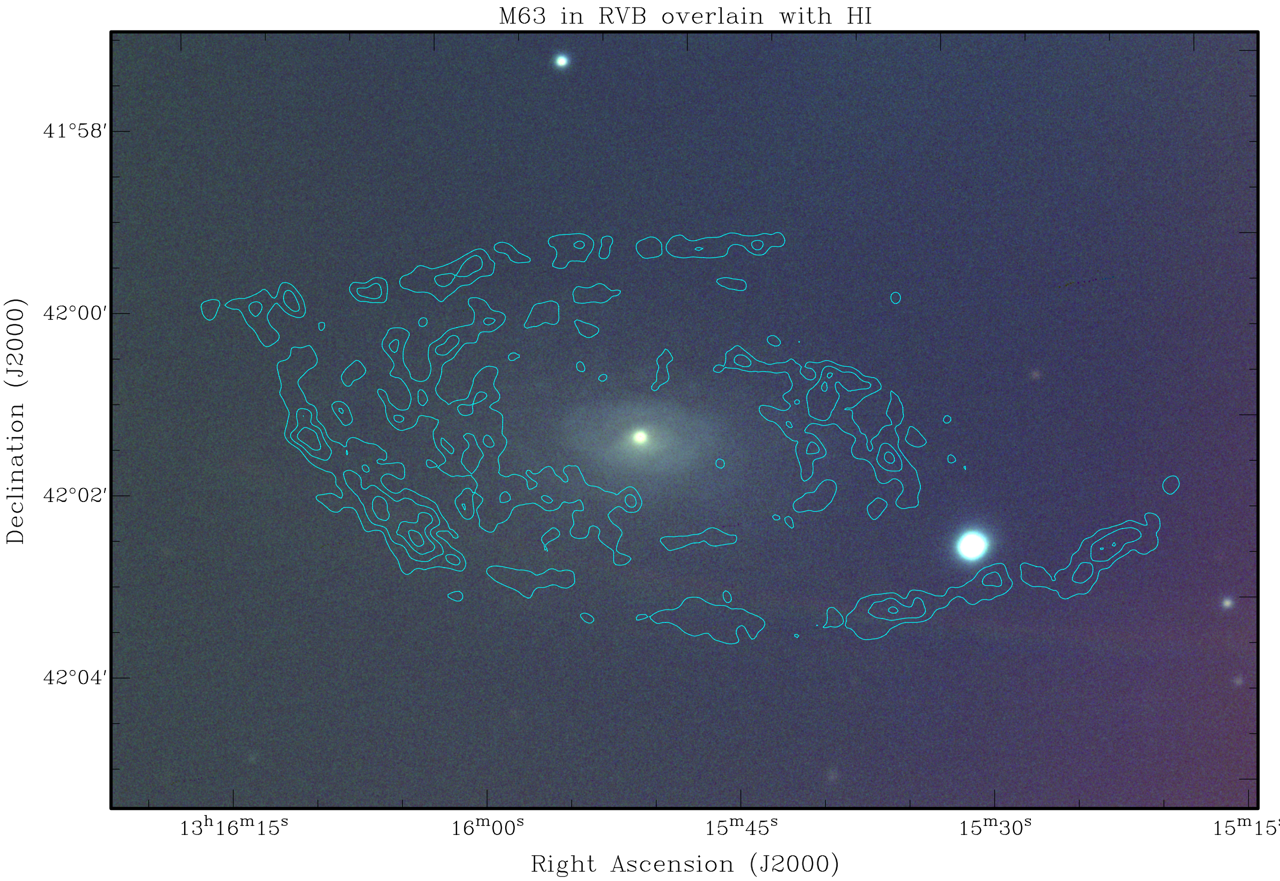


Figure 4: A tricolor image of M63 in R, V, and B as red, green, and blue with cyan contours of HI emission from the THINGS survey. The contours are at 45, 60, and 90% of the peak value in the HI image.