Comparing Ultraviolet and Infrared Star Formation Tracers

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Overview

The DS9 astronomical image viewing tool will be used to measure ultraviolet and infrared light from the places where stars are forming in a nearby spiral galaxy. These measurements can then be compared to each other to understand the advantages and disadvantages of using each of these forms of electromagnetic radiation for measuring star formation rates.
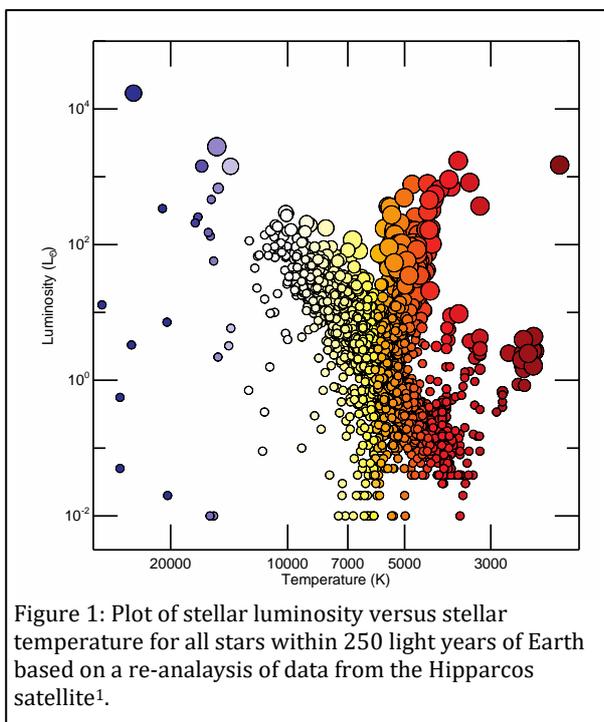

Figure 1: Plot of stellar luminosity versus stellar temperature for all stars within 250 light years of Earth based on a re-analysis of data from the Hipparcos satellite[1].

General Astronomy Concepts

When a group of stars form out of interstellar gas, the stars have a range of luminosities (the total energy radiated per unit time) and colours that follow a relation called the main sequence, which appears as a diagonal line from the upper left to lower right in Figure 1. The most luminous stars are also the bluest, the hottest, and the most massive. They also have very short lifespans; the largest only stay on the main sequence for a few million years before running out of hydrogen in their cores, which causes them to undergo a series of changes in which they first become red supergiant stars and then supernovae.

Since the blue main sequence stars have short lifespans, astronomers typically look for blue stars to identify where stars are forming. While it is easy to identify individual blue stars within our Galaxy, it is difficult to separate the blue stars from the other stars in most other galaxies, even using the Hubble Space Telescope. Instead, astronomers look for signs that many hot young stars are present.

Ultraviolet light is one tracer of the hot blue stars found in star forming regions. While all stars produce ultraviolet light, the hot blue stars produce much more than other stars, so regions with active star formation will produce a lot of ultraviolet emission. Figure 2 shows an image of M74 where the blue and magenta regions are locations producing ultraviolet light.

Some of the ultraviolet light from these hot young stars is absorbed by interstellar dust found in the gas clouds surrounding the star forming regions. This interstellar dust then heats up to temperatures above 100 K and produces mid-infrared emission in the 5-30 μm range that can also be used to identify star formation activity. This emission is shown in Figure 2 in red and magenta colours.

While ultraviolet and mid-infrared light could both be used to measure star formation, both have problems. As indicated above, interstellar dust can absorb the ultraviolet light from hot blue stars, making the ultraviolet light appear dimmer than expected for the given amount of star formation. In contrast, if no interstellar dust is present, then the star forming regions will produce no mid-infrared light.

The amount of dust in the interstellar medium depends on the amount of elements heavier than helium that are present to form that dust. While hydrogen, helium, and lithium formed soon after the Big Bang, all heavier elements have formed in stars since then. In older places within galaxies, the stars will have formed more of the heavy elements. These heavier elements can then form more interstellar dust, which will absorb more ultraviolet light from young blue stars and produce more infrared light.

This experiment is based on comparing the ultraviolet and mid-infrared light from multiple locations within one or more nearby galaxies. The analysis has two goals. The first goal is to determine whether the ultraviolet emission and mid-infrared emission are correlated within the galaxies. The second goal to determine whether the ratio of ultraviolet to mid-infrared emission varies within the galaxies and, if it does, to determine how it varies.
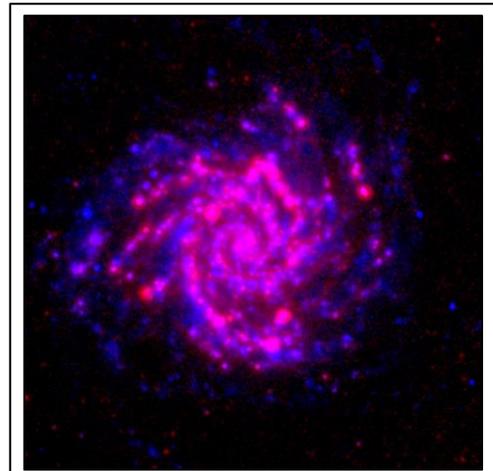

Figure 2: An image of M74 where the blue colours trace ultraviolet (226.7 nm) emission from hot young stars and the red colours trace mid-infrared (24 μm) emission from interstellar dust. The image appears magenta where both ultraviolet and mid-infrared emission are produced. The images are from two different surveys of nearby galaxies[2,3].

Additional Information: Units for Measuring Light

The data used in this experiment will be converted into units of Janskys (Jy). One Jy is equal to 10^{-26} W/m^2/Hz. This is a measurement of a quantity referred to as flux density (f_ν), which represents the amount of energy (ΔE) per time (Δt) observed within a given frequency range ($\Delta \nu$) that can be collected over a telescope area (ΔA), or

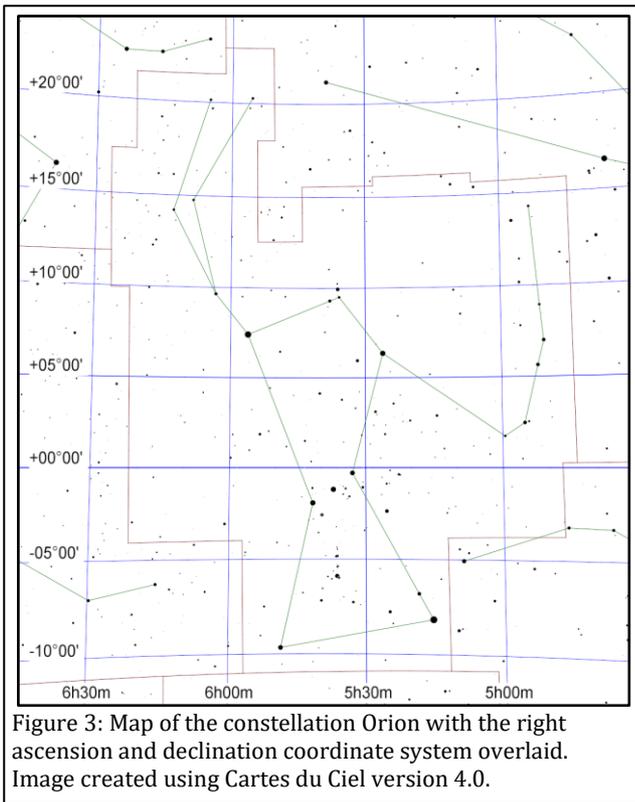$$f_\nu = \frac{\Delta E}{\Delta t \, \Delta A \, \Delta \nu}$$

Sometimes measurements are reported as surface brightness (I_ν), which is the flux density spread over an area of the sky ($\Delta \Omega$). This is given by the equation

$$I_\nu = \frac{f_\nu}{\Delta \Omega} = \frac{\Delta E}{\Delta t \, \Delta A \, \Delta \nu \, \Delta \Omega}$$

Additional Information: Coordinate Systems

Astronomers use a coordinate system similar to the latitude and longitude system applied to Earth. The astronomical equivalent coordinates are called right ascension and declination. Right ascension is equivalent to longitude, and it is often measured in hours, minutes, and seconds with a range from 0 to 24 hours, with 60 minutes in an hour, and with 60 seconds in a minute. Sometimes, however, right ascension is measured in degrees instead (with 1 hour equivalent to 15 degrees). Declination is equivalent to latitude, and it is measured in degrees, minutes, and seconds, with 60 minutes in a degree and 60 seconds in a minute. Declination ranges from +90:00:00 (at the point directly above the Earth's North Pole) through 00:00:00 (the location directly above the Earth's equator) to -90:00:00 (at the point directly above the Earth's South Pole). See Figure 3 for an example of this coordinate system overlaid on the constellation Orion.

Lengths and distances in the sky are often measured in degrees, arcminutes, and arcseconds, with 60 arcminutes in 1 degree and 60 arcseconds in 1 arcminute. For reference, the Sun and Moon are both 0.5 degrees (or 30 arcminutes) across. The Andromeda Galaxy, which is the nearest spiral galaxy, and the

Figure 3: Map of the constellation Orion with the right ascension and declination coordinate system overlaid. Image created using Cartes du Ciel version 4.0.

Pleiades cluster of stars are both 3 degrees across. Areas are often described as square versions of the angular measurements, such as square degrees (deg^2), square arcseconds ($arcsec^2$), and square radians or steradians (sr).

Preparation Procedure

1. Download and install DS9 from the DS9 download page (http://ds9.si.edu/site/Download.html). This software is available for Windows, Mac, and Linux.

2. Look up the sample for the Spitzer Infrared Nearby Galaxies Survey at http://iopscience.iop.org/article/10.1086/376941/pdf . Select several galaxies from the survey for the analysis. The best galaxies for this project will be face-on spiral galaxies with angular sizes of 5 arcminutes or more. Edge-on spiral galaxies, irregular galaxies, smaller galaxies, and elliptical and lenticular galaxies will all work poorly. See Figures 3 and 4 for examples.

3. Go to the NASA/IPAC Extragalactic Database (NED) website (http://ned.ipac.caltech.edu/). Type in the name of one of the galaxies in the search box.

Figure 3: Near-infrared (3.6 μm) images of the stellar emission from M99 (left), M100 (centre), and NGC 7793 (right). These galaxies are examples of face-on spiral galaxies that are good for this project. The images were produced by the Spitzer Infrared Nearby Galaxies Survey[4].

4. The image search results will be shown in a table visible under the tab labelled "Images". Look for an image where the telescope is listed as "GALEX" and the band is listed as "NUV" (which stands for near-ultraviolet). It may be necessary to page through the list to find the image. Download the FITS image. (If more than one image is listed, use the one with the refcode that begins with the most recent year. If the near-ultraviolet image for a galaxy is not listed, do not use the galaxy for the analysis.)
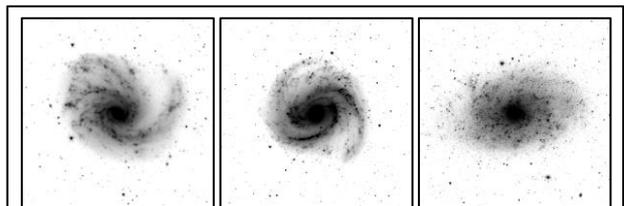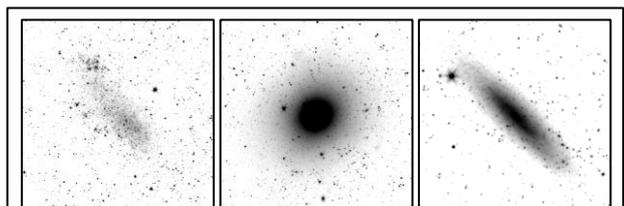

Figure 4: Near-infrared (3.6 μm) images of the stellar emission from the irregular galaxy IC 2574 (left), the elliptical galaxy M89 (centre), and the edge-on spiral galaxy NGC 24 (right). These are examples the types of galaxies that are not useful for this project. The images were produced by the Spitzer Infrared Nearby Galaxies Survey[4].

5. Look for an image where the telescope is listed as "Spitzer" and the band is listed as "MIPS24" or "MIPS.24um" (or something similar). The number 24 refer to the wavelength in microns; this wavelength of light is produced in the mid-infrared. Download the FITS image.

6. Repeat steps 3-5 for all galaxies in the sample.

7. If necessary, rename each downloaded FITS file so that it ends in ".fits".

Measurement Procedure

1. Start DS9.

2. Under "File" in either the menu or the button bar, click on "Open". Find and open the ultraviolet FITS file.

3. Under "Scale", select "log". This will change the way the image values are displayed on the computer screen.

4. If it is necessary to change the brightness and contrast of the image to see the galaxy better, first move the cursor to the image window, then hold down the right mouse button (or, on a Mac laptop, hold down the mouse button and the cmd key at the same time), and then move the cursor either up and down or side to side in the window. Do this until the entire galaxy is visible but without making the individual regions look so bright that they blur together. The result should look similar to Figure 6.

Figure 6: An ultraviolet image displayed in DS9 after setting the scale to log.

5. To re-center the image, middle click on the image. Alternately, go to "Edit", select "pan", and then left click on the image.

6. To zoom in or out, either use the scroll wheel on the mouse or go to "Zoom" in the menu or button bar and select one of the options.

7. As an additional option, change the colours by clicking on an alternate scheme under "Color" in the menu or button bar. (It may be necessary to repeat step 4 after doing this.)

8. Under "Edit" in either the menu or button bar, click on "pointer" or, if that is not listed, "region".

9. Left click on the image to draw a circle. Move the circle so that it is centred on a bright, point-like ultraviolet source. This can be done by clicking on the circle with the left mouse button and, while holding the left mouse button down,
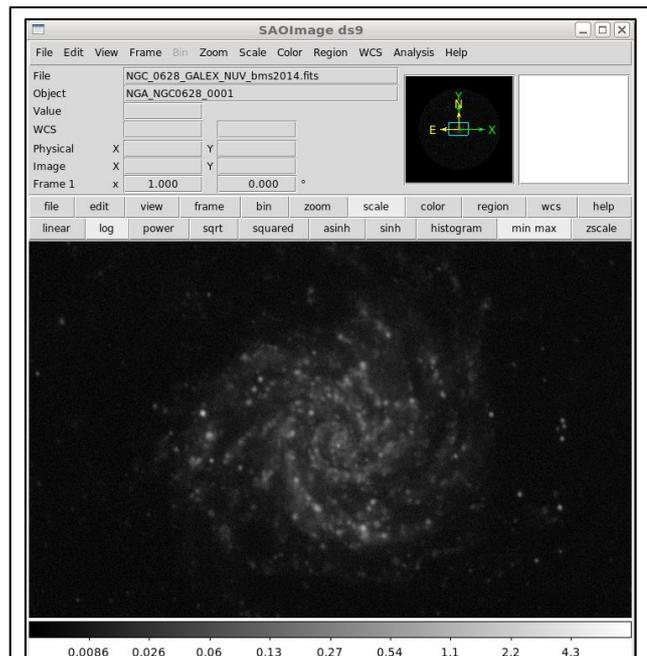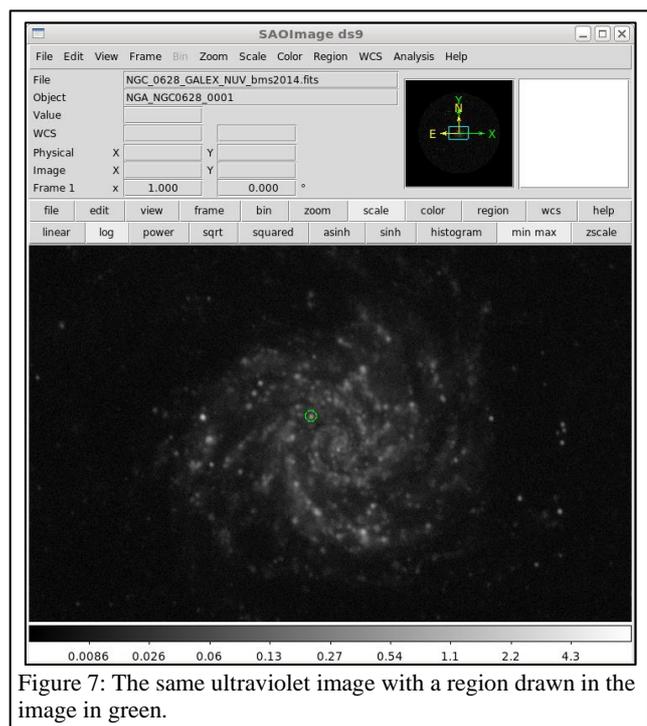

Figure 7: The same ultraviolet image with a region drawn in the image in green.

dragging the circle across the image. Alternately, use the arrow keys. See Figure 7 for an example.

10. Double-click on the circle. This will open a new window. Set the coordinates of the centre of the circle to "fk5". Make sure that "WCS" in the drop-down menu has a check mark next to it. After doing this, record the coordinates of the circle. Set the units of the circle radius to "arcsec". Make sure that "WCS" in the drop-down menu has a check mark next to it. After this, set the radius of the circle to 10 arcseconds. (If the galaxy is 10 arcminutes or larger in diameter, use circles with radii of 20 arcseconds throughout this procedure.)

11. Under "Analysis" in the menu for the Circle window, click on "Statistics". This will open a new window. Record the number listed under sum as the ultraviolet emission. Also record the number of pixels in the region.

12. Repeat steps 9-11 to measure the emission from at least 20 bright, compact regions within the galaxy, although using more regions may be necessary for very large galaxies. Draw a new region each time rather than moving the existing region. The result should look similar to Figure 7.

13. Repeat steps 9 and 10 for 10 regions of blank sky outside the galaxy. Under "Analysis" in the menu for each Circle window, click on "Statistics" to open the statistics window. For each region, open the statistics window and record the mean value and standard deviation. These measurements represent the background signal and background noise in the image.

14. Under "Region" in either the menu or button bar of the main DS9 window, click on "Save Regions". In the next dialog window that appears, give the region file a name and click "Save". In the second dialog window that appears, make sure that the format is set to "ds9" and the coordinate system is set to "fk5" and click "OK".

15. Repeat steps 2-7 to open and display the mid-infrared image.

16. Under "Region" in the main DS9 window, click on "Load Regions". Load the region file that was saved in step 14. (If a dialogue box appears, just click "OK".)

Figure 7: The same ultraviolet image with 25 regions drawn in the image.

17. Double-click on each circle within the galaxy and the repeat step 11 to measure the mid-infrared emission from each target region. Ensure that the mid-infrared measurements for each target region are listed next to the corresponding coordinates and ultraviolet measurements.

18. Double-click on each circle covering background regions outside the galaxy and then repeat step 13 to measure and record the mean background value and standard deviation.

19. Under "Region", select "Shape" and then select "Ruler".

20. Draw a line from the centre of the galaxy to one of the target regions. If it is difficult to tell where the centre of the galaxy is, the central coordinates can be looked up the on the NED website. Record the distance (which can be called the galactocentric radius) for the region. Repeat this for all target regions in the image.

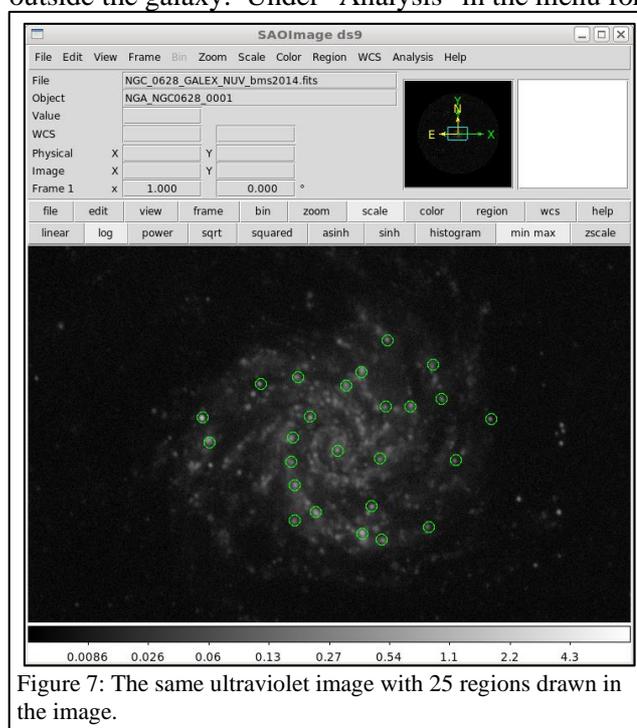21. Repeat these steps for all galaxies in the sample.

Numerical Analysis Procedure

1. For each image, calculate the average of the mean pixel values within the background regions. This is the average background signal per pixel. For each target region in each image, subtract the average background measurement for that image multiplied by the number of pixels in the target region.

2. For each image, calculate the average of the standard deviation values from the background regions. This represents the background noise per pixel. Use this number and the number of pixels in each target region to calculate the uncertainties for each measurement from each target region.

3. The GALEX near-ultraviolet data units are counts per second. Convert the near-ultraviolet measurements to Janskys (Jy) by multiplying them by 3.365×10^{-5}. After this, divide the measurements by the area of each aperture to convert the data to units of Jy/arcsec^2.

4. The GALEX data have a calibration uncertainty of 3% [5]. Combine these uncertainties with the uncertainties based on the background noise.

5. The Spitzer mid-infrared data are normally in units of megaJanskys per steradian (MJy/sr). Convert these values to Jansky/arcsec^2.

6. The Spitzer 24 µm image has a calibration uncertainty of 4% [6]. Combine these uncertainties with the uncertainties based on the background noise.

7. Calculate the logarithm of the near-ultraviolet flux densities and the logarithm of the mid-infrared flux densities. After doing this, plot the two flux densities versus each other. This is one of the major results of this experiment, and it shows whether the near-ultraviolet and mid-infrared flux densities are actually tracing the same star formation activity within the galaxy. Calculate the correlation coefficient for each relation.

8. Calculate the logarithm of the ratio of the mid-infrared flux densities to the near-ultraviolet flux densities. Create a second plot with this logarithmic value on the y-axis and the galactocentric radius on the x-axis. This is the other major result from this experiment. It shows where star forming regions are more obscured in galaxies. Calculate the correlation coefficient for each relation.

Discussion Questions

1. When viewing the near-ultraviolet and mid-infrared images, how do they look similar? How do they look different? Are any regions visible in the near-ultraviolet image but not in the mid-infrared image or vice-versa?

2. In the plot of near-ultraviolet flux density versus mid-infrared flux density, do the data look like they follow a linear relation?
    a. If the quantities are not related, try looking at the appearance of the near-ultraviolet and mid-infrared images to determine why the quantities are not related.
    b. If most of the data follow a linear relation but one of the data points does not fall on the relation, try to identify what is special about the region where that measurement was made.

3. In the plot of the ratio of mid-infrared to near-ultraviolet flux density versus radius, are the data correlated?
    a. If a correlation is present, what do the results indicate about where interstellar dust is found in the galaxy?
    b. If the correlation is weak or the data show complete scatter, what does this indicate?

4. In all of these plots, identify where the uncertainties are the lowest and highest relative to the measurements and explain why. Also, for any given region, are the uncertainties higher for the near-ultraviolet data, are they higher for the mid-infrared data, or are they about equal? Explain why the uncertainties may be similar or different for the two different wavebands.

Acknowledgments

References

[1] McDonald I. et al., *Fundamental parameters and infrared excesses of Hipparcos stars*, 2012, *Monthly Notices of the Royal Astronomical Society*, 427, 343

[2] Brown M. J. I. et al., *An Atlas of Galaxy Spectral Energy Distributions from the Ultraviolet to the Mid-infrared*, 2014, *Astrophysical Journal Supplement Series*, 212, 18

[3] Bendo G. J. et al., *MIPS 24-160 µm photometry for the Herschel-SPIRE Local Galaxies Guaranteed Time Programs*, 2012, *Monthly Notices of the Royal Astronomical Society*, 423, 197

[4] Kennicutt R. C. Jr. et al., *SINGS: The SIRTF Nearby Galaxies Survey*, 2003, *Publications of the Astronomical Society of the Pacific*, 115, 810

[5] Morrissey P. et al., *The Calibration and Data Products of* GALEX, 2007, *Astrophysical Journal Supplement Series*, 173, 682

[6] Engelbracht C. W. et al., *Absolute Calibration and Characterization of the Multiband Imaging Photometer for Spitzer. I. The Stellar Calibrator Sample and the 24 µm Calibration*, 2007, *Publications of the Astronomical Society of the Pacific*, 119, 859