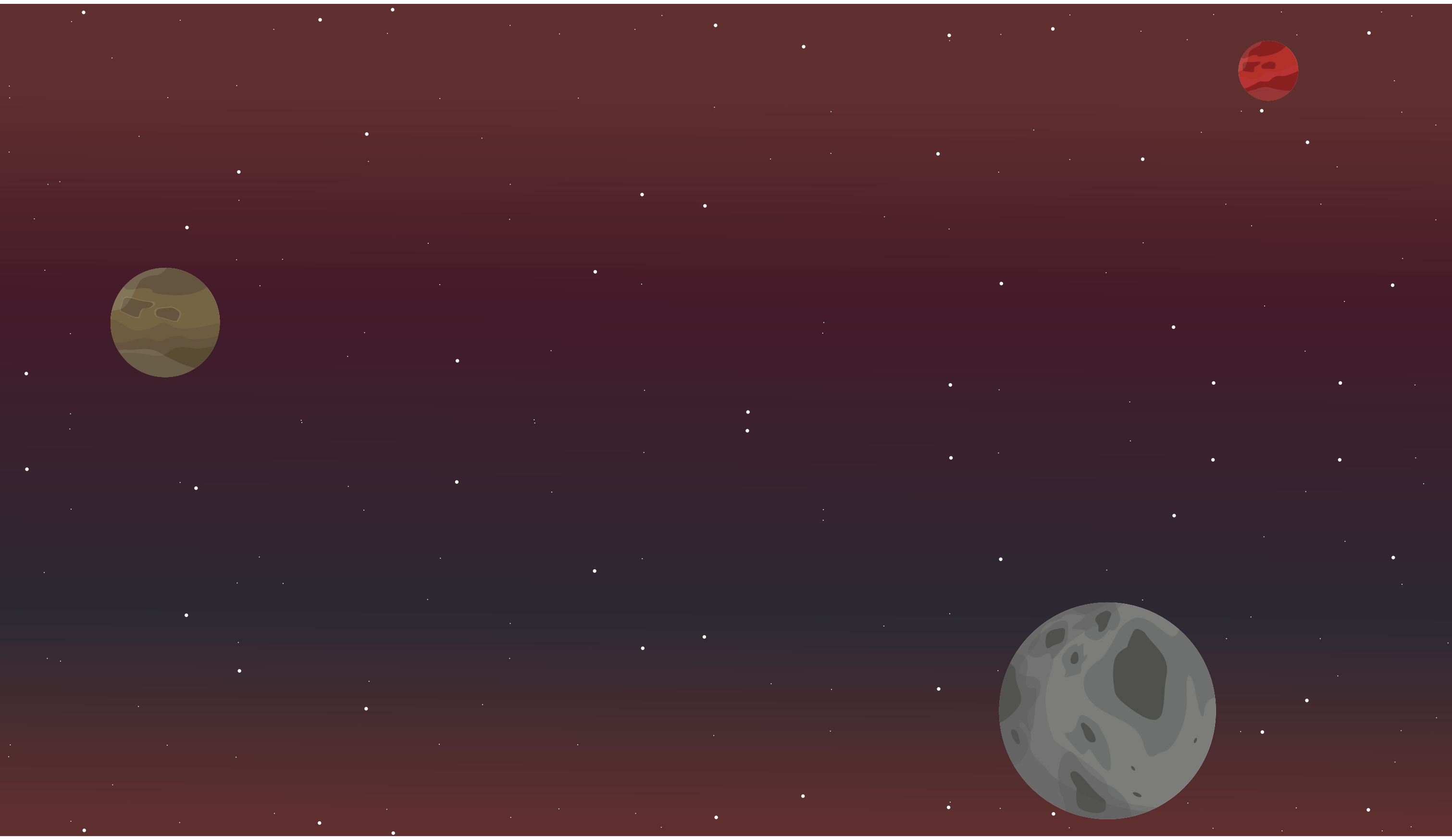

NASA Computational Case Study: Spectral Energy Distribution Fitting

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The need for faster, more efficient algorithms is an important aspect of scientific computing. Generally, scientists are exposed only to computational issues that arise in their field. Thus, collaboration between a numerical analyst and a scientist is becoming necessary for scientific computing. The purpose of this case study is to expose computer scientists to processes that an astronomer would use to obtain useful results from raw data. For example, astronomers are interested in determining the properties of galaxies and measuring changes in those properties as a function of time throughout cosmic history. To do so, they use certain models that are designed and refined over time via observations at different wavelengths of the light spectrum. The process of matching these models with observed data from studying celestial bodies is referred to as spectral energy distribution (SED) fitting.

In this case study, we learn how to perform the SED fit. This process requires knowledge of both the astronomical and computational issues involved when fitting *flux*, the total energy from a source as seen from Earth, to a set of physical templates.[1] Once a fit is complete, we can classify the source and estimate several physical parameters. The goal is to demonstrate how the computer science skill set can be used in the scientific community and possibly improve one or more of the computational aspects of this problem. The following provides some background on the astronomy issues, including information on the SED and related physical parameters, and the computational issues, including the fitting procedure.

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The Spectral Energy Distribution

The SED is a plot of flux from a source versus wavelength. Its primary use is to characterize astronomical sources. Generally, when examining the SED of an object, we need as many data points as possible spread from the ultraviolet (wavelengths in the hundreds of nanometers) to radio (centimeter wavelengths). Figure 1 shows an example SED. The more data points we have, the more accurately we can describe physical conditions and processes occurring in the source. Within galaxies, many factors influence the shape of the SED. For example, stellar age and the presence of active galactic nuclei, among other phenomena, affect the SED and may be uniquely derivable from the SED with a sufficient number of observations.[1]

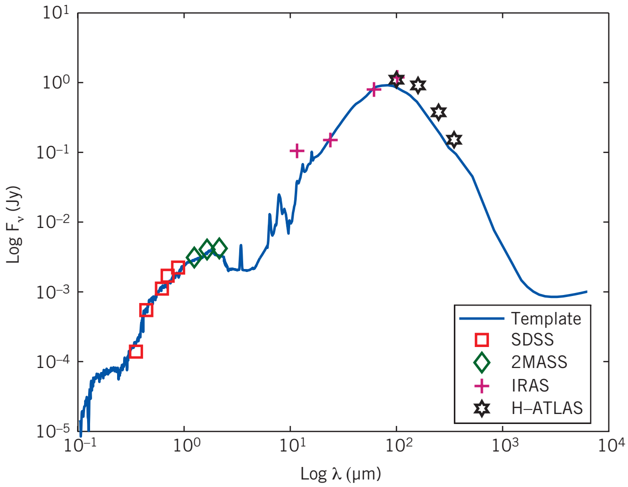


Figure 1. Example spectral energy distribution (SED) from galaxy J090746.91+003430.4. This is the best fitting galaxy template using the method described in this case study. The data points are taken from published catalogs: SDSS, 2MASS, IRAS, and H-ATLAS.

Physical Properties

The physical properties of galaxies alter the shape of the SED. There are several main areas that we must consider that affect the shape. Most of the UV/visible spectrum will be dominated by the stars that inhabit the galaxy. Properties such as mass, metallicity (abundance of heavy elements relative to that of hydrogen), and age can change the shape. Another main contributor is the dust and gas within the galaxy. Much of the UV/visible light emitted by the stars is absorbed by the *interstellar medium*, the dust and gas between stars, and is re-emitted at a longer wavelength. This will give distinct signatures at infrared wavelengths and can indicate properties such as dust temperature and star formation rate.

We must also consider the distance to the object. The more distant the object, the dimmer it will be. A galaxy has an intrinsic power output, called *luminosity*, which is analogous to the wattage of a light bulb. The most luminous galaxies are at least a million times more luminous than low-luminosity galaxies. The distance can be measured in terms of *redshift*. The redshift gives a measure of the movement of the galaxy and, indirectly, its distance from the Earth.[1] Both of these properties shift the SED, luminosity on the vertical axis, and redshift on the horizontal axis. The luminosity depends on the masses and ages of the stars that make up the galaxy. The wavelength of the peak brightness can be an indicator of star formation, particularly if the peak is in the far-infrared, as is the case in Figure 1.

Of the properties described by the SED, this project focuses on redshift. Specifically, we'll be computing *photometric redshift*, defined as a redshift obtained by examining the brightness of the object through a set of standard filters. Redshift can be measured precisely using spectroscopy to calculate the wavelength shift of spectral lines relative to their rest wavelengths measured in the lab. However, photometric measurements exist for many more objects than spectroscopic measurements, making photometric redshift a powerful tool, although a less accurate one than spectroscopic measurements.

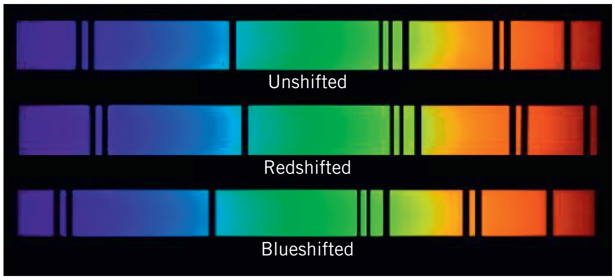


Figure 2. Illustration of redshift as seen in a spectrum. The top spectrum is unshifted, the middle spectrum is redshifted, and the bottom spectrum is blueshifted. The dark lines are absorption lines. Notice how the bottom two spectra are shifted. Image credit: http://coolcosmos.ipac.caltech.edu.

Redshift

The redshift, denoted by z, is the amount by which incoming light is shifted to the red end of the spectrum (see Figure 2).[1] Local redshift is a result of the *Doppler effect*. You can experience this effect for sound waves when hearing a quickly approaching emergency vehicle's siren. The pitch or, more precisely, the frequency of the sound waves changes as a sound source is moving toward or away from the listener. Instead of the effect of sound waves to a listener, redshift refers to the frequency of electromagnetic radiation with respect to an observer. As the object moves away from the observer, the frequency of the light appears lower; the wavelength looks longer to the observer. Conversely, as an object moves closer, the light will appear more blue. When looking at galaxies, the dominating redshift is the *cosmological redshift*, which is caused by the expansion of space between the

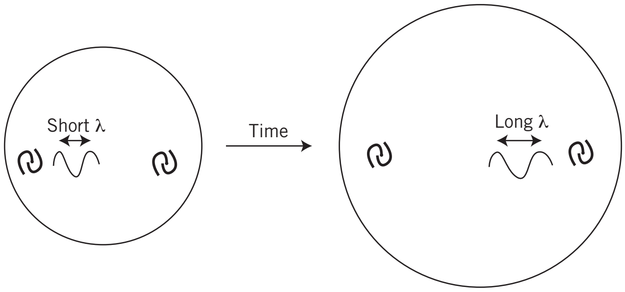


Figure 3. Illustration of cosmological redshift in terms of wavelength. As space expands between two objects, the wavelength increases, causing the object to appear more red. Image credit: http://bustard.phys.nd.edu.

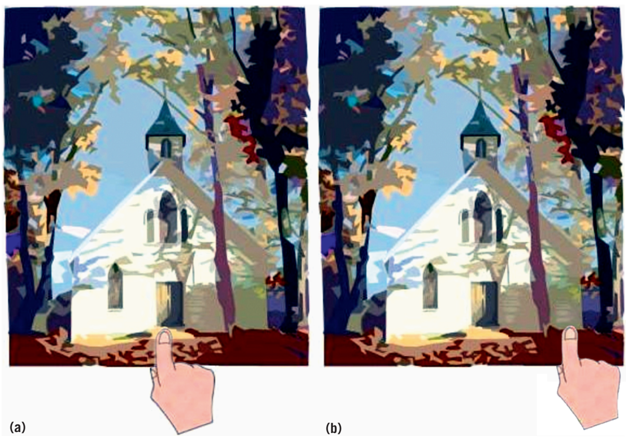


Figure 4. An experiment to demonstrate the concept of parallax. (a) Point A is the location where a finger points to a far object (door of a building in this case) when the left eye is closed and the right eye is open. (b) Point B is the location where the same finger points to when the right eye is closed and the left eye is open. The distance between points A and B is referred to as parallax and is often measured by the angle A and B make with the observer's eye.

observer and the source (see Figure 3). The relation between wavelength and redshift is given by

$$z = \frac{\lambda_{obs} - \lambda_{emit}}{\lambda_{emit}}, \quad (1)$$

where λ_{obs} is the observed, shifted wavelength and λ_{emit} is the true, emitted wavelength of the source.

In this case study, we'll be measuring the cosmological redshift. Edwin Hubble determined that the more distant an object is, the faster it moves away from the observer. The distance to the object can be computed by the redshift-distance relation,[1]

$$d = \frac{cz}{H_o}, \quad (2)$$

where c is the speed of light in km/s, d is the distance in megaparsecs, and $H_o \approx 70$ km/s/megaparsec (km/s/Mpc), is known as the Hubble constant. Extragalactic distances are often given in units of *parsecs*. To understand what a parsec is, we need to learn about another concept called *parallax* (see Figure 4).

Activity 1

Locate a far object such as a tree or building.

- Close your left eye. Have your pointing finger at your arm's length pointing to the center of that object. Call the location your finger is pointing at "point A" (see Figure 4a).
- Without moving your hand and finger, open your left eye and close your right eye. Where is your finger pointing at now? Call the location you are pointing at "point B" (see Figure 4b).

Note 1: The distance between apparent positions of the finger, which is the distance between points A and B, is referred to as *parallax*.
Note 2: Parallax, in our example, is measured by the angle, or semi-angle, that the finger makes with the two eyes. This angle is called the *parallax angle*.

In the above experiment, your finger seemed to move while the distant objects like trees and the building appeared constant. In astronomy, the two eyes observing an object can be two telescopes, cameras, or observers at different locations. In such observations from two points of view, nearby stars appear to be moving (similar to your finger in previous activity) relative to distant stars (similar to buildings and trees in previous activity). The two distinct points of view can also be caused by the Earth's orbit. For example, if you observe a star now and then again from the same place six months from now, the two different positions of the Earth in its orbit will cause parallax for the nearby stars.

Now that we know what parallax is, we can define parsec. A parsec is the distance to an object from Earth such that the parallax angle of the object (the angle between Earth, object, and the sun), as seen from Earth, is exactly one arcsecond (see Figure 5).[1] The other distance unit that we often see is the *lightyear*, which is the distance that light travels in one year. One parsec is approximately 3.26 lightyears, which is also approximately 3.086×10^{16} meters.

Activity 2

One of the most common spectral features in the universe is the H-alpha line. It's most often seen as a bright red line

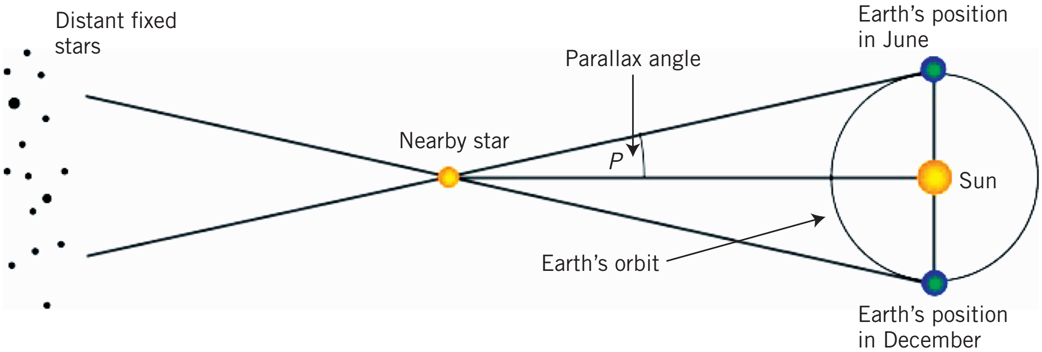


Figure 5. Illustration of parallax angle: the angle between Earth at one time of the year, a star, and Earth six months later. Earth's orbit causes nearby stars appear to move against background stars. A parsec is a unit of distance, equivalent to the distance from the sun to a celestial object that has a parallax angle of one arcsecond. Image credit: http://physics.weber.edu.

when looking at the spectrum of a star-forming region, such as the Orion Nebula. The H-alpha line occurs at a wavelength of 6,563 angstroms (1 angstrom = 1 Å = 10^{-10} m). If we examine the spectrum of a distant object and see this feature at 13,126 Å, what is

- The redshift of this object?
- The velocity of this object?
- The distance to this object?

Hint 1: Equation 2 defines the redshift-distance relationship. Hint 2: The velocity-redshift relationship for an object with velocity v and redshift z is $v = cz$, where c is the speed of light and $v << c$. In other words, the numerator of Equation 2 is the velocity of the object.

Flux and Energy Units

The SED can be represented graphically in several ways. The final plot will have flux on the vertical axis and either frequency or wavelength on the horizontal axis. The standard convention for units of flux are F_λ (ergs s^{-1} cm^{-2} $Å^{-1}$), F_v (ergs s^{-1} cm^{-2} Hz^{-1}), or Janskys (1 Jy = 10^{-26} Wm^{-2} Hz^{-1}).[1] The erg is a unit of energy equal to 100 nanojoules (1 erg = 10^{-7}J = 1 g cm^2/s^2). We can easily convert between these units:

$$F_v = F_\lambda \frac{\lambda^2}{c}, \tag{3}$$

where λ is the wavelength in angstroms and c is the speed of light in angstroms/sec.

There's one additional unit complication when looking at data from the sky catalogs. Generally, the brightness of an object is given in terms of *magnitudes*, a system that was originally based on what a human could see from Earth. In modern times, the definition has been quantified; however, it's still an unfortunate relic of ancient times. Magnitude is defined as a ratio of fluxes, in Janskys, between two different objects,[1]

$$m_1 - m_2 = -2.5\log_{10}\left(\frac{F_1}{F_2}\right). \tag{4}$$

To determine the magnitude of a selected object, we must compare it to an object that has zero magnitude. Thus, we need a *zero point flux*. The definition of a zero point is a reference with a known flux that's considered to represent a zero magnitude object. Usually this value is calibrated for the instrument that does the observation. So, the magnitude can be represented by the flux F from the object and a zero point flux, F_{zp},

$$m = -2.5\log_{10}\left(\frac{F}{F_{zp}}\right). \tag{5}$$

Therefore, we can compute the flux, in Janskys, from a given magnitude and a zero point flux.

Activity 3

The galaxy Arp 220 has a magnitude of 11.210 units when observed through a J-band filter (central wavelength of 1.235 μm). This observation was taken from the extended source catalog of the Two Micron All Sky Survey (2MASS), which has a J-band zero point flux of 1,594 Jy.[2]

- Compute the flux, in Jy, of Arp 220 in the J-band.
- Convert the flux into units of F_λ.

SED Fitting

This section describes the process for achieving an SED fit. The major considerations are separated into three parts: sky

Table 1. SDSS band pass wavelengths and zero point fluxes.

Band	λ (μm)	Zero point flux (Jy)
u	0.3551	3631
g	0.4686	3631
r	0.6165	3631
i	0.7481	3631
z	0.8931	3631

Table 2. 2MASS band pass wavelengths and zero point fluxes

Band	λ (μm)	Zero point flux (Jy)
J	1.235	1,594
H	1.662	1,024
K_s	2.154	666.7

Table 3. WISE Band Pass Wavelengths and Zero Point Fluxes

Band	λ (μm)	Zero point flux (Jy)
w1	3.35	306.681
w2	4.60	170.663
w3	11.56	29.0448
w4	24.24	8.2839

catalogs, SED templates, and the fitting procedure. Sky catalogs provide the flux and wavelength data available for the fit, and SED templates are fitted to the flux data from the catalogs. This lets us determine the redshift of the source and provides a crude galaxy classification. The final consideration is the fitting procedure. We use a χ^2 minimization to perform the fit (we'll cover minimization in more detail later, in the "Fitting Procedure" section). Generally, this gives a good fit to the data as long as at least one of the galaxy templates is similar in type to the source.

Sky Catalogs

Multiple sky catalogs can be used to derive an SED. It's useful to pick catalogs that span a large range of wavelengths, ideally from ultraviolet to far infrared or radio. The broader the wavelength range and the more densely sampled the SED, the more accurate the derived parameters and the resulting galaxy classification will be. This case study uses catalogs (SDSS, 2MASS, WISE, IRAS, and H-ATLAS) that range in wavelength from 0.35 μm to 500 μm. What follows is a description of each survey.

SDSS (Sloan Digital Sky Survey) covers approximately 35 percent of the sky in five band passes, from 0.35 μm to 0.89 μm. This covers the optical range of the galaxy spectrum.[3] Table 1 gives the SDSS band pass and associated wavelength and zero point flux. SDSS photometry is intended to be on what's called an AB system,[4] or a zero point flux value of 3,631 Jy across all its bands. SDSS uses a dedicated 2.5-meter telescope at Apache Point Observatory in New Mexico, and since 2000, it has created maps that contain more than 930,000 galaxies and 120,000 quasars.

SDSS data is located at www.sdss.org under the latest data release. You need to know the position, right ascension, and declination of the object to be found. As long as the object isn't an extended source, such as a nearby galaxy that fills the detector, the magnitude data should be reliable. Otherwise, it might be necessary to integrate over the extended source to extract the magnitude from the raw images.

2MASS (Two Micron All Sky Survey) used two telescopes, one located in each hemisphere, to map the entire sky. 2MASS observations were made in three near-infrared band passes to catalog stars and extragalactic sources.[2] The project took four years to complete and had a final data release in 2003. Table 2 shows each band pass and its associated wavelength and zero point flux.

2MASS data is located at http://irsa.ipac.caltech.edu under the "Data Sets" heading. You can search the point source catalog (PSC), extended source catalog (XSC), or the large galaxy atlas (LGA). All the catalogs have different types of sources depending on the type of galaxy. Very faint extended sources in XSC might not have correct flux values and thus we don't use them in this case study.

WISE (Wide-field Infrared Survey Explorer) is a NASA space telescope that launched in 2009. WISE performed an all sky survey at mid-infrared wavelengths, accessible only from space because of the atmosphere's absorbing properties. The image library produced by WISE contains data on the local solar system, the Milky Way, and the more distant universe. Included in the list of WISE discoveries are asteroids, brown dwarf stars, and very luminous infrared galaxies.[5] Table 3 gives each band pass and its associated wavelength and zero point flux.

Like the 2MASS data release, the WISE data is located at http://irsa.ipac.caltech.edu under the "Data Sets" heading. You can search the catalog to find a specific object or groups of objects. Included with the WISE data tables are also the 2MASS magnitudes for each object from the 2MASS PSC. If the object is an extended source, the 2MASS magnitudes can be inaccurate and thus can be avoided for this case study.

The IRAS (Infrared Astronomical Satellite) mission performed the first space-based unbiased, sensitive all sky survey at four wavelengths: 12, 25, 60, and 100 μm.[6] Like the wavelengths covered by WISE, light at these wavelengths doesn't penetrate the atmosphere, so the observations must be made from space. The US, the Netherlands, and the UK were partners on IRAS, and the survey was conducted from January to November 1983 to produce a reliable catalog of sources. Table 4 shows the bands and their associated wavelengths. There are no zero point fluxes for the IRAS data because the catalog already provides fluxes in Janskys (there's no need to convert the magnitude values to fluxes in Jy; we can use the flux data straight from the catalog). A catalog tool is located at http://irsa.ipac.caltech.edu under the heading "IRAS," and you can search several catalogs. For this case study, we focus on objects found in the point source catalog.

H-ATLAS (Herschel Astrophysical Terahertz Large Area Survey) uses the European Space Agency's Herschel Space Observatory to survey the far infrared and submillimeter bands.[7] The H-ATLAS project explores cold dust and gas regions out to redshifts of approximately 3 or 4. Table 5 gives each of the five band passes and their associated wavelengths. Similar to IRAS data, the H-ATLAS catalog provides fluxes in Janskys and hence there are no zero point fluxes listed.

H-ATLAS data is located at www.h-atlas.org. You can download the entire catalog, along with the catalog description, from the Public Data section. The H-ATLAS survey covers a smaller area than the other catalogs, so it would be useful to choose a list of objects in H-ATLAS because they'll most likely be available in the other catalogs. Also, H-ATLAS has spectroscopic redshifts for many of the objects that can be used to validate the photometric redshifts we obtain from the SED fit. You can download some of the catalogues we've used for this case study from https://encompass.gsfc.nasa.gov/data.html.

Table 4. IRAS band pass wavelengths.

Band	λ (μm)
1	12
2	25
3	60
4	100

Table 5. H-ATLAS band pass wavelengths.

Band	λ (μm)
1	100
2	160
3	250
4	350
5	500

Table 6. Positional uncertainties of various catalogs in arcseconds.

Catalog	Positional uncertainty (arcseconds)
WISE	0.3
2MASS	0.1
IRAS	16
H-ATLAS	2.4
SDSS	0.1

Activity 4

The primary issue when using multiple catalogs is matching sources between the catalogs. Positional uncertainty and limited instrumental resolution are the complicating factors. The following is an exercise that uses a simple algorithm to attempt to match sources across the catalogs that we'll be using:

- Download each catalog provided with the case study and read all of the columns into arrays (https://encompass.gsfc.nasa.gov/data.html).
- We'll use the *right ascension* (RA) and *declination* (DEC), standard sky coordinates, to perform source matching. Pick a source from one of the catalogs (such as Arp 220) and use its RA and DEC to locate the source in the other catalogs. The position won't match exactly across the other catalogs, so we'll attempt to get a best estimate by using a *tolerance factor* that's a function of instrumental and catalog limitations. The documentation for each catalog should give an estimate of the positional uncertainty and the instrument's spatial resolution. A thorough analysis will consider these limitations when selecting a tolerance factor. For this case study, we use a simpler approach. Consider the following positional uncertainties in Table 6 for each catalog.
- Let σ_1, σ_2, ..., σ_n be the positional uncertainties of the n catalogs being used respectively, and $\sigma = \sqrt{\sigma_1^2 + \sigma_2^2 + \ldots + \sigma_n^2}$ be our tolerance factor.

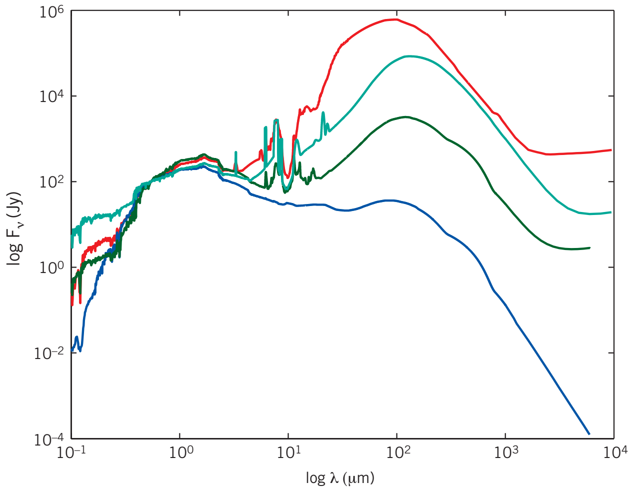


Figure 6. Example SED templates from the SWIRE template library.

- Find the nearest neighbor of the source point in each catalog. If the distance of the source point to its closest neighbor in each catalog is less than σ, declare this nearest neighbor a match. How many sources could be matched?

There are more sophisticated ways to do source matching using confidence intervals and other statistical approaches. Generally, this "nearest neighbor" approach will work for the purposes of this case study.

SED Templates

For this case study, we use the SWIRE (Spitzer Wide-area Infrared Extragalactic Survey) template library,[8] also posted at https://encompass.gsfc.nasa.gov/data.html. These are fixed galaxy templates, that is, there are no parameters that we can change to alter the shape. The benefit in using these templates is that we doesn't need extra knowledge about the physical properties that occur within the galaxy. The tradeoff is that the fits will be less accurate. To create better SEDs, we would include several parameters in the fitting procedure that correspond to galaxy properties that change the shape of the template.[9] However, this is beyond the scope of this case study. Figure 6 shows several of the templates.

The SWIRE template library consists of 25 SED templates created using a combination of simulation and observed spectra of real galaxies. The library includes three ellipticals, seven spirals, six starbursts, seven galaxies with Active Galactic Nuclei (AGN), and two composite spectra. Each template covers a wavelength range from 0.1 μm to 1,000 μm. The template is given in two columns, wavelength in angstroms and normalized F_λ (erg cm^{-2} s^{-1} Å^{-1}).

Activity 5

- Create a plot similar to Figure 6. Remember to convert the flux data in the template to units of F_λ and to convert the wavelength from angstroms to microns.
- You may notice that the template wavelength range is very spread out and the number of known data points at different wavelengths varies for each template. We can easily add more points to the template in a uniform way by using *interpolation*, estimating the values between two or more data points.
- To create more points on the wavelength axis of the template, use the Matlab routine `logspace`. The template should already contain around 1,000 points, depending on the specific template. Adding around 1,000 more points should work fine. Add these points to the already existing points from the template, using vertcat or a similar routine, and sort the resulting wavelength vector. These will be the new wavelength data points after the interpolation. (If there are any duplicated points in the wavelength range, you must use the unique routine to eliminate them, otherwise the interpolation will fail.)
- Use the Matlab routine `interp1` to do the interpolation of the data points from the template. There are a few polynomial options that you can use. Try several of them and see if the results or execution times are any different. For this case, the linear interpolation might be too simple; use either the quadratic or cubic interpolation. The result will be the flux data points at each of the new wavelength points that were created in the previous step.
- Plot the interpolated data sets in the same way as before. They should look nearly identical, but now the wavelength range is more uniform. This will be important when computing the χ^2 value of the fit of the template to the photometric data.

Fitting Procedure

With a set of templates and spectral data, you can fit a template to the catalog data and attempt to characterize the galaxy. There are a number of ways to do this. In this case study, we use three free parameters: the galaxy template, the redshift, and a luminosity scaling factor. All of the other possible galaxy parameters, such as stellar age, dust and gas extinction, AGN, and so on, are incorporated into the template because the template library was designed to span a range of galaxy types and physical conditions.

The fitting of each parameter of the spectral data to a galaxy template is a simple χ^2 minimization,[10,11]

$$\chi^2 = \sum_{i=1}^{N_{data}} \left[\frac{F_{data,i} - sF_{temp,i}}{\sigma_i} \right]^2, \quad (6)$$

where N_{data} is the number of spectral data points, $F_{data,i}$ is the flux at data point i, s is a template flux scaling factor to be determined, $F_{temp,i}$ is the ith data point of the template, and σ_i is the known uncertainty in the ith data point.

Activity 6

Generally, any minimization problem involves the derivative of the quantity to be minimized, in this case, the χ^2 value. When the derivative of a curve is zero, the point is either a minimum or maximum. Since Equation 6 is at most quadratic, there will only be one minimum value for χ^2:

- Find an explicit equation for the minimum for the flux scaling parameter, s, by taking the derivative of X^2 with respect to s and setting it equal to zero.

The next parameter to constrain is the redshift. This can be done by shifting the template horizontally and examining the χ^2 value.[12] In general, the lowest χ^2 will be the best fit to the data. Since the horizontal axis of the template is in units of wavelength, λ, there's a simple relation to take a test redshift, z_{test}, and apply it to the template to get a shifted wavelength, λ_{test}. The relationship is given by

$$\lambda_{test} = \lambda_{temp}(z + 1). \quad (7)$$

To find the best overall fit, we must loop though each template and a reasonable range of redshifts to find the template, redshift, and luminosity scaling factor combination that gives the smallest χ^2 value.

Activity 7

Now that we have the templates, catalog data, and an explicit equation for the flux-scaling factor, we can perform the SED fit. The following are the suggested steps:

- Create a grid of test redshifts to loop through for each template. The grid spacing should be fairly small. Remember, the finer the grid, the longer the calculation will take.
- Shift the template wavelengths depending on the test redshift.
- After shifting the template, the wavelengths of the photometric data might not correspond exactly to a data point in the template (this is required for computing χ^2). Write a routine that finds the closest corresponding point. Alternatively, perform an interpolation at each redshift that includes the wavelengths of the photometric data. This approach will be significantly slower.
- Compute the flux scaling factor based on the explicit equation derived earlier.
- Compute the X^2 value for the template, redshift, and flux-scaling factor combination using Equation 6.
- Repeat the previous steps for each redshift and scaling factor for each of the 25 templates. The combination that yields the lowest χ^2 value is the best fitting combination.
- Plot the data and the shifted spectral template that provides the best match. How well does the data match the shifted template?

After completing these steps, we have a redshift estimate and a crude galaxy classification based on the best fitting redshift and template. If the galaxy has a known spectroscopic redshift, we can compare it to the redshift estimate.

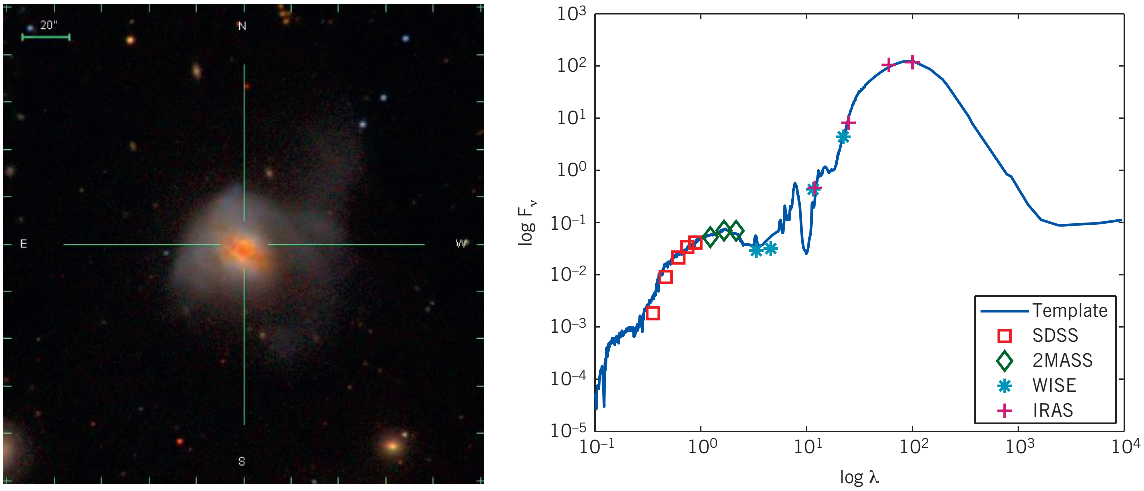
Hint 1: Work with the same source that you picked in Activity 4 (Galaxy Arp 220).
Hint 2: Galaxy Arp 220 has an actual redshift of 0.018.
Hint 3: No H-ATLAS data is available for galaxy Arp 220.
Hint 4: Figure 7 show SDSS image of Galaxy Arp 220 and a graph of our SED fit for it.

Activity 8

You can repeat the last Activity for Galaxy J090746.91+003430.4.

Hint 1: You've already seen our SED fit for this galaxy in Figure 1.
Hint 2: Galaxy J090746.91+003430.4 has an actual redshift value of 0.054.
Hint 3: No WISE data is available for Galaxy J090746.91+003430.4. You can benefit from H-ATLAS data instead.

The objective of this case study was to perform an SED fitting of WISE data to a set of physical galaxy templates. Since WISE data alone isn't enough to accurately fit an SED, we used several additional flux measurements from



(a) (b)

Figure 7. Image of Galaxy Arp 220 from (a) SDSS and graph (b) of our SED fit for it.

other catalogs. This gave a larger range of wavelengths. We achieved this goal via an algorithm based on standard χ^2 minimization techniques. We obtained a crude galaxy classification and a redshift estimate.

This case study teaches the astronomical and computational issues when fitting flux data. There are many more ways to achieve an accurate fit to the data. However, most require more specialized knowledge of the physical processes that occur within galaxies. As a teaching tool, this case study blends computer science and astronomy so that it's useful to both fields. ■

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